A Possible Signature of Magnetic Cavity Mode Oscillations in ISEE Spacecraft Observations

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(Received January 16, 1997; Revised May 20, 1997; Accepted June 27, 1997)

The structure of magnetohydrodynamic waves in the terrestrial magnetosphere is controlled by the dispersion relations of the wave modes, the inhomogeneities of the system and the boundary conditions. If the waves are confined within the magnetospheric cavity with proper boundary conditions, two types of spectra are predicted by MHD theory. One is a discrete compressional spectrum and the other is a continuous shear Alfvén spectrum. The discrete spectrum refers to compressional eigenmodes with spatially constant eigenfrequencies. The continuous shear Alfvén spectrum corresponds to field line resonances with spatially varying resonant frequencies. There have been many reports of observations consistent with the theoretical predictions for shear Alfvén waves. However, only a few spacecraft observations of the global cavity eigenmodes or the coupling between the two modes have been reported. Here we report an observation using ISEE 1 and 2 spacecraft magnetometer data. On a quiet day with low solar wind dynamic pressure and low geomagnetic activity, the ISEE 1 and 2 spacecraft identified a compressional wave with constant frequency throughout most of its inbound orbit in the outer magnetosphere. Multiple harmonics of shear Alfvén waves with spatially varying frequencies were observed in the azimuthal component. Evidence of the coupling between these two waves is found. Comparing our observations with the results of a computer simulation in a dipole field, we find qualitative (not quantitative) agreement. We also consider why so few examples of radially-extended monochromatic compressional oscillations have been found. We conclude that the exceptional circumstances required for development and identification of these wave structures occur very rarely.

1. Introduction

Magnetospheric MHD waves in a cold uniform plasma are characterized by two modes referred to as toroidal and poloidal because of their dominant polarizations. If wave disturbances are not fully axisymmetric, the two modes couple and no pure mode exists. In a dipole field, the toroidal mode corresponds to transverse pulsations with predominantly azimuthal magnetic perturbations that can propagate along field lines. With a high conductivity ionosphere at the ends of field lines, toroidal mode waves are reflected and a standing wave structure or the so called “field line resonance” harmonic structure is established. Field line resonances were successfully predicted by theory (Chen and Hasegawa, 1974; Southwood, 1974) and observed both on the ground and in space (Rostoker and Samson, 1972; Lanzerotti et al., 1976; Takahashi and McPherron, 1982, 1984; Yumoto et al., 1985; Engebretson et al., 1986; Anderson et al., 1989).

The poloidal mode corresponds to field-aligned pulsations, with magnetic perturbations predominantly compressional and radial, which can propagate across magnetic field lines. External energy sources such as surface waves generated by Kelvin-Helmholtz instabilities or impulsive compression of the magnetospheric cavity can couple to resonant field lines inside the magnetosphere through these compressional waves. In a quasi-steady state, compressional waves can stand in the cavity between radially separated boundaries if their frequencies correspond to cavity mode frequencies, and thus they can be observed after the initial impulsive excitation (Kivelson and Southwood, 1985, 1986; Allan et al.,
Alternatively, the cavity can act like an interferometer that absorbs power only at discrete frequencies (Pilipenko, 1990). Thus broadband upstream waves can also drive cavity modes. These discrete cavity modes decay by coupling to the transverse Alfvén waves on L shells where the frequency of the field line resonances matches that of the cavity mode. They can also decay by depositing Poynting flux from the wave into the low latitude ionosphere (Allan and Poulter, 1989) or by leaking energy into the magnetotail. In this latter case, the cavity may be better approximated as a wave guide (Samson and Harrold, 1992) with the azimuthal wavelength imposed by the source. The character of the solution on the dayside is little affected by this modification. A number of numerical simulations (Allan et al., 1986a, b; Inhester, 1987; Zhu and Kivelson, 1988, 1989; Lee and Lysak, 1989) show that these cavity modes are likely to exist, and provide insight into their behavior.

Despite the recent theoretical interest in cavity modes, there is little observational evidence that they exist, although there is abundant evidence for the more easily observed field line resonance mode to which the magnetic cavity mode couples. However, Kivelson et al. (1984) attributed a compressional MHD wave recorded by instruments on the ISEE-1 satellite to a magnetospheric cavity mode. Crowley et al. (1987) presented ground-based magnetometer and European Incoherent Scatter (EISCAT) radar observations of transient ULF pulsations excited by a sudden impulse. By using a model of standing Alfvén waves and ionospheric Pedersen conductance measured by EISCAT, they showed that the observed wave had a very low damping rate. They interpreted this low damping rate as evidence that the wave was driven by a compressional magnetospheric cavity mode stimulated by an earlier sudden pressure pulse in the solar wind. Numerical analyses (Allan and Poulter, 1989; Allan and McDiarmid, 1989) have provided insight into the relation between damping produced by direct energy losses to the ionosphere and damping arising from coupling to the continuous spectrum of field line resonances. Their analysis supports the interpretation of Crowley et al. (1987).

Here we report an observation of a radially extended quasi-monochromatic compressional wave structure in the ISEE-1 magnetometer data. On a quiet day with low solar wind dynamic pressure and low geomagnetic activity, such a wave was observed on an inbound orbit near the magnetic equator in the morning magnetosphere. Typical field line resonances were present in the azimuthal component through most of the 4-hour event. Evidence for coupling between the two modes is also found. We will compare our observations with the results of a computer simulation in a dipole field by Lee and Lysak (1989). We find qualitative and even some quantitative agreement between the theory and observations. We discuss the conditions required for observing a wave structure of the form reported and note remaining problems and discrepancies in the concluding section.

2. Data Presentation

2.1 Data preparation

This event was observed by the ISEE 1 and 2 spacecraft. ISEE-1 and its daughter ISEE-2 were launched from the Eastern Test Range on October 22, 1977. They were placed in highly elliptical orbits with apogees of 22.6 earth radii (Re) and perigees of about 700 km. For the purpose of this study, we retrieved a full year of ISEE-1 magnetic field data at 4-second resolution from the UCLA data archives. The data were transformed to GSM (Geocentric Solar Magnetic) coordinates. We plotted these data and identified the locations of the magnetopause crossings. On November 24, 1977, at 19:40 UT, the ISEE-1 spacecraft crossed the morning magnetopause at 10:00 MLT (Magnetic Local Time) and 12.4Re as shown in Fig. 1. The spacecraft remained within 12° of the magnetic equator from 20:00 UT (11.8°) to 24:00 UT (6.6°). Inside of the magnetopause, quasi-sinusoidal fluctuations at a number of frequencies were noted. To facilitate wave analysis, we transformed the data from GSM and spacecraft coordinates into a field aligned coordinate (FAC) system. The $\mu$ component of this right-handed, orthogonal system is parallel to the background magnetic field, and the two transverse components are $v$ which is normal to the background field and positive radially outward and $\phi$ which is positive azimuthally eastward and completes the right handed system.
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Orbit No. 14

Start Time: 1977 11 24 18:0 Stop Time: 1977 11 25 2:0

Spacecraft Trajectory

Nominal Magnetopause

Fig. 1. Orbit plot of orbit 14 of the ISEE 1 spacecraft. The left panel is the orbit projected into the GSM equatorial plane. The right panel is the orbit projected onto a meridian plane. Universal time on Nov. 24 and 25, 1977 is marked along the orbit. Three circles at 5, 10, and 15RE mark the radial distance from the center of the earth. The nominal magnetopause position is plotted as a dotted curve.

The background field was determined by two different methods. To produce dynamic spectra, a running average of length 5.4 minutes (81 data points at 4 second resolution) was performed on each GSM component of the field. The low pass filtered field and the spacecraft position in GSM coordinates were used to determine a time dependent transformation to field-aligned coordinates. For the line spectra, we fitted a 6th order polynomial to the components of the field in spacecraft coordinates and used this detrended field and the spacecraft position in spacecraft coordinates to determine the transformation. The total field and fluctuation in field-aligned coordinates as determined by polynomial detrending are plotted in Fig. 2. Waves are evident through most of the interval plotted. The final magnetopause crossing at 19:40 UT is evident from the increase of the magnitude of the background magnetic field intensity and the associated decrease in fluctuations (see $B_t$ in bottom panel). In the magnetosheath, before ISEE entered the magnetosphere, strong perturbations with peak to peak amplitude over 10 nT were present, predominantly in the compressional component. Inside the magnetosphere, the perturbation amplitude was 3–10 times smaller. Different vertical scales are used for plots of the first four hours and the last four hours in Fig. 2 for this reason. The plots of the interval 18:00–22:00 UT reveal clearly the difference in amplitude between perturbations in the magnetosheath and in the magnetosphere while the plots of the interval 20:00–24:00 UT show details of the smaller amplitude waves within the magnetosphere. The compressional and radial components, $\mu$ and $\nu$, contain wave power both centered at 24 mHz and distributed over a broad band below 4 mHz. In the interval 22:00–23:00 UT, the wave amplitude significantly decreased in all three components and both frequency bands. At 23:00 UT, these waves reappeared nearly simultaneously in all three components with power restored to the previous levels.
2.2 Dynamic spectra

We used dynamic spectral analysis to characterize the frequency of the waves and find possible harmonic relationships. This procedure included Fast Fourier Transforms (FFT) and calculation of auto spectra. Auto spectra of the three components were calculated from 20 minute segments advanced by 5 minutes. Seven Fourier coefficients were averaged to obtain each spectral estimate. Dynamic spectra are plotted in Fig. 3. The color scale represents the logarithm of wave power and it is plotted versus frequency and universal time. The wave power is shown separately for each of the three components in a field-aligned coordinate system determined by the running average method. Between 18:00 UT and 19:40 UT, there are no clear spectral peaks in the magnetosheath perturbations (Lin et al., 1991). Between 19:40 UT and 24:00 UT, the magnetospheric perturbations contain compressional wave power at a nearly constant frequency of about 24 mHz, evident as a horizontal band for about 2 hours from ~20:00–22:00 UT. After 22:00 UT, the wave signal vanishes for about an hour and reappears at ~23:00 UT with somewhat broader frequency distribution. Several harmonics with continuously increasing frequency are apparent in the azimuthal component. The power in these harmonics did not decrease until 22:30 UT. In the last hour, the harmonic structure in the azimuthal component is not clear and the overall power level is lower. No clear spectral peaks are present in the radial component. The power level of the radial component is also lower than the wave power in the other two components.
In order to enhance the spectral peaks against the background, we used a wave power whitening technique. A fourth order polynomial was fit to the logarithm of the power spectra vs. frequency to determine the trend in the background spectrum. Residuals of the power spectrum relative to the polynomial fit were then calculated. In Fig. 4, these residuals are plotted in color versus frequency and universal time. Figure 4 looks quite different from Fig. 3, with more clearly defined compressional and azimuthal spectral peaks. In Fig. 3, for example, the harmonics in the azimuthal component seem to disappear between 22:30 and 23:00 UT. In Fig. 4, these harmonics are evident throughout the whole hour (22:00–23:00 UT). The nearly constant frequency bands observed in the compressional component become apparent in the radial component as well. However, the trace is not so clearly defined as it is in the compressional component. The power at frequencies below 4 mHz, evident in the time series traces of Fig. 2, is not well-represented in the dynamic spectra because the 20 minute segments used in calculation contain less than 2 cycles of these waves, but the power at these frequencies produces the enhancement evident at the bottom of the dynamic spectra in Figs. 3 and 4.

There are obvious differences between the dynamic spectra in the magnetosheath (18:00–19:30) and in the magnetosphere (20:00–24:00). For the compressional component, broadband power was present in the magnetosheath while within the magnetosphere quasi-monochromatic compressional waves appeared. Figure 5 illustrates the differences. The first three panels compare the autospectral densities with five harmonics per estimate of the three field-aligned coordinate system components in the magnetosheath (thick top trace) and the magnetosphere (thin bottom trace). For all three components, broadband power was present in the sheath spectra without any clear spectral peaks. Inside the magnetosphere, wave power spectral densities are two to three decades lower than in the magnetosheath across the entire frequency band for all three components. Clearly the broadband turbulence observed in the magnetosheath is not
Fig. 3. Dynamic spectra of three magnetic field components in a field aligned coordinate system. The azimuthal axis is universal time and the vertical axis is wave frequency. The color scale shows the logarithmic wave power in nT²/Hz.
Fig. 4. Dynamic spectra of three magnetic field components in a field aligned coordinate system. The appearance differs from Fig. 3 because the wave power spectrum was whitened. Here, we show the residual of the wave power with respect to 4th order polynomial fits to successive power spectra. This technique enhances the wave power at high frequency and is useful for visualizing the evolution of narrow-banded peaks. The color scale gives the relative wave power on a logarithmic scale with respect to the polynomial fit. The color scale saturates when the wave power is 10 times larger or smaller than the polynomial fit to the spectra which we consider to be the trend of the background spectra power.
Fig. 5. Panels 1–3 show power spectra of the magnetic field in the magnetosheath (18:00 to 19:30 UT) and in the magnetosphere (20:00 to 24:00 UT). The three components are in a field-aligned coordinate system defined by a polynomial fit to the observed field in spacecraft coordinates. The fourth panel shows log-log plot of the spectra in the magnetosphere for the interval 20:00 to 24:00 UT. The thickest line corresponds to nu, and the thinnest line to mu components. Five harmonics (10 degrees of freedom) were used in each spectral estimate of every panel.
present with the same amplitude inside the magnetosphere. On the other hand, the spectra in the magnetosphere show a strong peak at ~24 mHz, especially in the compressional (µ) component.

The fourth panel in Fig. 5 displays the autospectra of the components in field-aligned coordinates inside the magnetosphere. To improve spectral resolution around 1 mHz we used all data from 20:00 to 24:00 UT and only 5 harmonics per spectral estimate. The spectra show that the radial and field-aligned components were significantly enhanced relative to the azimuthal component at frequencies below 4 mHz, but only a weak spectral peak at 1.6 mHz can be distinguished. Despite the absence of a prominent peak, polarization analysis shows that the signals in the radial and field-aligned components were highly polarized below 4 mHz. The major axis of the polarization ellipse was aligned in a magnetic meridian at ~72° to the field with a normal to the ellipse nearly in the azimuthal direction. The rms amplitudes of the three components below 4 mHz were 0.69, 0.28, and 0.78 nT respectively. For comparison, the rms amplitudes in the frequency band (5-50 mHz) including the strong peak were 0.06, 0.08, and 0.06 nT.

The autospectra plotted in panel 4 display an obvious artifact of the three-point (~12 sec) running average applied in the production of the 4-second samples used in our analysis. A minimum in wave power at 80 mHz corresponds to the first zero in the transfer function of this filter. An additional artifact is the flattening of the spectrum below 0.4 mHz which results from two steps in the data processing. The first is the effective low pass filter created by the field-aligned coordinate transformation using the polynomial background field method. The second is an additional fourth order polynomial detrending of the field-aligned coordinate data prior to spectral analysis. Spectra calculated in spacecraft coordinates without detrending display a continuous increase in spectral density to the lowest frequency estimate.

Not present in the line spectra of Fig. 5, but readily understood, is the effect of the 5.4 minute (81 point) running average used to obtain a background field for the field-aligned coordinate transformation used in calculating the dynamic spectra. This low pass filter passes all frequencies below 1 mHz. So the background field, and hence the field-aligned transformation, follows any fluctuation with frequency lower than 1 mHz. Consequently, these frequencies are absent in the transformed data making it appear to have been high passed. This produces a very strong peak at 1.6 mHz in the dynamic spectra which used this technique. However, as can be seen in the autospectra of panel 4 obtained by using a polynomial background for the field-aligned transformation, the peak at ~1.6 mHz is relatively weak.

2.3 Solar wind and ground observations

Solar wind parameters observed by the IMP-8 spacecraft are plotted in Fig. 6. During the wave event, the IMP-8 spacecraft was in the solar wind at (5.48, -36.67, 19.78) where distances are in RE in a GSM coordinate system. The upper panels show the solar wind plasma parameters measured by the Los Alamos instrument at ~4 min resolution. The solar wind bulk flow velocity (top panel) was near 300 km/sec for the entire interval. This is about 25% below the nominal 400 km/sec value. The second panel shows solar wind proton density. The proton density was ~8-9/cm³. The third panel gives solar wind dynamic pressure. Solar wind dynamic pressure was stable throughout the first four hours of the ISEE 1 observation. It increased by about 35% in the last two hours (22:00–24:00 UT), mainly because the proton density increased. The next panels show solar wind magnetic field properties sampled at 15 s time resolution. The fourth panel shows that the total field varied from ~5 nT to ~3 nT during the 6 hours. The fifth panel shows that the interplanetary magnetic field (IMF) Bz component was northward during the 6 hours except for a brief southward turning at ~22:55 UT. The sixth panel contains a plot of the IMF cone angle. The IMF cone angle was ~45–50° for the first four hours. In the one hour interval between 22:00–23:00 UT, the cone angle increased significantly reaching more than 100° (but <130°) by the end of the hour. Then during the last hour, the IMF cone angle returned to its initial value of ~45°.

The seventh panel shows the wave power of the compressional component at the frequency of 24 mHz observed by the ISEE-1 spacecraft along its trajectory. This is the center frequency of the persistent quasi-monochromatic wave power present in the dynamic spectra of the compressional component of Fig. 3. From 18:00 to 19:40 UT, the ISEE-1 spacecraft observed high power at this frequency (and all other frequencies) in the magnetosheath. The spacecraft entered the magnetosphere at 19:40 UT. The
Fig. 6. Solar wind parameters and the $Kp$ index. The solar wind data are from the IMP-8 satellite. The plasma data (panels 1–3) are at ~4 minute resolution. The magnetometer data (panels 4–6) are at 15 s resolution. The 7th panel shows the log of the wave power in the compressional component of the ISEE-1 magnetic field at a frequency of 24 mHz. Panel 8 shows the $Kp$ index.
compressional wave power dropped by about 1 decade across the magnetopause. During the first two
hours inside the magnetosphere (between 20:00 and 22:00 UT), the compressional wave power was nearly
constant. Starting near 22:00 UT, the compressional wave power decreased significantly by about 3
decades. After 23:00 UT, the compressional wave power returned to the previous level where it remained
to the end of the wave event. The averages of compressional power over the intervals inside and outside
the magnetopause differ by a factor of 30.

The bottom panel presents the $Kp$ index. It was a very quiet day with the $Kp$ index below 1 for the
entire interval. The $Kp$ index was zero for the two hours between 18:00–21:00 UT. Thus the magneto-
sphere was exceptionally quiet during that time.

3. Discussion

3.1 Selective absorption of magnetosheath wave energy

Clear differences between wave perturbations in the magnetosheath and in the magnetosphere
demonstrated in Figs. 2, 3, 4, and 5 help us understand how the magnetosphere responded to the
perturbations on its boundary. First, at frequencies above 4 mHz wave power dropped more than two
decades when the spacecraft crossed the magnetopause as obvious in Fig. 5. More precisely, integrated
over the band from 4 mHz to 125 mHz the ratios of external to internal power are 180, 204, and 635 for
the three components. Below 4 mHz the relative power spectral density in the meridional components rises
as frequency decreases becoming nearly half the external power spectral density. As a consequence the
ratios of total external to internal power in this lower band are 5, 57, and 20. Integrated over the entire
frequency spectrum these ratios are 12, 91, and 35. This implies that more than 90 percent of the wave
power was either not transmitted through the magnetopause or quickly damped within the magnetopause
boundary layer. Second, magnetosheath perturbations were broad band without clear spectral peaks. In
contrast, inside the magnetosphere quasi-monochromatic compressional waves were observed as evident
from the spectral peaks in Fig. 5. The magnetosphere appears to be acting like a Fabry-Perot interferometer
for some of the magnetosheath MHD wave power (Pilipenko, 1990). A Fabry-Perot interferometer
absorbs incident energy when the incident wave length $\lambda$ satisfies the relation $\lambda = nW$ where $n$ is an integer
and $W$ is the slab width. The system will absorb little power from waves that do not satisfy this relation.
The peak frequencies at -1.6 mHz and 24 mHz in Fig. 5 can be interpreted as frequency bands for which
the magnetosphere selectively absorbs magnetosheath waves but there are reasons to question this
interpretation for the -1.6 mHz waves which we discuss below.

Selective absorption of incoming wave energy can be explained by assuming that the magnetosphere
is a magnetic cavity or a wave guide with a broad band energy source at its boundary. The specific
frequencies that fit the global boundary conditions on the magnetic field and plasma flow are the ones for
which a Fabry-Perot type of resonance can occur.

3.2 Energy source and damping of cavity waves

In the plasma physics laboratory of space, we have no control of experimental conditions, but with
luck we may encounter something interesting. Below we argue that the steady upstream conditions
modified only by a rotation of the interplanetary field for an interval of 1 hour, enabled us to identify the
source of wave energy.

Figure 6 shows that the IMF $B_z$ was positive (near 3 nT until 22:00 UT) except for a short excursion
at -22:55–23:00 UT. The very low $Kp$ index (bottom panel of Fig. 6) implies that the magnetosphere was
in a very quiet and stable state before and during this wave event. The positive IMF $B_z$ and the low $Kp$ index
allow us to dismiss dayside reconnection or a substorm as probable energy sources for this event. We
believe that conditions were ideal for development of a quasi-static magnetosphere with constant cavity
size, plasma parameters and magnetic field configuration, a requirement for containing a cavity mode. The
analogy to an organ pipe (Fig. 7) illustrates the argument. If the length of an organ pipe changes without
changing the sound speed in its interior, its normal mode frequency will change rendering it incapable of
confining the originally resonant wave power and leading to wave damping. Changing solar wind parameters and magnetopause positions would similarly cause a cavity eigenmode with constant frequency to decay, although the rate of decay will depend on details of the changing configuration. However, in this event, the external conditions remained quite steady with the IMF cone angle near 45° and the solar wind dynamic pressure low and stable at about 1.2 nPa until 22:00 UT. This allowed the magnetosphere to contain relatively small amplitude waves (only ~0.4 nT for the 24 mHz wave and about 1 nT for the ~1.6 mHz wave) over a large spatial volume for a prolonged time.

In the middle of the event (between 22:00-23:00 UT), the compressional power at 24 mHz dropped to a low level. The change in compressional wave power was well correlated with the increase of the IMF cone angle (panels 5 and 6 of Fig. 6) at ~21:50 UT. This suggests that the disappearance of the compressional signal between 21:50 UT and 23:00 UT occurred when the IMF rotated away from an orientation within ±50° of the earth-sum line, that is, when its orientation no longer satisfied the condition that Greenstadt and Olson (1979) linked to the presence of Pc 3 power on the ground. IMF control of the Pc 3 wave power can be interpreted in terms of the magnetic geometry that allows upstream waves (Russell and Hoppe, 1983; Lin et al., 1991) generated near the nose of the bow shock to propagate to the dayside magnetopause. An empirical relationship, \( f (\text{mHz}) = 6B (\text{nT}) \) (e.g., Troitskaya et al., 1972), relates the upstream wave frequency to the IMF magnitude which was between ~5 and 3 nT between 18:00 UT and 24:00 UT. This implies that upstream wave frequencies fell in the ranges 18–30 mHz during the interval studied. Thus, it seems valid to suggest that upstream waves serve as the energy source of the 24 mHz wave power observed by ISEE 1 and that a relatively broad band perturbation at the magnetopause was driving the quasi-monochromatic compressional waves inside the magnetosphere. Given the IMF magnitude of 3–5 nT, it is hard to link the ~1.6 mHz signal to upstream waves.

The response of the magnetospheric wave power to the IMF cone angle change enabled us to estimate the \( Q \) of the outer magnetosphere system. Between 22:00–23:00 UT, as the IMF cone angle increased, the compressional wave power dropped. After 23:00 UT, when the IMF cone angle rotated back to ~45°, the power in the quasi-monochromatic compressional waves returned to the previous level. The correlation is clearest for the ~1.6 mHz wave. The IMF cone angle became >45° at about 22:00 UT. After that time, only 3 cycles of the ~1.6 mHz wave in the compressional and radial components are evident in Fig. 2 and, correspondingly, in Fig. 4 enhanced power lasted for ~30 minutes or 3 wave cycles at ~1.6 mHz. For the 24 mHz wave, 3 cycles last less than 2 minutes, so the enhanced power disappeared within one spectral estimate. We can estimate the \( Q \) value of the magnetospheric system from the relation:

\[
Q = \frac{\omega_c}{\Delta \omega}
\]
where $\omega_0$ is the peak frequency and $\Delta \omega$ is the half bandwidth defined by

$$P(\omega \pm \Delta \omega) = 0.5P(\omega_0).$$

Our calculation from line plots of the compressional component gives $Q \equiv 3$ for the $-1.6$ mHz wave and $Q \equiv 10$ for the $24$ mHz wave. These low values of $Q$ reveal that the wave power must be provided nearly continuously to pump the wave mode as these waves seem to be effectively damped in the magnetosphere. Possible damping mechanisms include coupling with local field line resonances, direct deposition of energy into the ionosphere, and transport of energy to the nightside.

### 3.3 MHD eigenmodes of the magnetosphere

If the observed waves are eigenmodes of the magnetospheric cavity or wave guide, they should not be a localized phenomenon but should extend over large parts of the cavity (except at spatial nodes and regions of decaying amplitude). With a localized observation (ISEE-2 was separated from ISEE-1 by only 500 km and therefore does not provide an independent measurement), it is hard to determine the spatial extent of these waves. Nevertheless, in Fig. 2, strong compressional wave power was present during the first two hours inside the magnetosphere (20:00–22:00 UT) as the spacecraft moved from 12RE to 9RE. Wave power disappeared for about an hour after 23:00 UT and reappeared in the last hour. In this interval the spacecraft moved from 7.6RE to 5.5RE. The compressional waves were therefore observed near the magnetic equator over 7RE in radial extent with nearly constant frequency, and with no significant change in wave power during the first two hours or the last hour. Since the one hour wave power “drop out” between 22:00–23:00 UT was well correlated with the change of IMF cone angle (Fig. 6), it is reasonable to assume that the IMF cone angle was controlling the wave power incident on the magnetopause (Russell and Hoppe, 1983). The GOES-2 satellite observed $-24$ mHz compressional waves from 16:30 to 24:00 UT in the afternoon sector, and the SMS-2 satellite also observed enhanced power at 24 mHz from 16:30 to 19:00 in the morning sector. Neither spacecraft observed compressional power at $-1.6$ mHz. Thus, during this event, the same ($-24$ mHz) wave frequency was observed simultaneously by three spacecraft over a region that extended radially from 6 to 12RE and over local times from 07:30 to 19:00 MLT. Whenever a source of wave energy was present at the magnetopause, continuous narrow-banded compressional wave power was observed over a large part of the outer magnetosphere and was not localized in radial or azimuthal extent.

It is of special interest to compare the spectral characteristics of the compressional signal with those of a wave event on October 17–18, 1992 observed in the GEOTAIL data by Takahashi et al. (1994). That event was interpreted as a fast magnetosonic wave propagating Earthward in the dayside magnetosphere. The spectra also peaked in the Pc 3 band but the spectral characteristics differ markedly from those reported here. The GEOTAIL case consisted of intermittent bursts with center frequencies $f$ varying from 30 to 45 mHz. The individual bursts had a frequency spread $\Delta f/f \sim 0.6$ (where $\Delta f$ is the full width at half maximum). The spectral peak in the ISEE 1 data remained in the range 20–25 mHz and was narrower-banded with $\Delta f/f \leq 0.3$ in hourly spectra. Thus this wave event differed in important ways from the propagating events of Takahashi et al. (1994). The signature that we describe is that of a global mode wave, but, as we have mentioned, narrow band or monochromatic compressional waves that sustain their wave power over a large part of the magnetosphere are not necessarily cavity eigenmodes. They may equally well be wave guide modes that are not bounded azimuthally (Samson and Harrold, 1992). In the wave guide, the azimuthal group velocity would have to be low enough to keep the wave power from escaping from the dayside in a few cycles. We are informed that computer simulations of compressional waves propagating in a dipolar cavity show low azimuthal group velocity (Lee and Lysak, 1991). It matters little to our interpretation of this event whether the compressional waves were resonant eigenmodes of a wave guide or MHD eigenmodes of a cavity. In either case, the magnetosphere absorbed compressional power preferentially at discrete frequencies. This suggests that the source contained power at frequencies that matched resonant frequencies within the magnetosphere.
Global compressional modes should couple into field line resonances of the same frequency (Kivelson and Southwood, 1986). Inside of the magnetosphere (from 19:40 UT to 24:00 UT) in Fig. 3, we find that the harmonics of the field line resonances (middle panel showing the azimuthal component) were enhanced when their frequencies matched the frequency of the 24 mHz compressional wave (top panel). This suggests that the compressional wave coupled into the field line resonant waves. During the hour (22:00–23:00 UT) when the compressional wave power disappeared, wave amplitude in the azimuthal component also decreased significantly (Fig. 2). However, wave power at harmonics of the field line resonant frequencies were still present above the background as can be seen in the detrended dynamic spectra (Fig. 4 middle panel). This suggests that even though the compressional wave power dropped below the observational threshold, there was still power to drive field line resonances. We do not think that the Q of the field line resonances was so high that they persisted for at least an hour. Broad band energy is required to excite the field line resonators at their harmonics over a range of radial distances. The frequency selectivity that we have compared with the Fabry-Perot effect must be only partially effective, allowing some wave power to cross the magnetopause at all frequencies. One could propose that the field line resonances might have been excited by an internal broad band source rather than the solar wind, but the close correlation between harmonic wave power and the IMF orientation suggests an external energy source for this event.

Although we believe that the 24 mHz signal was that of a global standing wave, we question whether the ~1.6 mHz wave corresponds to a cavity resonance. Some of its properties, such as a relatively narrow-bandwidth and rapid decay after the IMF rotated beyond ~45–50°, are consistent with expectations for a cavity mode wave. However, the frequency is too low for a standing wave. Consider that the longest standing wavelength is not expected to exceed twice the scale of the dayside cavity, ~20RE. Typical MHD wave speeds are of order of 1000 km/s. This implies that cavity resonances should be found only at frequencies >8 mHz. In addition, one expects a cavity mode signal to extend over a large spatial region, yet the ~1.6 mHz signal was not observed by the two spacecraft near the geostationary orbit. This would be reasonable if the ~1.6 mHz waves were confined to the outer magnetosphere beyond L = 7 and the geostationary orbit were inside the turning point of the standing wave power (Kivelson and Southwood, 1986). Yet the minimum frequency for a standing wave confined to the outer magnetosphere is even higher, say ~16 mHz. Thus, we think it unlikely that the ~1.6 mHz wave was a cavity mode wave. It seems more probable that it was directly driven. Although there is no evidence of power at ~1.6 mHz in the data from the solar wind, it is possible that waves were driven by compressional pulses generated at the quasi-parallel bow shock (Fairfield et al., 1990). In that case, the decay of the signal (which decayed in 3 cycles after the IMF cone angle rotated above 50°) after 22:00 UT can be understood as a shift of the quasi-parallel portion of the bow shock away from the Earth-sun line.

3.4 Why have few cavity mode events been reported?

We searched one year of ISEE-1 magnetic field observations and found only this one case of persistent narrow banded ULF compressional wave power that we identify as a global mode wave. If the global mode waves can exist in the dayside magnetosphere, why has only one event been found? We recapitulate several reasons why the magnetospheric cavity mode has been rarely observed:

(1) The Q value of the magnetospheric cavity system is low. In order for cavity mode waves to persist, there must be continuous energy input. Persistence is essential for detection from a single spacecraft in order that the spacecraft can move across a range of L-shells large enough to verify the constancy of the wave frequency.

(2) Coupling of upstream wave power into the magnetosphere occurs efficiently only when \( \theta_{Bx} \leq 45–50° \) (Greenstadt and Olson, 1979), but the IMF cone angle is highly variable. This means that energy input is rarely steady for a time long enough for a spacecraft to identify the global signature of the cavity mode. We have verified this statement by analyzing 5 months (October 1977 to March 1978) of IMP-8 solar wind data. In this time interval, the IMF cone angle was <45° for 39% of the time. The probability decreased to 8% if we imposed the additional requirement that the cone angle remain below 45° for at least 40 minutes.
A Possible Signature of Magnetic Cavity Mode Oscillations in ISEE Spacecraft Observations

(3) The magnetospheric cavity must be stable in size and configuration. This requires steady solar wind dynamic pressure. The requirement for stable solar wind dynamic pressure reduces the probability of observing a magnetospheric cavity mode below the 8% noted above.

(4) Changes of magnetic configuration and plasma convection of the magnetosphere can also relate to internal dynamical processes. The requirement for a very quiet magnetosphere can be expressed in terms of auroral activity indices such as $Kp$. The event that we report corresponded to an exceptionally low level of activity with $Kp < 1$ throughout the interval. Requirement of very low $Kp$ further restricts the probability of observing global mode waves.

(5) The amplitudes of the compressional fluctuations in cavity mode waves are small compared with background magnetic field even though the total energy stored in the magnetosphere can be large. Detection of a persistent signal may require special data processing.

(6) Assuming that all of the stability conditions are satisfied, there must be a spacecraft in the right orbit to detect the signal. In the event we consider here, the spacecraft remained within 12° of the magnetic equator, which is where Zhu and Kivelson (1991) found compressional power and where compressional waves in the outer magnetosphere of Lee's (1996) simulation are localized. (The rather high inclination of the ISEE orbit means that data are not generally acquired in regions near the magnetic equator.) If a spacecraft is to identify global mode waves, it must remain in the region of finite wave amplitude long enough to observe multiple wave periods while also moving radially far enough to verify the constancy of frequency across L-shells.

The probability that all of the above conditions are satisfied simultaneously is small which makes it clear why there has been little success in identifying magnetospheric cavity modes in spacecraft data. As noted previously, we found only a single event in a full year of ISEE 1 data and only a few spacecraft observations of the cavity mode have been reported since the theory was proposed in 1984 (Kivelson et al., 1984).

3.5 Magnetospheric cavity mode waves of short duration

Although the conditions required to identify magnetospheric cavity mode waves rarely exist, we suggest that magnetospheric cavity mode waves of short duration may occur rather frequently. The arguments are as follows. We have found that cavity mode waves can be set up in the whole dayside magnetosphere within a short time. In the event presented in this paper, the 24 mHz wave power increased at geosynchronous orbit (at the GOES-2 and SMS-2 satellites) within a few wave cycles after the IMF changed its direction. When the energy source turned off, the waves damped quickly. Thus we suggest that driven cavity mode waves grow and damp in close synchronization with the energy source that is driving them. It is plausible that many short-lived compressional wave events observed inside the dayside magnetosphere are global mode waves. Simultaneous multi-satellite observations are needed to confirm this hypothesis.

4. Comparison with Theory and Simulations

4.1 Comparison with computer simulations

Computer simulations and numerical solutions use simplified models (Allan et al., 1985, 1986a; Inhester, 1987; Lee and Lysak, 1989; Zhu and Kivelson, 1989) but they reveal various important features of cavity eigenmode oscillations. A comparison of our observations with previous analyses of the global mode support our interpretation of the wave mode present in our data.

Theoretical and numerical studies of the magnetospheric waves often establish the wave perturbations by applying an impulsive compressional stimulus at the boundary of the magnetospheric cavity. Inhester (1987) used a box model for his simulations; Allan et al. (1985, 1986a) demonstrated the development of cavity eigenmodes in a cylindrical model of the magnetosphere. Lee and Lysak (1989) (referred to as L&L) investigated the structure and properties of both poloidal and toroidal modes in a dipole magnetosphere. Their model assumes a realistic spatial variation of Alfvén speed (L&L Fig. 2), a
magnetopause at 10RE, a plasmapause at 5RE, and an ionosphere at 2RE. All the boundaries are taken as perfect reflectors. The response of the magnetosphere is followed for about 40 minutes after excitation by an impulse lasting ~40 seconds (L&L Fig. 3). Global compressional mode oscillations with dominant frequencies of 27, 37, 60, and 90 mHz are identified (L&L Plate 1). The toroidal mode exhibits a continuous spectrum of field line resonances. In particular, the simulation shows that the amplitude of the field line resonances increases at positions where the field line resonance frequency is the same as that of a compressional cavity wave.

The scale of the system used in the simulation is different from our event. In our event, the ISEE-1 spacecraft crossed the magnetopause at about 12.4RE and the plasmapause at about 7.6RE. (The plasmapause location was identified from plots of the plasma wave power spectra on ISEE-1, kindly provided by Roger R. Anderson of the University of Iowa.) The stable solar wind conditions monitored by the IMP-8 spacecraft allow us to assume that the magnetopause position changed little during our event. This means that the simulation used an outer magnetosphere about 40 percent smaller than the one relevant to our observations but the resonant frequencies could have been similar if the Alfvén velocity profiles were different.

Comparing the top panels of our Fig. 3 with L&L Plate 1, the observed compressional component contains elevated power in a quasi-monochromatic band at a frequency of about 24 mHz, which is near the frequency of 27 mHz found in the simulation. However, the 3 higher harmonic waves in the simulation (34, 60, 90 mHz) were not present in the ISEE observations. The ~1.6 mHz compressional wave observed by ISEE-1 was absent in the simulation results. In the simulation, the higher frequency harmonics have weaker amplitudes and narrower band width, but even if the higher frequency harmonics were weak, we should have observed them. Recall that Fig. 4 was created by removing 4th order polynomial background trends from successive log spectral power densities. This technique enhances spectral peaks in dynamic spectra, especially at the high frequency end. Note that this technique was not used in L&L and their plot shows the true power. The fact that higher compressional harmonics were not observed by ISEE even after removing the background trend, indicates that they were either not excited or that their relative amplitude was significantly smaller than obtained in the simulation.

The azimuthal wave spectrum shows good agreement between the observation and the simulation. Since the frequencies of the azimuthal waves are determined by local field and plasma conditions, this implies that the nominal variation of plasma density adopted for the simulation provided a good model for the conditions in our event. The middle panels in our Figs. 3 and 4 and L&L Plate 1 all exhibit a continuous spectrum of field line resonances. In Fig. 3, four harmonics are evident in the spacecraft observations as fan-like rays starting at the magnetopause about 19:40 UT and apparently disappearing about 20:30 UT. These harmonics are more distinct and long-lived in the enhanced spectrum, Fig. 4. The lowest harmonic stated with a frequency below 5 mHz near the magnetopause and reached about 15 mHz near 7.6RE (23:00 UT). The trace of this harmonic is obscured between 20:00 UT and 22:00 UT where it is seen only as two modest enhancements. However, it is very clear between 22:00–23:00 UT. The next harmonic started around 16 mHz near 10.6RE (21:00 UT) and reached 40 mHz around 7.6RE (23:00 UT). Another harmonic was also observed, starting at about 20 mHz near 11.4RE (20:30 UT) and reaching about 45 mHz around 8RE (22:40 UT). The highest harmonic can been seen between 20:10–21:50 UT with its frequencies about 10 mHz higher than that of the next lower harmonic. These harmonics relate well with harmonics present in the simulation result (fundamental, third, fifth, and seventh as evident in the middle panel in L&L’s Plate 1). Higher harmonics present in the simulation result were not observed by the ISEE spacecraft. Although we do not have the data needed to identify which harmonics were observed by ISEE-1, we will refer to the fundamental, third, fifth, and seventh harmonics based on the relation to the frequencies of the excitations in the simulation. Note that these are the harmonics expected if the magnetopause perturbation is symmetric about the equator.

The power in the third and the fifth harmonics was enhanced when their frequency matched the frequency of the compressional cavity mode. Figure 8 demonstrates this enhancement. In Fig. 8, instead of using a logarithmic scale and a prewhitening technique, we have plotted the actual wave power in the
A Possible Signature of Magnetic Cavity Mode Oscillations in ISEE Spacecraft Observations

Fig. 8. Dynamic spectra of azimuthal magnetic field plotted on a linear color scale. The abscissa is universal time and the ordinate is wave frequency. As contrasted with Figs. 3 and 4, the wave power is plotted on a linear scale (nT²/Hz). Only the portion of Fig. 4 between 20:00–22:30 UT and frequency from 0–50 mHz are plotted.

Azimuthal Component

The enhancement of azimuthal wave power at positions of resonant field lines was envisaged in the theoretical description of cavity modes by Kivelson and Southwood (1985, 1986). They recognized that the original form of field line resonance theory (Southwood, 1974; Chen and Hasegawa, 1974) does not provide an explanation of the presence of band-limited signals and thus fails to explain why latitudinal chains of ground stations sometimes observed nearly monochromatic signals. Their papers point out that the cavity mode theory picks out discrete compressional frequencies that preferentially excite field line resonances of the same frequencies. It is these resonant excitations that dominate the ground signals. In Fig. 8, there is a strong enhancement of the field line resonance at about 10 mHz which is half of the observed compressional wave frequency. At this moment we do not have a clear explanation of this enhancement.

The radial component (bottom panel of Fig. 4) displays wave power at the same frequency as the compressional component. However, the structure is not so clear as in the compressional component. In L&L’s simulation result (bottom panel of L&L Plate 1), the spectral peaks present in the radial component appear either in the compressional component or in the azimuthal component. This mixture may account for the poor definition of peaks in the spectra of the radial component both in the simulation and in the observations.

Consideration of energy sinks suggests why higher harmonics present in the computer simulation (in both compressional and azimuthal components) were absent in the ISEE-1 data. In the L&L simulation, the inner plasmapause and outer magnetopause boundaries of the cavity were perfect reflectors corresponding to extremely steep density gradients. The ionosphere was assumed to be a perfect conductor. This model
magnetosphere obviously lacks energy sinks. Yet the ionosphere is a significant energy sink for ULF waves. Furthermore, it is known that some wave energy can cross the plasmapause into the inner magnetosphere (Takahashi et al., 1990), a result that has also been explained theoretically (Allan et al., 1986b; Zhu and Kivelson, 1989). Neither the real plasmapause, nor the real magnetopause are the ideal reflectors assumed in the simulation, nor is the real magnetosphere azimuthally symmetric as assumed in the model. Energy sinks in the real magnetosphere reduce the wave power and damp the waves. In addition, the boundaries in the simulation are fixed in position. On the other hand, in the magnetosphere, small departures from steady boundary positions will preferentially damp high frequency, waves if fluctuations occur over distances comparable with their wavelengths. These same fluctuations would affect low frequency, long wavelength waves little. Thus, a number of mechanisms exist to account for differences between the simulations and the observations and to explain why some of the wavepower is missing.

The \(-1.6\) mHz compressional wave observed in our data is not present in L&L's simulation result. However, the pressure pulse used in L&L's simulation was only about 40 seconds long. This impulsive energy source contained very little power to excite the low frequency band around \(1.6\) mHz. However, we reiterate that we are puzzled by its presence in the ISEE 1 data. The extremely low frequency signal straddles the band of frequencies in which Samson et al. (1992) identifies discrete signals for which there has been no fully satisfactory explanation. We find it interesting that the same frequency band appears in our data and we have suggested a possible source at the bow shock, although it is also possible that the \(-1.6\) mHz signal has a source in the magnetotail.

By assuming perfectly reflective boundaries and an infinitely conducting ionosphere, L&L found that global cavity eigenmode wave and field line resonances persisted for at least 40 minutes in their simulation. In the model magnetosphere the eigenmode waves can stand long after the energy source disappears. The real magnetosphere requires a continuous energy source to keep the cavity eigenmode waves going. Once the energy source vanishes, the cavity eigenmode damps out quickly.

4.2 Spatial and harmonic structure

Except for the fundamental mode, a standing wave should have several nodes along the radial direction where wave amplitude reaches a minimum. Such nodes are evident in the dipole magnetosphere simulation (top panel in L&L Plate 1) which shows that the branch with frequency of 37 mHz has a wave power gap near 8RE. The gap (or node in a standing wave) is about 1RE in radial extent. The higher the frequency, the more minima of wave amplitude are present in a radial cut through the magnetosphere. However, no nodes were observed in our event. Thus, the waves either had no nodes in their radial structure or a node was crossed between 8 and 9RE during the interval of low wave amplitude. By assuming an Alfvén speed of 1000 km/sec, we estimate the wavelength as 6RE for the 24 mHz wave. This is reasonable for the fundamental of the cavity mode. A large fraction of heavy ions in the magnetospheric plasma would reduce the Alfvén speed and correspondingly reduce the estimated wavelengths. Another possibility is that the signal amplitude remained finite near nodes as discussed by Allan et al. (1987). More information is needed to understand how these observations correspond to the harmonics of the cavity modes.

5. Conclusions

The long-lasting compressional ULF wave event observed by the ISEE spacecraft on November 24, 1977 displays many features comparable to the computer simulation results of Lee and Lysak (1989) and the numerical solutions of Allan et al. (1986a) and Zhu and Kivelson (1989). Several important conclusions have been drawn from this event:

(1) The magnetosphere was quiet and stable. Such stability may be a necessary condition for the identification of cavity eigenmodes. At the very least, the magnetosphere must remain quasi-static for the duration of the spacecraft traversal of a large L range if radially standing waves are to be observed.

(2) Broad band waves on the boundary can serve as the energy source of cavity eigenmodes. Despite
the broad band nature of the source, the power within the magnetosphere is narrow-banded. This implies that non-resonant frequencies are not transmitted efficiently into the magnetosphere. The presence of wave power within the magnetosphere is closely related to the IMF cone angle in the solar wind.

3) The cavity eigenmodes decay rapidly. A continuous energy source may be necessary to supply energy to the cavity eigenmodes. An "impulse driven cavity mode" in a model magnetosphere with highly reflective boundaries may not be realistic in the real magnetosphere. The cavity eigenmodes set up by an impulse may not last long enough to be observed. The decay of wave energy may be accelerated through leakage down the tail, in which case the cavity may be better described as a wave guide.

4) Harmonics of the field line resonances are enhanced where their frequencies match the frequency of the compressional wave consistent with coupling between the radially standing compressional waves and field line resonant waves.

5) The amplitude of this wave event was about 1 nT for the ~1.6 mHz wave (which may not be a cavity mode wave) and 0.5 nT for the 24 mHz wave. Since the magnetospheric cavity mode is a large scale phenomenon, the wave amplitude is expected to the small everywhere even though the total wave power contained in the entire dayside magnetosphere may be large. Waves with low amplitudes can be identified only by using techniques that extract small amplitude perturbations from the large, slowly varying background field. This means that it is much harder to observe this mode than to observe field line resonances.

One remaining puzzle about this event is: What is the relationship between the ~1.6 mHz waves and the 24 mHz waves? It is hard to relate them as harmonics. The low frequency waves may have been generated elsewhere in the magnetosphere. Samson and Harrold (1992) reported that waves with 1–3 mHz frequency are often seen in the HF radar at Goose Bay in the interval from local midnight to early morning. Siscoe (1969) calculated the eigenmode frequency of earth's magnetotail. He estimated that the fundamental period of the antisymmetric mode is approximately 11 minutes (1.5 mHz). Possibly the ~1.6 mHz wave was the dayside signature of a wave generated in the night side or even in the tail. However, the similar response of the ~1.6 mHz waves and the 24 mHz waves to changes of the IMF cone angle from 22:00 to 23:00 UT suggests that the ~1.6 mHz waves were also generated on the day side, possibly driven by pressure perturbations at the bow shock as suggested by Fairfield et al. (1990).

As discussed in our review at the beginning of this report, there have been few spacecraft observations of magnetospheric global mode waves. Our report can be seen as a step towards rectifying this situation. We hope the interesting signatures which we observed will stimulate others to identify similar events. Simultaneous multi-spacecraft and spacecraft-ground observations are required for further study of this phenomenon and the advent of a fleet of ISTP spacecraft in the magnetosphere encourages us to believe that progress will be made.

Computing resources for this study were supplied both by the Institute of Geophysics and Planetary Physics and the Department of Earth and Space Science of UCLA. We appreciate the kindness of R. R. Anderson and the University of Iowa who provided plots of the plasma wave power spectra for our use. Solar wind data were provided by the NSSDC courtesy of R. Lepping and J. Gosling. We are particularly grateful to one of the referees whose insightful comments helped us improve this paper. This work was supported in part by grants from the Division of Atmospheric Sciences of the National Science Foundation, Grants ATM91-15557 and ATM93-14239, the National Aeronautics and Space Administration, Grant NAGW-2054, and ONR, Office Naval Research Grant N00014-85-K-0556.

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