A Storm Time, Pc 5 Event Observed in the Outer Magnetosphere by ISEE 1 and 2: Wave Properties

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A classical, storm time Pc 5 event (T ~ 160 s) was recorded by the satellite pair ISEE 1, 2 during an inbound pass on August 21-22, 1978. Irregular and quasi-periodic pulsations composed of several harmonics (f ~ 2-10 x 10^-3 Hz) were recorded from just inside the magnetopause at 11 Re to a distance of ~8 Re, where the pulsations became nearly sinusoidal, and disappeared at ~7 Re just outside the plasmapause. Comparison of signals from the two spacecraft throughout the pass shows remarkable similarity of waveform at the second spacecraft following a few hundred to a thousand kilometers (~300 s) behind the first. This duplication of waveforms having wave periods concomitant with the spacecraft separation time suggests that the two satellites were sampling slightly different phases of the same wave cycle. The more distant, irregular pulsations were encountered by the two spacecraft with essentially no consistent delay between them, while the innermost, regular waves were always encountered first by the leading spacecraft. Cycle-by-cycle hodograms show nearly linear or highly elliptical polarization in the meridian plane everywhere on the inbound orbit, dominated by compressional waves. During the last few cycles the ellipses broadened and reversed phase at both satellites, just before the oscillations terminated, while the azimuthal amplitude went to zero at one satellite but not at the other. The Pc 5 pulsations occurred during an interval of strongly southward interplanetary magnetic field and substorm activity and were accompanied by Pc 1 waves at the spacecraft.

INTRODUCTION

Waves classified morphologically as Pc 5 in the records of magnetometers on the earth's surface have also been recorded in the magnetosphere by satellites. These waves are observed at geosynchronous distances [Barfield and McPherron, 1972] and have been classified into noon and dusk types by Kremser et al. [1981]. The waves in the dusk meridian have been associated with substorms [Barfield et al., 1972], but there has been little opportunity to examine the storm-connected waves in the dusk meridian outside of L ~ 6 because eccentric satellites pass so rapidly through their region of occurrence and do so only during limited intervals, when orbital parameters place the trajectories in the proper local time zone. Indeed, only a few examples of these pulsations outside synchronous orbit were displayed by Hedgecock [1976] despite inspection of data from many orbits of HEOS.

Fresh opportunities to observe these evening sector pulsations were provided by the satellite pair ISEE 1, 2, launched in October 1977. During the first seasonal sampling of the dusk sector, in August 1978, an outstanding event was detected by several plasma and energetic particle experiments as well as by the magnetometers. Although chance has delivered us one such event so far, and hence no statistical basis for stating that the prevailing storm conditions were anything but coincident, we adopt the view that we are dealing with a representative storm time example, and we anticipate that a full characterization and improved understanding of storm time Pc 5 pulsations in the dusk sector will eventually emerge from the treasury of data collected for this event. In this initial report on our event, we describe the event and its geomagnetic context as recorded by the magnetometers, using one of the unique advantages of the ISEE system, namely, the simultaneous observations by two spacecraft close together in the same eccentric trajectory. This advantage has already proved its value in studies of pulsations of the morning magnetosphere [Singer et al., 1979, 1982; Takahashi et al., 1985].

A midmorning, compressional, monochromatic event, with a clear phase reversal very similar to the one described here, was recently reported in 1981 data from the same satellites at L ~ 5.6-7.3 by Takahashi et al. [1965]. They interpreted their wave train as an azimuthally propagating wave and the phase reversal as the node of a standing wave through which the two spacecraft happened to pass slightly above the geomagnetic equator. As this paper will show, only one of the satellite pair detected the reversal in our case, and the monochromatic wave event seemed to be part of a larger-scale wave phenomenon affecting an entire, although longitudinally narrow, sector of the magnetosphere out to great L distances.

THE EVENT IN CONTEXT

Spatial context. The magnetic wave signature for the inbound magnetospheric pass of August 21-22, 1978, is displayed in Figure 1. The three components of the ambient field measured by ISEE 1 are plotted in GSM coordinates (X toward the sun, the X-Z plane containing the dipole axis), together with the total field magnitudes BT from both ISEE 1 and ISEE 2. The similarity of waveform, cycle by cycle, at the locations of the two spacecraft is visible throughout the pass.

TO place the wave in the context of the ISEE magnetospheric profile, we have included an inset of the 64-s average of BT at ISEE 1 in the upper left, where the hatched subsection of the inbound pass corresponds to the interval displayed in the larger figure; the peak in the inset signifies that orbit's perigee low in the magnetosphere. The waves first appeared at 2151 UT (ISEE 1), shortly after the spacecraft crossed the magnetopause, as we shall describe later. The similarity of the wave observations to cases described by Hedgecock [1976] can be appreciated by comparison with his Figures 3 and 4.

The event on which we concentrate in this paper is the second.
The spatial region over which the wave event was observed is shown in several coordinate planes in the various panels of Figure 2. In each of the orbit panels the magnetospheric waves are denoted by an elongated box enclosing the trajectory; the Pc 5 event occurred where the inner end of each box is shaded. The asterisks on an arc of geosynchronous trajectory in the drawing at lower left signify the locations of GOES 2 and GOES 3 at the time of the Pc 5 event.

We see that the data were obtained near the magnetic equator, just sunward of the dusk meridian, from slightly inside the magnetopause to slightly outside the radius of geosynchronous altitude. This is significant because, with the exception of Hedgecock's [1976] observation, much of the Pc 5 wave activity measured in the magnetosphere has been detected with geosynchronous satellites or Scandinavian Twin Auroral Radar Experiment (STARE) radar.

The separation vector of the two satellites during the Pc 5 event is shown in the panel at the top of Figure 2. ISEE 2 was leading ISEE 1 inbound and southbound, almost in a common meridian plane, by 386 km. The Z separation, not drawn to the same scale as the separation distance, was about 200 km, with ISEE 1 closer to the equator than ISEE 2. The radial distance of ISEE 2 to the earth is, of course, not drawn to the same scale as the separation distance in these panels.

The actual relationship of the magnetic waves to the local electron density in the present case can be obtained from Figure 3, where B at ISEE 1 is plotted above a wideband spectrogram of the simultaneous electric wave data, also from ISEE 1. Electron density is related to the observed plasma frequency, in kilohertz, by \( n = f^2/80 \). The plasma frequency rose rapidly just after the end of the figure, reaching about 75 kHz \( (n \sim 70 \text{ cm}^{-3}) \) by 0112. The sinusoidal Pc 5 waves occurred at the beginning of the gradient in electron density at 0015 associated with what appeared to be an external, enhanced density extension bordering an expanded plasmapause.

**Temporal context.** Following an interplanetary discontinuity at about 1925 seen in \( B_x \) of the center panel of Figure 4, there was a second discontinuity in which the interplanetary magnetic field (IMF) at ISEE 3 turned almost directly southward in GSM coordinates at 2025, about 75 min before the final entry of ISEE 1 and 2 into the magnetosphere and an hour and a half before ISEE 1 and 2 encountered the waves we describe. The second (southward) discontinuity reached the two spacecraft at 2108, some 43 min after it passed ISEE 3, and almost simultaneously with the first magnetopause crossing by the satellite pair, visible at ISEE 1 as the end of the bright vertical band at the left edge of the spectrogram of Figure 3. There was an excursion in the IMF at ISEE 3 from about 2040 to 2100 that on arrival at 1 AU caused a return of ISEE 1 to the magnetosheath from 2128 to 2140, seen as a vertical stripe in Figure 3. The end of this interval marked the last magnetopause crossing by ISEE 1 at 2140; the first waves appeared a few minutes later. Following the initial interval of almost purely southward field for over an hour, the GSM X and Y components drifted away from zero, but the negative \( B_z \) continued to dominate, and for the next three hours the solar wind provided an outstanding example of sustained southward magnetic field.

The magnetospheric substorm caused by the episode of southward IMF began just before 2200, about the time the waves started at the spacecraft. The bottom panel of Figure 4 shows that the bulk of the substorm, as defined by two surface stations, coincided with the pass of ISEE 1, 2 through the outer magnetosphere, signified by the shaded strip, which ended with the Pc 5 event near the plasmapause. The top panel of Figure 4 displays four channels of whistler wave data from ISEE 3, indicating that the solar wind contained in the interval of interest was significantly noisier than that before the southward turning. Note that the field magnitude \( B_T \) underwent a sharp jump at the same time \( B_z \) went negative. The field and whistler patterns together suggest that the southward turning may have been in connection with an interplanetary shock, since whistler noise customarily rises behind a shock. We have not studied the interplanetary event closely, but we observe that the possible immersion of the magnetosphere in postshock solar wind, or in a piston plasma, could have influenced the nature or existence of the pulsation event we are describing.
Compressional PC5 Pulsations
Spacecraft Separation Geometry in GSM Co-ordinates
78 August 22 0037UT

Wave Analysis
Frequency spectra. Spectra were calculated by first editing, detrending, and fast Fourier transforming the magnetic field vector time series. The Fourier transforms of each component were then multiplied to obtain autospectra and cross spectra at each Fourier coefficient. These Fourier spectra were low-pass filtered with a running average, normalized, and plotted. The frequency resolution of the resulting spectra, defined as the distance between totally independent estimates, is given by

$$\Delta f = N_g/(2N_{est} \Delta t)$$

where $N_g$ is the number of points in the filter, $N_{est}$ is the
Fig. 3. Wideband plasma wave spectrogram for the August 21-22 pass of ISEE 1, with corresponding magnetic field magnitude in the upper panel. Time ticks at 10-min intervals. The white, irregular band through the center of the spectrogram denotes electron plasma waves, whose upper bound is a measure of the local density according to the formula in the text.
number of Fourier coefficients (half number of data points), and Δt is the time resolution of data (4.0 s).

Spectra calculated for half-hour intervals, filtered with a threepoint average, have a resolution of 1.7 mHz. A 2-hour interval and filter length of five points provided a resolution of 0.7 mHz. The actual location of the frequency of peak power can be determined somewhat more accurately than the resolution as every filtered Fourier spectral estimate is plotted.

Figure 5 displays three sets of five-point power spectra corresponding to selected segments of ISEE 1's field data. Each spectral panel represents the frequency analysis of the time series above it, to which it is referenced by the slanted lines. The first two segments are spaced throughout the outer magnetosphere; the last covers the heart of the pulsation event itself.

Spectral power was distributed differently with the frequency along different parts of the trajectory, but all spectra share two common characteristics: Each had at least one clear peak, plus other lesser ones; and one component of the field, the Z component, carried most, if not all, of the power in every peak, indeed, throughout every spectrum. The second characteristic implies the waves were essentially linearly polarized everywhere at all frequencies. Examination of the five-point spectra discloses two dominant peaks with maxima at frequencies 4.0 and 6.0 mHz. The lower frequency was present immediately inside the magnetopause and persisted until about 2320 at a distance of 9.3 R_E. The higher frequency appeared at that time but was mixed with still higher frequency signals of 10 and 20 mHz. After 0000 UT there was a change in the characteristics of the pulsations which became very monochromatic at a frequency close to 6.0 mHz. The wave activity vanished suddenly about 0050. A zero crossing analysis of the waveform 0000-0050 interval gives a period of 167 ± 2 s (f = 5.99 mHz) in good agreement with the spectral peak for this interval.

Four significant peaks have been emphasized and labeled in Figure 5; three of them, at 85-, 167-, and 250-s periods, immediately suggest harmonic pairs of, roughly, 4 and 12 mHz, or 6 and 12 mHz. The fourth, at 110 s, suggests that the broad 250-s peak may include an element (T = 220 s) of another pair, 4.5 and 9 mHz. The harmonic number in any of these potential sequences appears to have increased with decreasing radial distance. Verification of such sequences, and their relationships to magnetospheric geometry, will require further study, probably at higher resolution than this data set permits. We note for the record that Barfield et al. [1972] recorded harmonics at synchronous altitude during a magnetic storm in the afternoon sector.

Polarizations. Cycle-by-cycle hodograms confirm an extremely elliptical polarization through almost the entire duration of the wave event, as already indicated by power spectra. Four examples, each showing planes of maximal and minimal variance, are shown in Figure 6, where the disturbance vectors are seen to have traced long, narrow, irregular patterns confined almost entirely to the planes of maximal variance.

To examine the arrangement of wave polarization relative to B throughout the inbound passage of the ISEE spacecraft, we performed a cycle-by-cycle minimum variance analysis. This analysis included several steps. First, the entire orbit was divided into intervals over which the direction of the magnetic field was approximately constant. For each interval a field-aligned coordinate transformation was defined. Data in each interval were rotated from spacecraft to field-aligned coordinates, which we designate B_x, B_y, B_z, for radial, longitudinal (also called azimuthal), and total field components, and then band-pass filtered. The passband, 2–8 mHz, was chosen to include the two predominant peaks at 4 and 6 mHz revealed by spectral analysis. Next, the pulsation waveform was examined visually, and successive cycles of the pulsations were defined by an interactive graphics program. For each interval thus defined, minimum variance analysis was performed to obtain properties of the magnetic perturbation within the passband of the filter. These properties included the total and component power in the perturbations, the apparent wave period, the orientation vectors of the perturbation ellipse, and the sense of rotation.

Results of the foregoing analysis are summarized in Figures 7 to 13, which show the temporal changes in wave properties as the spacecraft ISEE 1 moved inward. The plots begin at 2200 UT as ISEE 1 entered the magnetosphere and continue until 0100 when it entered the plasmasphere. Figure 7 shows the total power in the perturbation in the top panel, and the
ellipticity in the bottom panel, where ellipticity is defined as the ratio of the minor to major axis of the perturbation ellipsoid. There were three intervals of large-amplitude wave activity roughly centered at 2200, 2310, and 0030 UT (see Figure 1). In the first interval of intense, long-period waves the ellipticity was small, indicating nearly linear polarization. During the second interval the ellipticity was somewhat higher, ~0.3. In the third interval, however, the period of the waves was shorter, and the ellipticity varied systematically with amplitude. As the waves were first seen, the ellipticity was high, ~0.6; then, as the spacecraft moved inward and wave amplitude increased, ellipticity decreased. At the point of maximum power in the parallel component the waves were linearly polarized. Subsequently, as wave power decreased, the ellipticity again increased. However, the sense of rotation was reversed as a consequence of a 180° phase change in the azimuthal component. Outside the maximum in parallel power the transverse magnetic perturbation was right elliptically polarized, while inside it was left elliptically polarized. Figure 8 illustrates these points with filtered waveform plots and superimposed vertical lines of constant phase.

The top panel of Figure 8 shows the three components at ISEE 1 in field-aligned coordinates for the key 50 min of the third, monochromatic, interval. A maximum is clearly seen in the compressional component, with largest amplitude at around 0035. The vertical lines through the positive peaks of \( B_T \) line up with the positive peaks of \( B_R \), but we see the alignment is violated in comparing the \( B_\phi \) waveform. The detail in the linked panels below, from 0020 to 0040, shows that in comparison with the positive peaks of total field \( B_T \), the azimuthal component shifted by 180°, from correspondence of the ascending zero crossings to correspondence of the descending zero crossings with the phase of \( B_T \). This 180° change in phase was coincidental with the amplitude maximum of \( B_T \) and is the expected phase signature of the azimuthal component of a standing, resonant, transverse wave. The 180° phase shift occurred over five or six cycles of the wave; from the period of 167 s and the spacecraft velocity of 2.7 km/s, we infer the phase reversal region's radial thickness of 2250–2700 km, or 0.35–0.42 \( R_E \). This measurement from a complete radial pass through a magnetospheric phase reversal agrees well with previous thickness estimates of resonant phase reversals from less continuous data [Hughes et al., 1978; Hughes, 1980]. We emphasize, by repeated use of the phrase "polarization reversal," rather than "resonance," in the rest of this paper, that the whole combination of minimal transverse and maximal compressional amplitudes at phase reversal is not the expected signature of a standing transverse wave resonance.

A cumulative area analysis has also been applied to the filtered and transformed data. In this analysis it is assumed that the tip of the magnetic perturbation vector projected in a coordinate plane, no matter how erratic its progress, rotates around a series of ellipses as a function of time. As the vector rotates, the angle of rotation and the area swept out by the vector change depending on the properties of the wave. If the perturbation is linearly polarized, the area does not change, but the angle increases or decreases in 180° steps. If it is elliptically polarized (counterclockwise in the \( R\theta \) plane), both increase with time. A change in the sense of rotation causes an extremum in both parameters.

Application of the cumulative area technique to data from ISEE 1 gives the results summarized in Figure 9. The three traces show the cumulative area, cumulative rotation angle, and the instantaneous wave power (amplitude squared) as functions of time for the first hour of August 22. An amplitude maximum associated with the phase reversal of \( B_\phi \), although not obvious in either transverse component alone, appears, as might be expected for a resonance, in the envelope of their combined magnetic perturbation vector, i.e., in the envelope of the wave power perpendicular to \( B \), \( B_\perp = B_R + B_\phi \), plotted as the dotted curve in the figure. Twice each cycle of the perturbation this vector passes through maxima and minima corresponding to times of alignment with the principal axes of the ellipse. If the perturbation is linearly polarized, the vector varies between zero and some positive value. If it is elliptically polarized, it varies between two positive values whose ratio is the instantaneous ellipticity of the perturbation.

In Figure 9 the oscillating, transverse wave magnitude is seen to have reached a sharp peak between 0030 and 0040 exactly when the cumulative area and angle swept out by the rotating \( B \) (solid curves) reached their maxima, indicating that
the transverse power maximized when the sense of polarization reversed and each cycle's polarization parameters began to be subtracted from the cumulative totals. However, the envelope also maximized at about 0024 and 0044, as wave amplitude shifted back and forth between $B_R$ and $B_A$. We see this effect in the separated components in Figure 8, and we see that the azimuthal component did not maximize at its phase reversal, thus nullifying the suggestion of an azimuthal resonance. Indeed, the ISEE 2 azimuthal amplitude went to zero just as the phase reversed.

Note that the slope of the rotation angle trace gives the instantaneous wave period. Approximating the average slopes by straight line segments yields an initial wave period of 150 s, followed by an interval of wave period about 180 s, and a postreversal period of about 190 s. The average of these periods, weighted by the lengths of the intervals used to evaluate each slope, is 170 s, close to the 167-s peak of the spectrum computed over the whole interval.

It is evident from the angle and rotation traces that at the beginning of the interval the perturbation was right elliptically polarized (positive slope). As time progressed, the polarization became more and more elliptical until at 0034 UT it was exactly linear. Subsequently, the polarization continued to
change, becoming left-handed throughout the remainder of the interval.

Reversal offset. A similar analysis of ISEE 2 data produced the results plotted in Figure 10, but with a time offset accounted for by this spacecraft's earlier arrival in the phase reversal shell. There was also an offset of the maximal transverse amplitude at ISEE 2 from the maximal cumulative angle seen by the same magnetometer. However, since two of the $B_{\text{max}}$ excursions (semimajor axis of $B_{\text{p}}$) correspond to each wave period, and the two spacecraft crossed the reversal about half a period apart, the absolute magnitude recorded at either satellite was highly sensitive to the wave phase at which the satellite chanced to arrive: ISEE 2 probably missed the actual conjunction of the two maxima.

The polarization reversal was observed earlier at ISEE 2 than at ISEE 1. Figure 11 exposes this point by superposing the area and angle traces from the two spacecraft. The upper panel indicates that ISEE 2 encountered the polarization changes about a minute and a half (100 s) earlier than ISEE 1 on the basis of the average ascending displacement and somewhat less (80 s) on the basis of the descending displacement. The lower panel shows more irregularity of the displacement, which favors a larger offset of 100–180 s. As mentioned before (Figure 2), ISEE 2 led ISEE 1 on the trajectory and passed through spatially localized features first. At the time of this event (~0037) the spacecraft were separated radially by 880 km. The delay should have been ~325 s at a satellite velocity of 2.7 km/s.

It thus appears that ISEE 1 encountered the polarization reversal earlier, i.e., further out, than it should have if a phase reversal shell were localized and stationary. One explanation of this discrepancy is that the reversal region was moving radially outward. Of course if this explanation is valid, then the estimated thickness of the reversal from either satellite would be too small, so 0.4 $R_E$ would have to be regarded as a minimal thickness, and double this value would not be unreasonable.

Wave offset. We return to the bottom panels of Figure 8. Filtered waveforms from both ISEE 1 and ISEE 2 are plotted, which illustrate the character of the instantaneous offset, that is, the delay between the two records of the waves. The offset was virtually constant at an observed value of about 12 s between the two signal records. The offset is clearly visible on the $B_{\text{p}}$ plot but is lost temporarily from $B_0$ during the latter's phase shift, when the ISEE 2 signal actually vanished for one cycle. Physically, this offset means that ISEE 1, following ISEE 2 inbound, recorded each cycle of the wave train 0.072 period, or 26° phase behind ISEE 2, where we have taken the average wave period as 167 s. The implied azimuthal wave number is $m = (2\pi R/\Delta \Phi/T) = 55$, where $R$ is the radial distance, $\Delta \Phi$ is the azimuthal separation in kilometers of the spacecraft, $\Delta t$ is the phase time delay, and $T$ is the wave period. Thus the observations match the large-$m$ case of Takahashi et al. [1985] for a longitudinally (azimuthally) propagating wave.

Radial invariance. The overall history of the time offsets in the two signals is displayed in the bottom right panel of Figure 12. Quantity $\Delta t$ denotes the delay between detection of the same wave phase at ISEE 2 and ISEE 1, as drawn at bottom left of Figure 12. We note there was essentially no measurable delay in phase between the records of the two magnetometers in the outer magnetosphere until about 2330, when $\Delta t$ attained values of 8–16 s, which continued until the end of the interval. We will discuss this property again later.

The sketch at upper left defines angles $\theta$ and $\Phi$ which characterized the polarization ellipse in the magnetic meridian plane. The three panels indicate clearly the relatively constant "base" polarization of the waves throughout the inbound pass: The perturbation ellipse was almost in the meridian plane before 2230 and after 2330 ($\Phi = 0^\circ$, 180°), and the major perturbation was close to the nominal $B$ everywhere ($\theta = 10^\circ$–20°). Angle $\Phi$ seemed to drift toward 90° until about 2250, then slip to 270°, and drift back to 180° on average by about 2330, but except for a few minutes around 2315, the power during these drifts was very low and may not represent a significant contribution. The switch of between 180° and 0° at about 0005 is an artifact of the polarization code convention and has no physical significance. In general, deviations from the common values of $\theta$, $\Phi$ just described occurred when the filtered wave power was low (Figure 7; see also Figure 13), that is, when wave activity was minimal; so the common
values truly represent almost fixed wave polarization during
the three hours depicted. The major exception was the orienta-
tion of about 240° during irregular waves between 2250 and
2330.

The plots of Figure 12 illustrate one of the striking charac-
teristics of the events of the August 21–22 pass; namely, the
tendency for important wave parameters to have remained
nearly steady in the data with little regard for the location
of the spacecraft or changes in other parameters. The angle
$\Phi$, for example, took little notice of the change in phase delay at
2330, and angle $\theta$ was substantially the same at the beginning
of the interval as it was during the last hour and a half.

These characteristics are also apparent in Figure 13, where
the cycle-by-cycle phase delay is reproduced in the first (top)
panel for comparison with other parameters. The second
panel presents the cycle-by-cycle period of each measurable
wave cycle within the passband of the 2- to 8-mHz filter. Two
horizontal dashed lines corresponding to the two predominant
peaks in the power spectra are drawn at periods of 250 and
167 s. We see that the instantaneous periods at 100, 160, and
250 s tended to recur while the ellipticity in the third panel,
replotted from Figure 7, was effectively stable between 0.1 and
0.3, when significant power was present, until ~0000 UT. The
bottom panel shows even more emphatically that the com-
pressional wave power $P_{\parallel}$ was a substantial fraction of total
power ($P_{\parallel}/P_{\perp} \sim 0.8$) almost everywhere, independent of the
interspacecraft phase delay (top panel) or the period (second
panel). Thus throughout most of the inbound orbit and partic-
ularly during the intervals of high activity, roughly 80% of the
power in the wave perturbation was parallel to the ambient
field. Conversely, transverse power $P_{\perp}$ was typically less than
20% of the total power. We see further that the low ellipticity
was independent of the wave period dominant at any particu-
lar time.

The foregoing observations argue that the wave phenomena
encountered by the two spacecraft shared common properties
essentially independent of radial distance within the narrow
meridional sectors sampled in this case.
Surface observations. Magnetograms covering the interval of ISEE's inbound pass have been collected from the Air Force network, whose Rapid City, South Dakota (RPC), and Camp Douglas, Wisconsin (CDS), stations were at almost the same local times as the ISEE pass. Waves of irregular waveform and long period were recorded at all stations but between 2330 and 0100 UT were most prominent at the RPC, CDS, and MCL (Mount Clemens, Michigan) locations and were appreciably reduced at Lompoc, Sudbury, and Tampa both west and east of ISEE's meridian. Identification of these waves as being those found in the outer magnetosphere will require detailed spectral, polarization, and propagation analysis of digital data from these stations. Specifically, periods of 140–160 s appear to have been present.

Geosynchronous observations. As marked in the bottom panel of Figure 2, the GOES 2 and 3 satellites bracketed the local meridians of ISEE's trajectory. Each spacecraft recorded sharply defined bursts of pulsations, but at periods of roughly 60–80 s, quite different from those seen by ISEE, with two exceptions: GOES 2 detected some radially polarized waves of 215 s period, and longer, between 0000 and 0300 UT, and GOES 3 detected some 162-s compressional waves for over an hour, between 0210 and 0340 UT, as it passed through the meridians where ISEE had been before it entered the plasma-
pause. Here again, computer analysis will be required to
decide whether the same phenomenon was in progress as
GOES 3 passed the dusk meridian. For the present, two cir-
cumstances are clear: No observation point 2 hours or more
away from the local time of ISEE recorded waves obviously
similar to those at ISEE, and the waves apparent at geosyn-
chronous altitude around 0300 UT had not been present
shortly after 0100 when ISEE passed the radial distance of
synchronous orbit. We thus conclude that the Pc 5 pulsations
were spatially localized, confined to about 30° of longitude
centering on, or an hour west of, the dusk meridian.

SUMMARY OF OBSERVATIONS

Our initial investigation of the storm time, dusk pulsation
event observed by ISEE 1 and ISEE 2 on August 21-22, 1978,
have disclosed the following properties of the waves composing
the event: (1) monochromaticity ($T \sim 167$ s) in strong field
and density gradients at the edge of the plasmasphere; (2)
dominant compressional component; (3) well-defined, phase
reversal of the azimuthal component, with radial thickness of
about 0.5 $R_E$; (4) essentially constant phase difference $\sim 26^\circ$
between spacecraft measurements of monochromatic wave-
forms surrounding reversal; (5) irregular waveforms between
the magnetopause and plasmapause, with spectra suggesting
components harmonically related to each other and to the
monochromatic segment; (6) confinement to distant mag-
netosphere (outside plasmasphere) and limitation in longitude;
(7) phase reversal offset between spacecraft measurements in-
compatible with static reversal location; (8) common parame-
ters of phase, direction, and power throughout the data inter-
val; and (9) large wave number $m \sim 55$.

DISCUSSION

The afternoon-to-dusk sector of the magnetosphere is the
scene of complex wave phenomenology in the Pc 4-5 range,
the source of which can be Kelvin-Helmholtz (K-H) waves on
the magnetopause surface [Southwood, 1974; Chen and Hase-
gawa, 1974] or ion drifts related to the ring current or plasma-
pause [Southwood et al., 1969; Hasegawa, 1969; Lanzerotti et
al., 1969]. The complexity arises, presumably, because sources
may coexist and because any one source can excite wave
modes that coexist in the asymmetric, dipolar, multigradient
magnetosphere and will couple to other wave modes [Lin and
Parks, 1978; Walker et al., 1982; Patel et al., 1983; Southwood

Although "pure" modes attributable to single sources have
been observed (K-H [Walker et al., 1978]; ring current ion
drift [Allan et al., 1982, 1983]) or extracted from compound
records (K-H [Poulter, 1982]), mixed-mode events are not un-
usual, at least at geosynchronous distances [Barfield et al.,
1972; McPherron, 1980]. By mixed mode, we mean waves
having both transverse and compressional components or, in
a magnetospheric context, combinations of toroidal, poloidal,
and compressional components having both longitudinal and
meridional propagation vectors. Certainly, the greatest com-
plicity is expected during storm conditions, when the solar
rejected westward into the premidnight magnetosphere. This eastern, northern, and southern flank and ions are being injected and difficult to interpret than might have been expected, however. Thus the data do not present a self-consistent pattern supporting the notion of K-H as the source of the resonance in this case.

An ion drift or bounce resonance explanation of the wave train centered on 0030 UT would be compatible with the detection of the wave train where the large density gradient associated with an apparently inflated plasmapause was crossed and with the dominance of a compressional contribution almost everywhere. Also, the phase delay between spacecraft through the resonance could have been the result of westward propagation from ISEE 2 to ISEE 1, but it could as well have indicated outward radial propagation. The sporadic appearance of limited enhancements of electron density throughout the pass would support the inference of particle injections into the sector of the magnetosphere through which the ISEE spacecraft were traveling. But the other well-defined wave trains, around 2200 and after 2300 UT, although spec-

trally similar to each other, did not display a consistent relationship to the density enhancements. Moreover, there were apparently no phase delays supportive of westward or radial propagation before 2330 UT. Thus particle enhancement was not obviously correlated with wave enhancement along the satellite trajectory, while overall spectral similarities and possible harmonic relationships pointed to a connection of the final wave train with more distant wave activity, rather than to a purely local instability.

The shared characteristics of our wave event(s) throughout the radial pass seem to beg for interpretation in terms of a global compressional mode, together with some coupling to transverse oscillations. The theory of such global magnetospheric excitation, by either impulses or wave trains, has been receiving considerable attention lately [Kivelson et al., 1984; Allan et al., 1985; Kivelson and Southwood, 1986]. Unfortunately, the term "global" refers primarily to longitudinal, rather than radial, coherence, at low azimuthal wave numbers (explicitly m ≈ 3, in the Allan et al. [1985] paper), so that our event cannot accommodate this body of theory. We have estimated a large wave number and documented a narrow sector confinement with the GOES measurements. The evidence here indicates that regardless of whether global compressional oscillations couple to transverse modes, the appearance of mode coupling does not necessarily imply the presence of global oscillations.

The combination of wave properties surrounding the azimuthal phase reversal recorded by ISEE 2 duplicated closely the properties of the event described by Takahashi et al. [1985]. Our data therefore confirm that the circumstances of their measurements were not unique, but we have added the more distant observations, showing that the monochromatic waves shared parameters with waves that occurred in the outer magnetosphere. The present data do not, however, confirm the Takahashi et al. interpretation of the azimuthal phase reversal as the crossing of a node by the spacecraft, because, while they observed the azimuthal component reverse phase and pass through an interval of zero amplitude at both satellites, our ISEE 1 wave train exhibited a phase reversal but no accompanying minimum in amplitude. An interpretation of the azimuthal signal as a westward propagating high-m wave decoupled from the other modes as to have its own private node must be weighed against the distinction between our ISEE 1 and ISEE 2 records and the evidence of shared, i.e., coupled, attributes of waves throughout the inbound pass.

At this stage of our investigation, we favor the conclusion that the events of the August 21–22 pass resulted from a com-
combination of sources, namely, distant wideband excitation and ion drift instability, plus a coupling of wave modes. It seems very likely that the phenomenon we have described was a radial cross section of the type of event reported by Barfield et al. [1972], because all the events shared so many fundamental characteristics, e.g., local dusk sector, storm association, wave harmonics, and meridional polarization. The distant source could have been surface waves starting after the satellites crossed the magnetopause, waves driven by the solar wind at another location further downstream along the boundary, and/or waves instigated by drift instability. Certainly, we have expanded our concept of the region of the magnetosphere involved in the phenomenology of a monochromatic pulsation with phase reversal at or near the plasmapause. The radial dimension of our observation was some 4 $R_E$ greater than the roughly 3.4-$R_E$ arc of the 30° sector in which our event seemed to be confined. We expect future combination of the magnetometer data with electric field and charged particle measurements will determine the direction of propagation of the various wave components and delineate the most probable wave source or sources.

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