Compressional ULF Waves in the Outer Magnetosphere

1. Statistical Study

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Using 14 months of magnetic field and plasma data observed by the ISEE 1 and 2 spacecraft, ULF waves of period 2 - 20 min in the outer magnetosphere were studied. Statistical properties of the ULF waves can be summarized as follows: (1) Intense compressional waves are a persistent feature near the two flanks of the magnetosphere. They are mainly polarized in a meridian plane with comparable compressional and transverse amplitudes and have larger amplitude at magnetic latitudes below 20º than at higher latitudes. The magnetic pressure perturbations for the waves are in antiphase with the plasma pressure perturbations; (2) Transverse waves polarized in the azimuthal direction (azimuthal waves) are found to be mainly a nightside phenomenon. Their appearances on the nightside magnetosphere seem to be associated with substorm activity; (3) Compressional wave power and plasma β, the ratio between the plasma pressure and the magnetic field pressure, are correlated, but ULF wave power in the above noted period range is not significantly correlated with AE, plasma pressure or VA; (4) The compressional waves are most likely to be generated internally in the regions where plasma β and field line curvature are large.

INTRODUCTION

The study of ultralow frequency (ULF) waves in space plasmas has a long history with its origins in the study of ground magnetic pulsations in the last century [Stewart, 1861]. That ULF wave observation remains an area of active research interest reflects on the one hand the importance of such waves in coupling plasma motions in locations remote from one another, and on the other hand the difficulty in fully characterizing waves of extremely large spatial scale. Within the terrestrial environment the lowest frequency portion of the ULF wave band, referred to as Pc 4 or Pc 5 (periods of 45 s to 10 min) and Pi 2 (periods of 40 s to 150 s) [Jacobs et al., 1964], is associated with waves that arise as excitations of entire flux tubes in the magnetosphere. Such waves can be generated in many different ways. Almost anything that perturbs the magnetosphere on a large scale can initiate ULF waves, no matter whether the disturbance is of internal or of external origin and whether the disturbance changes fluid properties or destroys phase space equilibrium. Thus one must avoid the temptation to identify any unique mechanism for the generation of ULF waves and instead seek to determine what types of waves are present under what conditions.

Surveys of ULF waves have been carried out both from ground observatories and in space. Ground-based surveys have the advantage of giving continuous coverage over large portions of the surface of the Earth. However, the signals sensed on the ground are only those that propagate through the ionosphere. Shear Alfvén waves generated in the magnetosphere produce perturbations that are readily detected by ground magnetometers, although they may be screened or distorted by ionospheric conductivity [Hughes, 1974] and ionospheric inhomogeneity [Poulter and Allan, 1985]. However, the purely fast compressional wave mode is typical of other large-scale wave perturbations that carry no field-aligned current and are reflected effectively at the foot of the field line [Kivelson and Southwood, 1988]. Only a transverse signature can be detected at ground level. Thus wave surveys that rely on ground magnetometer measurements could be incomplete and may fail to identify interesting wave modes. Radar studies of wave events, however, provide complementary data that increases the value of ground based observations [Allan et al., 1983a, b].

Spacecraft observations provide in situ measurements and, despite the problems associated with the difficulty of obtaining complete spatial and temporal coverage of a system as large as the magnetosphere, have greatly enhanced our understanding of ULF waves. Early studies, based on magnetometer data only, confirmed that ULF waves are common in space [Sonett et al., 1962; Judge and Coleman, 1962; Patel and Cahill, 1964]. Joint ground-satellite studies revealed that pulsation events in the magnetosphere and on the ground were often observed simultaneously if the conjugate latitude of the spacecraft was within 15 deg in longitude of the ground station [Lanzerotti et al., 1974, 1975].

Statistical studies of Pc 4 and 5 waves in space have concentrated on data from geostationary orbit. Most of the reports have emphasized the properties of the shear Alfvén waves, but there are several important exceptions. Barfield and McPherron [1972, 1978] described a class of compressional pulsation events observed during
the main phase of geomagnetic storms. These waves are polarized mainly in a meridian plane with comparable compressional and transverse components. Their peak occurrence is in the 1200 – 1900 local time sector which is in the region of substorm-associated enhancements of the partial ring current. Su et al. [1977] used particle data to study some wave events and was able to infer the wave propagation direction. Wave occurrence rate was found to peak on both dawnside and duskside of the magnetosphere, but duskside events dominated. Using measurements of electron and ion fluxes and the magnetic field data from the GEOS 2 spacecraft, Kremser et al. [1981] found that ion flux variations ($E_i > 27$ keV) are always in antiphase with variations of the magnitude of the magnetic field. The electron flux of comparable energy ($E_e > 22$ keV) can vary either in phase with the ion flux (inphase events) or out of phase with the ion flux (out-of-phase events). As the plasma pressure is dominated by the ion pressure, the total plasma pressure is always in antiphase with magnetic pressure. The peak occurrence of out-of-phase events was found near 1800 LT, in the local time sector of the Barfield and McPherron events. On the contrary, the peak occurrence for inphase events was found to be localized near 1200 LT. Pulsations during the recovery phase of a geomagnetic storm were found to be of longer duration than the main phase events [Highie et al., 1982; Nagano and Araki, 1983; Takahashi et al., 1985]. More recently, Higuchi and Kokubun [1988] used 2 years of GOES 2 and 3 data to study compressional Pc 5 waves more extensively. They constrained the peak occurrence region of the compressional Pc 5 waves to the sector near 1500 – 1700 local time. Special harmonic properties of the Pc 5 waves were also studied in their work.

Beyond geostationary orbit, reports on the local time and L shell distribution of ULF waves are somewhat limited. Most of the studies found Pc 5 waves principally in the morning sector between $L = 6 – 13$ and 0300 – 1200 local time. This was true for the investigation of Heppner et al. [1972] who surveyed compressional Pc 5 waves at local times from 2100 to 1200 and to investigations of Pc 5 waves polarized predominantly in the transverse direction [Kokubun et al., 1976; Singer and Kivelson, 1977].

In the distant magnetosphere, waves were found just within the magnetopause by Hedgecock [1976] who used HEOS 1 magnetometer data. He found that large amplitude Pc 5 waves were common between 8 and 12 RE near the dawn and dusk flanks of the magnetosphere. When compressional waves were present, the ambient magnetic field was depressed in amplitude. In an initial visual inspection of the ISEE spacecraft data, Zhu et al. [1988] found these waves are common near both flanks of the outer magnetosphere. Figure 1 shows events typical of total magnetic field measurements made by the ISEE spacecraft in each quarter of 1978. Clear compressional

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Fig. 1. Typical total magnetic field measurements observed by the ISEE spacecraft on inbound orbits in each quarter of the year in 1978. The plots of $b_t$ versus UT are superimposed on a schematic of the equatorial plane of the magnetosphere with the solar direction on top. Intense compressional waves were observed on the dawnside and duskside of the magnetosphere. The information below each sample data plot gives universal time, spacecraft local time, radial distance RE, and geomagnetic latitude from top to bottom.
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ULF wave activity is evident in the events shown near dawn and dusk. The spikelike perturbations near the magnetopause for the event near noon were caused by multiple magnetopause crossings and are not pulsations inside the magnetosphere. When the spacecraft trajectories were near midnight sector, there was not much wave activity.

This paper presents results of a full statistical survey of wave power in the outer magnetosphere based on more than 1 year of ISEE magnetic field measurements and plasma moment data. The purpose of this study is to provide an overview of how wave power in different vector components of the magnetic field is distributed inside the magnetosphere and how the wave power correlates with the properties of the plasma and with levels of geomagnetic activity. The wave properties are compared with expectations for different wave modes thought to be relevant and are discussed in relation to probable wave generation mechanisms.

DATA AND METHOD

Fourteen months (from December 1977 to January 1979) of magnetic field and plasma data were surveyed in this study. The magnetic field data were obtained from the University of California at Los Angeles (UCLA) Magnetometer Experiment (MAG) [Russell, 1978] on the ISEE 2 spacecraft. The plasma moment data were inferred from the LANL/MPI Fast Plasma Experiment (FPE) on both the ISEE 1 and ISEE 2 spacecraft [Bame et al., 1978]. They were obtained from the National Space Science Data Center (NSSDC). The plasma moments were calculated from ion distribution functions over the energy range from 70 eV to 40 keV, assuming protons as the only ion species. The ion distribution function was sampled every 12 s in the plane perpendicular to the spacecraft spin axis, which is almost parallel to \( \mathbf{Z}_{\text{GSE}} \). Therefore the above noted plane was very close to the GSE \( x - y \) plane. The moment data were averaged to 1-min resolution. We joined the two types of data at 1-min resolution as a single data set for the statistical study. There are more gaps in the FPE measurements than in the MAG data, so we filled in gaps in ISEE 2 FPE data with ISEE 1 FPE measurements if the latter were available. This substitution is justified for studies of low-frequency perturbations as the two measurements are very similar on time scales of minutes and longer because of comparatively small spacecraft separation.

We used mean wave amplitude (MWA) to characterize the statistical properties of the waves in space. MWA was defined as the square root of the sum of the power spectrum density over the frequency range from \([20 \text{ min}]^{-1}\) to \([2 \text{ min}]^{-1}\) (the Nyquist frequency) and is given in nanoteslas. Each power spectrum was estimated from 60 sequential independent (nonoverlapping) data points. In order to assure good spectral estimates we required that 75 % or more of the data points in each spectrum estimate (i.e., 45 or more out of 60 data points) be good. Otherwise, the spectrum estimate is rejected. Any data gap, which should be less than 25 % of total data points for any given interval, was filled by linearly interpolating between the good data points.

The MWAs of different components of the magnetic field were calculated when the ISEE spacecraft was inside of the magnetosphere as verified by visual inspection of the data. When the spacecraft moved close to the Earth, the magnetic field was dominated by the Earth's dipole field. We stopped the spectrum calculation when the total magnetic field exceeded 200 nT; this corresponds to the field strength somewhat inside of the 6.6 \( R_E \) synchronous orbit. Selection of 200 nT is arbitrary, but it guarantees the spectrum calculation stops inside the synchronous orbit. Further inward from the synchronous orbit, the magnetic field increases rapidly with decreasing radial distance. In a region with field strength above 200 nT, compressional waves are usually absent and the rapid variation of the ambient field strength along the spacecraft trajectory interferes with the detection of small perturbations.

Because the MWA was used to characterize the statistical properties of the waves, it is essential to remove spikes from the data as they contribute spurious wave power if not removed. As can be seen from Figure 1, multiple magnetopause crossings near the dayside magnetopause contribute one type of spike. To remove them, the ISEE 2 plasma density and the \( x \) component of the proton mean velocity \( V_z \) were used to identify measurements made in the magnetosphere. The criteria we used to identify the magnetosheath and to distinguish it from the magnetosphere were: (1) the plasma density is above 2 \( \text{cm}^{-3} \) and (2) the magnitude of \( V_z \) is greater than 100 \( \text{km/s} \) in the \(-x\) direction in the spacecraft frame, which is very close to the GSE frame. If the magnetopause was encountered more than once on an orbit, we always eliminated data prior to the last crossing on an inbound orbit and subsequent to the first crossing on an outbound orbit. By these criteria we may have removed some intervals within the magnetosphere near the boundary from our study, but our objective was to assure ourselves that we were keeping only intervals when the spacecraft was unambiguously and continuously within the magnetosphere. Bad data points also contribute to data spikes. We have used statistical properties of the data to remove them. One can order the data by MWA and divide it into quartiles bounded by \( DV_1, DV_2, \) and \( DV_3 \). Here \( DV_1 < DV_2 < DV_3 \). With such a division, \( DV_2 \) is the median for the data in a given interval and the range \((DV_1 \text{ to } DV_3)\) contains 50 % of the data distributed on both sides of \( DV_2 \). Data spikes could be defined as data that fall outside the range \((DV_1 \text{ to } DV_3)\). However, one can extend the range from \((DV_1 \text{ to } DV_3)\) to \((LB \text{ to } UB)\) where \( LB = DV_1 - N(DV_2 - DV_1) \) and \( UB = DV_3 + N(DV_3 - DV_2) \) with \( N \) arbitrary. Any data that fall outside the range \((LB \text{ to } UB)\) are considered as data spikes. There is arbitrariness in selecting \( N \) but it is usually taken as less than 10. We set \( N = 3.5 \) in despiking data. Later we will refer to the above procedure as the despike procedure.

Using the despike procedure and the restriction for obtaining reliable spectrum estimates mentioned above (i.e., 75 % or above of good data points for a given interval are required to estimate a power spectrum) 14 months of data yielded about 1.8 thousand (1800) individual spectrum estimates. Figure 2a shows the time series plots of two segments of data of the total magnetic field. Each segment is of 1-hour duration. The continuous curve plots a wave event which started at 0900 UT, August 5, 1978. The dashed curve plots an event with
very small wave activity which started at 2225 UT, May
28, 1978. The power spectral densities for both events
are plotted in Figure 2b. It is seen that they differ by
2 orders of magnitude in the frequency domain. The
MWA corresponding to the two spectrum estimates are
5.618 nT and 0.117 nT, respectively, and these levels are
close to the fluctuation levels evident in the time series
plots. It is seen therefore that MWA characterizes the
ULF wave fluctuation levels in the magnetosphere rea-
sonably well. By visual inspection of all events in the
compressional component that reveal substantial wave
power in the frequency band of interest we have con-
firmed that MWA is close to the wave amplitude in the
time series.

Figure 3 plots the orbital coverage after the selection
of data within the magnetosphere, which contains ~
3400 hours of data. The projection of the orbits into the
GSE x–y plane is shown in Figure 3a. The model mag-
netopause and bow shock positions [Holzer and Slavin,
1978] are also plotted. Evidently, the coverage of lo-
cal times and radial distances is quite complete. The
envelope of end points of the trajectories on the day-
side magnetosphere defines the average position of the
innermost excursions of the magnetopause. Its shape
agrees well with the shape of the model magnetopause.

The systematic inward displacement of the end points
from the model magnetopause position (≤ 2 Re) is to
be expected for two reasons. First, the plot represents a
minimum rather than average magnetopause distance.
Second, the plotted spacecraft trajectories are equato-
rial projections of the orbits, whereas the model is ap-
proximately an ellipsoid of revolution, a representation
in $r_{GSE}$ versus $\sqrt{r_{GSE}^2 + z_{GSE}^2}$. The projection of the
actual orbits onto the GSE equatorial plane neglects the
contribution of the finite $r_{GSE}$ of the spacecraft posi-
tion and thereby reduces the apparent distance from the
Earth-Sun line. Figure 3b shows the distribution of the
spacecraft orbits (solid traces) in magnetic latitude and
radial distance from the geomagnetic dipole axis. $R_L$ is

Fig. 3a. Projection of the portions of the ISEE orbits inside
of the magnetosphere used in this study onto the GSE x–
y plane (solid curves). The model magnetopause and bow
shock position are also plotted.

ISSE Orbit Latitude Coverage
spacecraft distance away from the dipole axis, and $Z_L$ is the normal distance to the magnetic equatorial plane. Two dashed lines which start from the origin and end at $R_L = 15~R_E$ are drawn at an angle of $\sim 38^\circ$ from the magnetic equator. The envelope of the spacecraft trajectories is predominantly within these two lines. One sees that the spacecraft orbits cover reasonably well the region within $38^\circ$ magnetic latitude of the magnetic equator assuming that the sign of the latitude is irrelevant. The northern and southern asymmetry of the orbital coverage is not a major concern for a ULF wave study as the low-frequency waves usually stand along field lines and are either symmetric or antisymmetric with respect to the magnetic equator.

Figure 1 shows that the wavelike perturbations of the magnetic field are superimposed on a slowly varying background field. The latter decreases monotonically with radial distance from the earth. In order to analyze the magnetic perturbations, we detrended the magnetic field data as follows: (1) Using a least squares fitting routine; 41 min of data (41 data points) were fitted to a second order polynomial; (2) The fitted expression was used to define the average magnetic field at the central time of the 41 min of data; (3) The fitting procedure was repeated with a shift of one data point. This running least squares fitting assures the smoothness of the average magnetic field, which we will refer to as the running averaged magnetic field.

The running averaged magnetic field was used for the following purposes: (1) to subtract it from the measured field to get the magnetic perturbation and (2) to define a mean-field coordinate (MFC) system. The latter application requires also the knowledge of the spacecraft position. The MFC system is defined with its $z$ axis parallel to the running averaged magnetic field direction, its $y$ axis parallel to the vector product of the spacecraft position vector and the $z$ vector (and thus azimuthal and positive westward), and its $x$ axis completing the triad. The perturbation magnetic field was rotated into this new coordinate system. In MFC the magnetic perturbations are presented in a readily interpretable form. Compressional wave modes have finite $z$ components and the perturbations of $B_{total}$ and $B_z$ are equivalent. Transverse components in the meridian plane (i.e., with finite $x$ components) are usually associated with compressional perturbations of the magnetic field but azimuthally polarized waves (i.e., with finite $y$ components) are usually noncompressional.

Figure 4 shows data from a compressional wave event observed inside the magnetosphere. The solid curves in the top four panels of Figure 4a correspond to measured magnetic field components in a GSE coordinate system and the total magnetic field. The dashed curves plotted in the same panels are running averages of these quantities used to define the MFC. In the last panel, plasma $\beta$ (the ratio of the plasma pressure to the magnetic pressure) is plotted. In Figure 4b the first three panels show the perturbation field components rotated into the MFC coordinate system; the lower three panels show traces of the plasma pressure, the magnetic pressure, and the total pressure, which is the sum of the previous two. From Figure 4b it is seen that the plasma pressure is in antiphase with the magnetic pressure. Because of this antiphase relationship, the fluctuations in the total pressure (lowest panel) are much smaller than the fluctuations in magnetic field or plasma pressures individually. The near constant total pressure is often found in the compressional wave events in this study. More examples will be shown in Figures 7 and 8.

![Fig. 4a. A typical compressional wave event. The first four panels are magnetic $b_x$, $b_y$, $b_z$, $b_t$ components (solid curves) in nanoteslas in GSE coordinates and running least squares fits (dashed curves) to the data. The last panel plots $\beta$, the ratio between the plasma pressure and the magnetic field pressure. The quantities are plotted versus universal time.](image)

![Fig. 4b. Data from the same wave event as in Figure 4a, displayed in mean field coordinates. The top three panels show components of the detrended magnetic field perturbation in the MFC frame in units of nanoteslas. The lower three panels plot plasma pressure, magnetic pressure, and total pressure in units of $10^{-9}$ dyne/cm$^2$. The quantities are plotted versus universal time.](image)
SPATIAL DISTRIBUTIONS

In order to display the spatial distribution of the MWA and other physically interesting quantities, we projected MWA, etc., into the GSE z-y plane. We divided the area inside of \(-15 \leq z \leq 15 \text{ RE}\) and \(-15 \leq y \leq 15 \text{ RE}\) evenly into a 15 x 15 rectangular grid. MWA calculated for a 1-hour interval and weighted by the fraction of the hour the spacecraft spent within a bin was allocated to the bins through which the spacecraft moved during the hour. After allocating all data the weighted wave amplitudes in each bin were added together and normalized by the total number of hours spacecraft spent in the bin.

In order to obtain a meaningful statistical distribution of MWA over space we decided to exclude the possibility that the MWA in a bin is dominated by one event containing a bad data point or anomalously large power produced by natural causes (such as a solar wind pressure pulse). Events of this type can be regarded as "data spikes" in the spectral domain and therefore a "despike procedure" was used in each bin to eliminate them. Since the despike procedure uses statistical properties of the data to remove extreme values, it is essential to have enough data in each bin to obtain a meaningful distribution. We require that each bin have at least 7 (or 5 when we divide the data according to its magnetic latitude) independent spectral estimates. For bins that have fewer than 7 (5) independent spectral estimates, no MWA is estimated. Plotted in Figure 5 is a shaded contour plot of the number of independent spectral estimates in each bin. The intensity scale is linear and divides evenly the range from 5 estimates to 30 estimates by the label 0-1 through 9-10 near the contour line. Including bins which have no spectral estimates (outside the magnetopause and near the Earth) or fewer than 7 estimates, 135 bins out of a total of 225 bins (15 x 15) contain data for the \(b_z\) component. The despike procedure removed very few data points from the spectral estimates. For example, 21 spectral estimates were removed from a total of 1735 estimates for \(b_z\), the quantity for which the largest number was removed for all components. For the \(b_y\) component, only 5 spectral estimates were removed. Figure 6 plots the time series that corresponds to one of the spectral estimates removed by the despiking procedure. The figure shows that there was a sudden change of the magnetic field at about 2116 UT on May 15, 1978, and the spectral power associated with this change appeared as a "data spike." Evidently, the rejection of this type of event is desirable in a statistical study of wave power.

Statistical fluctuations of the MWA in adjacent bins were reduced by taking weighted averages of the wave amplitude over adjacent bins. In obtaining these averages a weight of 1/2 was assigned to data in the center bin and the data in each of the eight surrounding bins was weighted at 1/16 of their values. After such an average was completed we further interpolated the bins from 15 by 15 to 60 by 60. Such an interpolation provides a smooth transition between adjacent bins. Figure 7 and 8 plot a few selected wave events observed on the two flanks of the magnetosphere. On each side of the magnetosphere we selected four wave events with quasi-monochromatic frequencies. The examples in 7 are compressional waves on the dawn side of the magnetosphere. Figure 8 shows similar waves on the dusk side. These waves contribute to the large compres-
sional wave power near the two flanks of the magnetosphere that appears in the statistical study, as will be seen in the next figure. The waveforms shown in Figures 7 and 8 resemble very closely those reported by Hedgecock [1976].

Figure 9 plots the spatial distributions of the MWA for the compressional ($b_x$) component independent of magnetic latitude (Figure 9a) and for measurements made within 20° or beyond 20° of magnetic latitude (9b and 9c, respectively). As a subset of data used in plotting Figure 9a were used for Figures 9b and 9c, we required there be at least five (instead of seven) independent spectral estimates in each bin. Despite the reduced restriction, more bins were blanked in the latter two plots due to insufficient data. Superposed in Figure 9 are the model magnetopause and bow shock positions [Holzer and Slavin, 1978] in the GSE x–y plane. Two circles with respective radii of 6.6 $R_E$ and 9 $R_E$ represent synchronous orbit and the distance to the apogee of the AMPTE/CCE spacecraft. As we did not analyze data from regions with total magnetic field intensity greater than 200 nT, a blank region surrounds the Earth. In this and the following plots the quantity plotted was divided into 10 levels logarithmically (base 10). These levels were designated as 0-1, 1-2, ..., 9-10 in the contour labels in the figure. For Figure 9 (as well as Figures 10 and 11) the MWA varies from 0.32 nT to 3.2 nT. Table 1 lists the parameter range corresponding to the contour labels for Figures 9-11 and 13-15. It should be emphasized here that as the same range of intensity is used for the MWA plots in Figures 9, 10, and 11, one can compare directly the wave intensities among the different components.

Figure 9a reveals that strong compressional waves are a persistent feature near the two flanks of the magnetosphere. In addition to the two flanks, relatively weaker wave activity is also present near the dayside magnetopause (where the intensity scale reaches 5-6). While the wave amplitude monotonically decreases toward the Earth at the two flanks, the wave activity near the noon meridian seems to penetrate from the magnetopause as far as the location where our data were cut off.

The MWA of the compressional waves near the two flanks of the magnetosphere has intensity near 7-8, which maps to an average amplitude 1.6–2.0 nT. This amplitude is substantially lower than the amplitude of
the individual wave events presented in Figures 7 and 8. The absence of waves on some orbits results in a MWA distribution with amplitude lower than the amplitude of typical wave events.

A dawn-dusk asymmetry in the wave amplitude distribution is apparent for the compressional waves. In particular, Figure 9a shows that the compressional waves of the highest intensity occupy a broader region (a larger area) on the dawnside of the magnetosphere than on the duskside. In the next section we will suggest how such an asymmetry arises.

The compressional waves have different latitudinal distributions at different local times. Figures 9b and 9c show that on the two flanks of the magnetosphere, large-amplitude compressional waves tend to occur near the magnetic equatorial plane. The waves near noon and midnight, however, do not show such a trend. One even sees a peak at high latitude on the nightside. It is hard to account for other differences between Figures 9b and 9c as it is uncertain whether they are statistically significant.

ULF waves polarized in the azimuthal direction have a spatial distribution different from that found for the compressional waves. Azimuthal MWA, plotted in Figure 10, is found to have a major peak on the nightside of the magnetosphere. Furthermore, examining Figures 10b and 10c in which the azimuthal wave power was divided according to magnetic latitude, one sees that the regions of the most intense azimuthal wave power are at higher magnetic latitude near the midnight sector. Azimuthal waves in other parts of the magnetosphere generally are of smaller amplitude than the compressional waves in the same region. Near the noon meridian the azimuthal waves also penetrate deep into the magnetosphere just as the compressional waves do. Figure 10b shows that azimuthal waves near the nightside equatorial region have a peak in the premidnight sector and the peak is even clearer at higher latitudes (Figure 10c). This peak may be due to the association of these waves with magnetic activity in the tail. More discussion will be found in a subsequent section.

Transverse ULF waves polarized in a meridian plane are distributed spatially in a manner that mimics characteristics found both in Figures 9 and 10. Figure 11 plots the spatial distribution of MWA for the transverse meridional component ($b_x$ component). The peak wave amplitudes are found on the dawnside and duskside of the magnetosphere (as for the $b_z$ distribution) and on the nightside of the magnetosphere (as for the $b_y$ distribution). The largest wave power near the two flanks, on the other hand, is at lower magnetic latitudes as was true of the $b_z$ component. Except for the regions near local noon, the wave component also shows a general decrease in amplitude toward the earth.
Fig. 9a. Spatial distribution of mean wave amplitude (MWA) for the compressional component of magnetic field fluctuations. This plot uses all spacecraft trajectories in the data set. The inner circle has radius of 6.6 Re which locates the synchronous orbit altitude. The outer circle has radius of 9 Re which is the locus of the apogee of the AMPTE/CCE spacecraft. Model positions of the magnetosphere and the bow shock from Holzer and Slavin [1978] are also plotted. Contour levels are quantitatively defined in Table 1.

As was noted, Figures 9, 10, and 11 are all plotted on the same intensity scale, so the wave intensities of the different components can be compared readily. From Figures 10 and 11 it is seen that statistically \( b_x \) and \( b_z \) near the two flanks have similar amplitudes. This is because the waves in the region are polarized mainly in a meridian plane, as is seen in the waveforms in Figures 7 and 8.

For virtually all compressional wave events represented by Figure 9 the plasma pressure and the magnetic field pressure are in antiphase. Figure 12 reveals this phase relation. In this histogram the number of events in each 10-deg bin of phase difference is plotted versus the phase difference between the magnetic pressure perturbation and the plasma pressure perturbation.

Figures 13 and 14 show contour plots of the distribution of the Alfvén wave velocity \( (V_A) \) and \( \beta \), respectively. The quantitative significance of the contour labels, which divide the range of the plotted quantity logarithmically, can be found in Table 1. In plotting Figures 13 and 14 we required that there be at least 5 hourly averaged plotted quantities in each bin. Otherwise the bin was blanked. The blank region on the night side of the magnetosphere in both figures results from a continuous data gap for the plasma moments. As noted earlier, plasma properties are obtained from ion distribution measurements of the FPE. In the inner magnetosphere this instrument, whose highest-energy channel

<table>
<thead>
<tr>
<th>( \text{MWA nT} )</th>
<th>( \beta )</th>
<th>( V_A \text{ km/s} )</th>
<th>( \text{AE nT} )</th>
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Fig. 9b. The same as Figure 9a but only for portions of spacecraft trajectories within ±20° of latitude from the magnetic equator.

Fig. 9c. The same as Figure 9a but for portions of the spacecraft trajectories beyond ±20° from the magnetic equator.
has a mean below 30 keV, may underestimate the total pressure. (Near the midnight meridian the plasma pressure is underestimated by FPE measurements inside of 12 RE [Spence et al., 1989].) We have also noted that electron pressure is neglected and all ions are assumed to be protons. Thus the values plotted for $\beta$ should be recognized as lower limits, especially inside of AMPTE/CCE orbit. Similarly, the values plotted for $V_d$ should be recognized as upper limits since plasma with energy below 70 eV and heavier ions were neglected in the density calculation.

Figure 15 plots the distribution of magnetic $AE$ index. It shows the average $AE$ index in each region during the times that the ISEE spacecraft was in the region. Table 1 lists how contour labels map to quantitative $AE$ values.

**Correlation Study**

Correlations of wave amplitude with various plasma and other parameters may cast light on wave generation and attenuation mechanisms. In this study we calculated the correlations of the wave amplitude for the compressional and the azimuthal components with $P$ the plasma pressure; $\beta$; the Alfvén velocity; and the
Fig. 11b. The same as Figure 9b for the transverse radial component.

Fig. 11c. The same as Figure 9c for the transverse radial component.

Fig. 12. Histogram of the number of the compressional wave events as binned according to the phase difference between the magnetic field perturbation and the plasma pressure perturbation.

Fig. 13. Spatial distribution of the Alfvén velocity (VA) in the GSE x — y plane. Orbital coverage and other features of the plot are similar to Figure 9. Contour levels are defined in Table 1.
lines in the plot are printed at the bottom of each figure. From Figure 16 it is seen that the compressional wave amplitude correlates positively with the plasma $\beta$ and the amplitude of compressional waves becomes significant predominantly in regions of high $\beta$. The MWA is roughly proportional to $\sqrt{\beta}$.

Figure 17 plots the wave amplitude for the compressional component, $b_z$, versus $V_A$, the Alfvén velocity. Again, logarithmic scales are used for both quantities. The correlation coefficient between MWA and $V_A$ (-0.45) is smaller than that found for the correlation with $\beta$ (0.6) despite the strong link between the $\beta$ and $V_A$.

(Both quantities are the ratios between the magnetic field and the plasma moment and can be expressed as $8\pi nkT/B^2$ and $B/\sqrt{4\pi \rho}$ respectively.) The difference indicates that $\beta$ is more directly linked than $V_A$ to the amplitude of the compressional waves.

We have also calculated correlation coefficients between other physically interesting quantities. Table 2 lists the correlation coefficients of $b_x$, $b_y$, and $b_z$ with $\beta$; $V_A$; $P$ and $T$ (proton pressure and temperature); and
mechanisms for the following reasons: The compressional waves near the two flanks. Different mechanisms may be responsible for producing waves in different regions or waves of different polarizations. In this section we discuss mechanisms that fit the observations. We start with compressional waves near the two flanks.

Large-amplitude waves can be excited in several ways such as by field line resonance [Chen and Hasegawa, 1974a, b; Southwood, 1974], local generation of the compressional wave within a flux tube of the magnetosphere remains as a viable inter-

**TABLE 2. Correlation Coefficients**

<table>
<thead>
<tr>
<th>b_x</th>
<th>V_A</th>
<th>P</th>
<th>T</th>
<th>AE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>0.30</td>
<td>0.36</td>
<td>0.34</td>
<td>0.26</td>
</tr>
<tr>
<td>0.25</td>
<td>0.12</td>
<td>0.27</td>
<td>0.27</td>
<td>0.34</td>
</tr>
<tr>
<td>0.60</td>
<td>0.43</td>
<td>0.47</td>
<td>0.44</td>
<td>0.17</td>
</tr>
</tbody>
</table>

the AE index, respectively. From the table it is seen that except for the correlation between b_x and β, other quantities correlate weakly. Of particular interest is the lack of correlation of the compressional MWA with AE which is the basis of our statement that magnetic activity does not correlate with the compressional waves in the outer magnetosphere.

**GENERATION MECHANISMS**

ULF waves of different polarizations are differently distributed in the magnetosphere. Even for a single polarization there may be several peaks in different parts of the magnetosphere. Different mechanisms may be responsible for producing waves in different regions or waves of different polarizations. In this section we discuss mechanisms that fit the observations. We start with compressional waves near the two flanks.

Large-amplitude waves can be excited in several ways such as by field line resonance [Chen and Hasegawa, 1974a, b; Southwood, 1974], local generation of the compressional wave within a flux tube of the magnetosphere remains as a viable inter-

The observed waves occur in regions where conditions needed to couple the shear and the slow magnetosonic wave are probably present. On the bases of the azimuthal localization of the compressional waves in the region of high β plasma and large curvature [Southwood and Saunders, 1985; Walker, 1987; Taylor and Walker, 1987; Ohtani et al., 1989a, b] and the drift mirror wave in a realistic (curved field) geometry [Cheng and Lin, 1987]. Both theories are formulated in a similar parameter regime (high β; field line curvature; and in the limit of a large k_r/k_o ratio) but approach the problem differently. The former uses the fluid approach which simplifies the mathematics but may sacrifice some physics. The latter employs the gyrokinetic formalism which takes wave-particle interaction into account but is mathematically more complicated. Nevertheless, both conclude that compressional waves are likely to occur in regions of high β plasma. It is even possible that the two theories discuss similar phenomena in different languages. For heuristic purposes we use the language of wave mode coupling to discuss the compressional waves.

The observed waves occur in regions where conditions needed to couple the shear and the slow magnetosonic wave are probably present. On the bases of the azimuthal localization of the compressional waves and on the result of a case study (to be published later), the azimuthal wavelength of the waves is estimated to be of the order a few R_E. The parallel wavelength is hard to measure but is expected to be comparable to the length of the field line. Therefore the condition k_r >> k_o is probably satisfied. Other features of these observations are consistent with the suggested generation mechanism. For example, the wave amplitudes are largest near the equatorial region where the curvature of the magnetic field lines is large. The transverse component is polarized mainly in the meridional plane which is also one of the requirements for the mechanism to work.

The shear Alfven wave is guided along magnetic field lines. This is also true for the slow magnetosonic wave in the limit of k_r > k_o. The dispersion relation for either wave mode in the decoupled case can be written as

\[ \omega^2 = k_r^2 v_p^2 \]

where v_p is the wave phase velocity. For the shear Alfven wave v_p = V_A, and for the slow magnetosonic wave (in the limit k_r >> k_o) v_p = C_{SL}, where

\[ C_{SL}^2 = V_A^2 C_S^2/(V_A^2 + C_S^2) \]

with C_S being the sound velocity. These dispersion relations allow us to estimate the amplitude variation of the wave along the ambient mag-
netic field line when the background is inhomogeneous in the field-aligned direction. For such a circumstance, $k_\parallel$ should be regarded as an operator and the dispersion relation expressed as

$$\left( \frac{\partial^2}{\partial s^2} + \frac{\omega^2}{v_p^2} \right)b = 0$$

where $b$ is a variable that characterizes the wave perturbation.

The WKB solution to the above equation has the form:

$$b \sim \sqrt{\frac{\omega}{v_p}} e^{\int s \frac{\omega}{v_p} dz}$$

Thus it is seen that the largest wave amplitude is expected in the region where the phase velocity is the slowest along a magnetic field line. For the terrestrial magnetosphere the phase velocity is slowest near the magnetic equator where the field strength is weak. This provides a consistent explanation of the intensity maximum found near the equator. The argument we have given here ignores the effects of the curvature of $B$ and the effect of wave mode coupling. These effects are not expected to change the results qualitatively.

The distributions obtained in our analysis are biased by the fact that the ISEE spacecraft does not sample different latitudes uniformly at all local times. After examining the spacecraft orbital trajectories we found that the spacecraft stayed closer to the magnetic equator in early 1978 than in late 1978. The apogees of the ISEE spacecraft in early 1978 were in the postmidnight sector which allowed the spacecraft to sample a wide range of latitudes in the postmidnight regions; the apogees of the spacecraft in late 1978 were in the premidnight sector. Therefore the spacecraft spent more time in low Alfvén velocity regions (near the equator) on the dawnside than on the duskside. This could skew the wave power distribution and the resultant asymmetry could be responsible for producing a larger dark area on the dawnside than on the duskside for the $b_z$ distribution of Figure 9a. Asymmetry arising in this way can be eliminated by plotting the quantity $v_p b_z^2$. From the above expression it is seen that this quantity corrects for the amplitude modulation that is caused by variations of the phase velocity of the waves.

Approximating the phase velocity as the Alfvén velocity (for regions where $\beta \sim 1$, the Alfvén velocity and sound velocity are of comparable magnitude), we plot $V_A b_z^2$ in Figure 18. The absolute units are not important as we are concerned only with relative amplitudes. Figure 18 shows that the dawn-dusk asymmetry reduces substantially once the wave amplitude is scaled by the phase velocity. Furthermore, from the plot one can see that the peak of this spatial distribution is located well within the magnetopause which supports the view that the waves are generated internally rather than being driven by surface waves near or on the magnetopause.

The compressional waves near the noon meridian seem to be caused by mechanisms different from that driving their counterparts near the two flanks. We inspected a few wave events near noon and found some of the wave events are associated with impulsive solar wind dynamic pressure variations. These waves seem to be initiated by a sudden change of the solar wind dynamic pressure and they are presently under further investigation.

The azimuthal waves have amplitudes strongly peaked on the night side of the magnetosphere. We isolated a few spectral estimates that contribute to the peak distribution of the wave near the midnight sector. Plotted in Figure 19 is the time series of one of the events. The detrended magnetic field components in MFC were plotted in the first three panels. In the last panel the magnetic index $AE$ was plotted. It is seen that as a consequence of the substorm development (indicated by increases of $AE$), large azimuthal waves were observed after 0900 UT of February 14, 1978. Therefore these large-amplitude transverse waves could be substorm associated. This also helps us to explain why the most intense azimuthal wave power is at higher magnetic latitude near the midnight sector. The field line from the location ($-5$ to $-10$ RE in $x$) of the dark area in Figure 10c may map to the region of the magnetotail where magnetic substorms are initiated.

The large-amplitude azimuthal waves near the magnetic equatorial plane (Figure 10b) occur in the premidnight region that the ISEE spacecraft traversed during active periods (see Figure 15). As magnetic activity occurred with rather high frequency in a rather limited portion of the analysis interval, this peak may reflect the association of the azimuthal waves with substorm activity.

Both compressional and azimuthal waves near the noon meridian have similar distributions and penetrate far earthward. However, we have not been able to identify reasonable models of the generation mechanism for waves in this sector.
forms found in the two studies are, however, quite similar than in Hedgecock's HEOS-based one. The wave amplitudes at high magnetic latitudes as reflected in Figures 9b and 9c. Therefore the higher occurrence rate in the near-equatorial region than did the HEOS spacecraft with an inclination of 52°. The same near-equatorial localization explains why we find ULF wave events more often on the ISEE spacecraft orbital plane was inclined by (23°) which enabled inbound trajectories than on the outbound ones as the former typically traversed lower magnetic latitudes than the latter.

There are discrepancies between the wave distributions found near the synchronous orbit in this study and in the study by Barfield and McPherron [1972, 1978]. In this study, very small wave amplitude or virtually no wave activity was observed near synchronous orbit (the inner circle surrounding the earth in Figure 9a). On the contrary, Barfield and McPherron found that compressional wave power is appreciable at geostationary orbit and that the average wave period is 200 s. We believe this is because Barfield and McPherron’s waves are activity related and Figure 15 shows that the ISEE passes through synchronous orbit in the afternoon sector occurred during intervals of relatively low activity.

In our analysis and interpretation of ULF waves we have not corrected for Doppler shifts and frequency [Baumjohann et al., 1987, Anderson et al., 1989]. This is because the Doppler shift effect is probably not important for the compressional waves in the outer magnetosphere. The principal reason is that the magnetic field strength is so low that compressional waves usually have large wavelengths. In a well-studied wave event, Lin et al. [1988] found the wavelength of a compressional wave in the outer magnetosphere to be 10,000 km. Using similar techniques, we also found in a case study that waves in the outer magnetosphere have wavelengths of several $R_E$ (to be reported later). The typical spacecraft velocity is about 3-5 km/s, so the estimated Doppler shift is usually negligible compared with the wave frequency.

Although the ISEE spacecraft did not observe significant Pc 5 waves near geostationary orbit, the wave distributions at larger radial distances revealed some features similar to those of compressional waves at geostationary orbit, for example, Kremser et al. [1981]. Our local time distribution of the compressional waves on the duskside of the magnetosphere is generally in good agreement with Kremser et al.'s distribution of out-of-phase events. We also observe a weak peak near local noon. Unfortunately, we do not have electron data to verify whether they are in-phase events or not.

Since magnetic and plasma pressure perturbations are mostly in antiphase and often cancel each other, the total pressure (the sum of the two) typically maintains a nearly constant value. Further inspecting Figures 7 and 8, one finds this constancy was better maintained for the waves near dusk than near dawn. When there were total pressure fluctuations, it is seen from the figures that they were always in phase with the magnetic field perturbation. This leads us to speculate that for these times the assumptions used to obtain the plasma pressure may not have been valid and that the pressure was significantly underestimated, as would occur, for example, if heavier ions like oxygen were present. Consequently, we think it likely that for all waves in this survey the total pressure fluctuations are significantly smaller than the magnetic and plasma pressure variations. Further studies are needed to explore this possibility.

Since this work was completed, two related papers have been published. Takahashi et al. [1990] studied 23 harmonically related compressional wave events using AMPTE/CCE observations. For the wave events they studied the frequency of the compressional component was twice that of the transverse component (double-frequency events). Virtually all of their events were found near the apogee of the AMPTE/CCE spacecraft near $9\,R_E$ and were located at the duskside and duskside of the magnetosphere. Their events occurred near the regions of peak compressional wave power as seen in the distribution pattern in Figure 9. Some of the waves in Figures 7 and 8 also are double-frequency events. In fact, when we inspected the ISEE spacecraft data in the outer magnetosphere on the duskside and duskside of the magnetosphere but mostly beyond $9\,R_E$, we often found double-frequency events [Zhu et al., 1988]. Anderson et al. [1990] used AMPTE/CCE observations for statistical studies of ULF waves of different spectral types. They classified the waves into 15 different spectral types and obtained their statistical properties. Many of their results are similar to ours. In particu-
lar, (1) Anderson et al. found that radially polarized waves and compressional waves are found mainly near the equatorial plane, analogous to our conclusion that the MWAs for the $b_x$ and $b_z$ components peak near the equatorial region; (2) they found that the azimuthal events have a higher occurrence rate at higher magnetic latitudes and so did we, especially for the $b_x$ component in the nightside of the magnetosphere; (3) they found that stormtime type Pc 5 waves occurred on the two flanks of the magnetosphere and this is also true for the $b_x$ distribution in our study; (4) they found that the average wave power in the compressional component and the radially polarized component are similar, which we also noted. There are differences in the results of their study and ours. In particular, we found that the wave power for the components polarized in the radial and the field-aligned directions is significantly stronger than that for the azimuthal component. This is opposite to what Anderson et al. found. They also found a large occurrence rate of the so called "harmonic mode events" (azimuthal waves with higher frequencies than the fundamental mode when several harmonics were present) on the dayside magnetosphere, but we found large amplitude azimuthal waves near midnight. Although the two studies are related, direct comparisons are difficult as Anderson et al. obtained distributions of occurrences and we presented mean wave amplitudes. Some of the discrepancies may stem from different variables used to characterize the waves. Some may relate to the larger radial range that we investigated. For example, Figure 9a shows that the amplitude of compressional waves is substantially smaller near the AMPTE/CCE apogee than at the larger radial distance that we studied using ISEE data. The differences could relate to solar cycle effects as the ISEE and AMPTE/CCE observations were made at different phases of the 11-year solar cycle. Further study is needed to understand the discrepancies.

**SUMMARY**

1. Compressional waves with typical wave periods of 10 min are common on the two flanks of the magnetosphere. They are polarized close to a meridian plane with comparable compressional and transverse components. Transverse waves polarized in the azimuthal direction are a nightside phenomenon.

2. The compressional wave amplitude peaks well inside of the magnetopause after proper normalization and correlates well with $b$, its amplitude being roughly proportional to $\sqrt{b}$. This suggests that internal plasma instabilities are the most probable wave generation mechanism.

3. In the compressional waves, plasma pressure and magnetic pressure are mostly in antiphase. The fluctuations of the total pressure are often noticeably smaller than the fluctuations of either plasma or magnetic pressure. We suggest that for those events in which the fluctuations of the total pressure are not small, the ion moment based on the FPE measurements underestimates the plasma pressure and that the fluctuations of the total pressure would become small if the true thermal pressure were known.

4. Large-amplitude compressional waves are more common within 20ø of the equator. Azimuthal waves on the nightside of the magnetosphere have largest amplitudes at latitudes above 20ø.

5. ULF waves of both transverse polarizations near local noon penetrate deep into the magnetosphere and are not limited to latitudes near the magnetic equator.

6. In our data set there is a dawn-dusk asymmetry in the average compressional wave amplitude. This asymmetry is most probably caused by asymmetry in sampling regions of low Alfvén velocity on the dawnside and dusk-side of the magnetosphere. When the compressional perturbations, $b$, are scaled by the Alfvén velocity, the peak distribution of the quantity $V_A b^2$ is located well inside the magnetospheric boundary and is symmetric about the noon-midnight meridian plane.

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