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Plasma and Field Observations of a Pc 5 Wave Event

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Micropulsation measurements of a Pc 5 wave event on July 14, 1982, in the afternoon magnetosphere are reported as observed by wave and particle instruments on board the Dynamics Explorer I (DE 1) spacecraft. The overall structure of the Pc 5 event as noted in the low-energy particle and quasi-static electric field data seems to order the event into two distinct halves. The appearance is reminiscent of a wave packet and suggests a temporal or spatial variation of the micropulsation, which has a scale of 20 min or 3000 km. The wave packet structure is also well correlated with a variation in the pitch angle distribution of the low-energy plasma with single direction field-aligned flow associated with the maximum amplitude of the wave packet structure and bidirectional field-aligned flows associated with the nodal point of the wave packet structure. The field-aligned velocities of the observed H+, He', 0', N+, and 0++ ions combined with the elliptical E x B wave oscillation in the first half of the event produce a helical motion of the plasma along the field line. In the second half of the event although all ion species are still present, strong magnetospheric convection seems to have a significant effect on the field-aligned motions and Pc 5 oscillations of the low-energy plasma. The event is characterized in the low-energy plasma by a left-hand to near-linear polarized rotation of the plasma over the first half of the event. Variations of the eccentricity over the first half of the event which are indicated by both the quasi-static electric field detector and the low-energy particle detector suggest that the center of resonance lies just radially inside of the DE 1 orbit (L = 4.7) and just outside of the dayside plasmapause, which appears to be located at L = 4 as indicated by experiments on board the DE 2 spacecraft. Comparisons of the measured Pc 5 wave period to the theoretical period derived from in situ evaluation of the plasma mass loading factor yield values of 190 s and 192 s, respectively. This is consistent with the center of resonance being nearly coincident with the DE 1 orbit. The second half of the event occurs in a region of enhanced magnetospheric convection, which makes determination of the eccentricity of the wave difficult and harder to interpret. The wave is found to be right-hand or linearly polarized during this portion of the event, which suggests DE I is just radially inward of the resonance center. However, disagreement between the measured period of 233 s and the derived period of 189 s does not necessarily support this interpretation. Density variations of plasma along the field line which are hemispherically asymmetric may explain the inconsistencies between the measured and derived period in this half of the event.

1. INTRODUCTION

Micropulsation measurements in the magnetosphere provide important information on the processes of basic plasma physics, the fundamental structure of the magnetosphere, and substorm processes. Analysis of micropulsation events to determine the wave modes, growth characteristics, and propagation is therefore vital to an understanding of the magnetosphere. In this paper, we will show observations of a Pc 5 event seen near the magnetic equator by the retarding ion mass spectrometer (RIMS), the energetic ion composition spectrometer (EICS), the magnetometer (MAG), and the plasma wave instrument (PWI) on board Dynamics Explorer 1 (DE 1).

Satellite measurements of micropulsations have been made by magnetometers, quasi-static electric field instruments, energetic particle experiments, and, in a few cases, thermal plasma instruments. Magnetometer measurements in the Pc 3 to Pc 5 frequency range are particularly numerous near geosynchronous altitude, and substantial progress has been made in identifying wave modes and energization mechanisms. This progress was summarized recently by *Kokubun [1981]* , *Hughes [1981]* , *McPherron [1981*], and *Southwood [1981]*.

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A large percentage of Pc 4 and Pc 5 waves can be interpreted as standing Alfven waves drawing energy from a Kelvin-Helmholtz instability at the magnetopause or the ring current *[Cummings et al., 1969; Dwarkin et al., 1971; Barfield et al., 1972; Cummings et al., 1975; Hughes et al., 1977, 1978]*. The type of event analyzed in this paper probably draws its energy from a Kelvin-Helmholtz instability at the magnetopause.

The use of multiple instruments to study a micropulsation, as in this paper, has occurred infrequently. One such comprehensive wave mode study was by Hughes et al. [1979] who used data from ATS 6, SMS 1, and SMS 2 to study a compressional Pc 4 pulsation in the evening sector (2100-2400 LT). In addition to the magneto-meter data from the three satellites, they used particle data to infer the electric field component of the wave at ATS 6. They deter-mined that it was a second harmonic field line resonance, powered by a bounce resonant interaction with ring current protons. A similar study by *Cummings et al. [1975]* of a Pc 4 event at local dawn using ATS 6 magnetometer and particle data showed that there was an odd mode (most likely the fundamental) standing wave along the magnetic field, propagating azimuthally from noon toward dawn.

Thermal plasma data from the mass spectrometer on OGO 5 were analyzed by *Kivelson [1976], Kokubun et al. [1977],* and *Singer and Kivelson [1979]* and used in Pc event studies. *Harris et al. [1970]* noted several events outside the plasmapause, but did not discuss them beyond noting their location. The ATS 6 and OGO studies showed that use of the additional detector dramatically increased the observed percentage of occurrence of Pc events, and this was attributed to the idea that the fundamental modes of the standing Alfven waves are odd, and the equator is a node for magnetic oscillations in that geometry. The OGO 5 work also indicated that detached plasma regions are prime locations for the occurrence of Pc 5 events.

Kaye and Shelley [1981] combined magnetic field and ion composition data from the SCATHA spacecraft to infer a wave electric field of 10 mV m-' in a large-scale hydromagnetic oscillation near synchronous altitude in the dayside magnetosphere. They inferred a wave motion of approximately 1.5 RE radially and from this motion inferred the radial gradients of the ion distributions. They concluded that the ions were energized via both the compressional wave component and their drift along the wave electric field.

Walker et al. [1982] showed GEOS 2 magnetometer and energetic particle observations from a storm time Pc 5 in the afternoon sector (1500 LT) and compared their results to Scandinavian Twin Auroral Radar Experiment (STARE) radar electric field measurements of the ionosphere. They demonstrated agreement between their observations and a model for coupling between a standing Alfven wave and a drift instability. They concluded that their Pc 5 event was a drift wave which was propagating westward at 6.6 RE with a wavelength of about 1 RE. The ionospheric data showed only the footprint of the standing Alfven wave. Energetic particle data for this event were shown by *Kremser et al. [1981]*.

Direct electric field observations of micropulsations like those shown in this paper have only recently begun to appear in the literature. Pedersen et al. [1978] and Pedersen and Grard [1979], using GEOS 1, found Pc 5 waves with amplitudes of 5-10 mV/m on the day side of the earth. These Pc 5 events were concentrated at L = 7.5; however, this concentration may have been biased by the limited range of L values surveyed in the study.

Singer et al. [1979] combined ISEE electric field and magnetic field measurements with those of several synchronous satellites to study field line resonances in the Pc 3 to Pc 5 frequency range and found events consistent with standing Alfven waves in spatially localized regions. They found both fundamental and second harmonic waves on the same field lines. *Lanzerotti and Wolfe [1981]* analyzed the ground data for the period analyzed by Singer et al. and found wave resonances at the plasmapause location as identified by ISEE.

Singer et al. [1982] examined data from four dayside Pc 5 events, using both magnetic and electric field data from ISEE 1 and 2, and determined the radial extent and harmonic structure for these events. The spatial extent ranged from 0.2 to 1.6 RE; the waves were radially polarized; and, where plasma information was available (two of the four events), the location was near the plasmapause. These were shown to be second harmonic standing waves. It appears that these events were all nominally quiet time dawn pulsations.

The previous efforts in using multiple instruments to characterize micropulsations have shown that substantially different perspectives are obtained by use of direct particle and electric field measurements. By making direct measurements of the mass composition, plasma density, electric, and magnetic fields, a nearly complete picture can be obtained from one satellite, as we demonstrate below.

1.1 Satellite

The DE 1 satellite offers a unique orbit for observing hydro-magnetic waves in the magnetosphere. The polar, elliptical orbit provides the opportunity to follow one L shell for 1 to 2 hours. In the middle of 1982, the DE 1 apogee (4.65 RE) was in the afternoon quadrant of the magnetosphere near the magnetic equator, providing an excellent opportunity to study hydromagnetic waves over a 20 degree range of latitudes near L = 4.7.

1.2 Instruments

The RIMS instrument is described fully by *Chappell et al. [1981]*. The instrument consists of three nearly identical ion detector heads aligned parallel, antiparallel, and perpendicular to the spacecraft spin axis, denoted -Z, + Z, and radial (RL), respectively. The instrument comprises a high-resolution mass spectrometer preceded by a retarding potential analyzer (RPA) stage, covering an energy range of 0 to 50 eV and a mass range of 1 to 32 amu. For a typical survey mode, in 16 s the instrument measures the integral flux spectra for the six principal ion species: H+, He+, O+, N+, He++, and 0++. RIMS has been working successfully since launch apart from one anomaly; after 1981 day 329, the RPA on the radial detector failed to function (the RPA voltage remains fixed at 0 V regardless of the RPA command setting); however, the RPAs on the + Z and -Z head detectors are still functioning normally. This means RPA analysis from the radial head is not possible for the chosen event.

The energetic ion composition spectrometer (EICS) has been discussed by *Shelley et al. [1981]*. It resolves all major magnetospheric ion species and covers the energy range from spacecraft potential to 17 keV/e. In the data presented here, 15-point energy spectra for H+ and 0+ were obtained for 24 "look" angles every 24 s. The lowest-energy channel was operated with a 10-V bias to reject all ions with energy less than 10 eV/e above the spacecraft potential. The lowest channel has a broad energy response and is sensitive to ions with energies up to -100 eV/e.

The University of Iowa plasma wave instrument (PWI) includes a static electric field detector, which is used to measure Pc 5 electric fields directly. In high gain, the instrument is capable of measuring electric fields down to --0.5 mV/m, using the long electric antenna. This 200-m antenna is a fine-wire dipole, which is insulated except for 30 m on each end. Effective center-to-center separation of the uninsulated portions of the antenna is 173 m *[Shawhan et al., 1981]*.

The Goddard Space Flight Center (GSFC) magnetometer is a triaxial flux gate magnetometer providing 16 vector samples per second. Details are given by *Farthing et al. [1981]*.

1.3 The Pc 5 Event of July 14, 1982

The observations of the Pc 5 wave event of July 14, 1982 (82195), reported here are unique due to the breadth of instrumental coverge. The event was observed near the magnetic equator at an L value of 4.7 by both the RIMS and EICS particle detectors aboard the DE 1 spacecraft over an energy range from spacecraft potential to several keV. The event was also observed by the PWI quasi-static electric field detector and the magnetometer on DE 1, together with simultaneous measurements by ground-based magnetometers located at Roberval and Siple near the foot points of the DE 1 field line. The results of the ground-based and satellite magnetometer measurements reported by Cahill et al. [1984] indicate that the event began at 1832 UT with a brief compressional pulsation. A transverse pulsation then developed with a period near 200 s and an amplitude of about 5 nT. Near 1850 UT, this pulsation amplitude decreased and was replaced by a 240-s azimuthal pulsation which grew rapidly and slowly decreased in amplitude after 1910 UT.

In addition to the unique complement of instruments that observed in this complex pulsation event, the event is interesting in that it occurred during the early recovery phase of an intense magnetic storm which began on July 12 near

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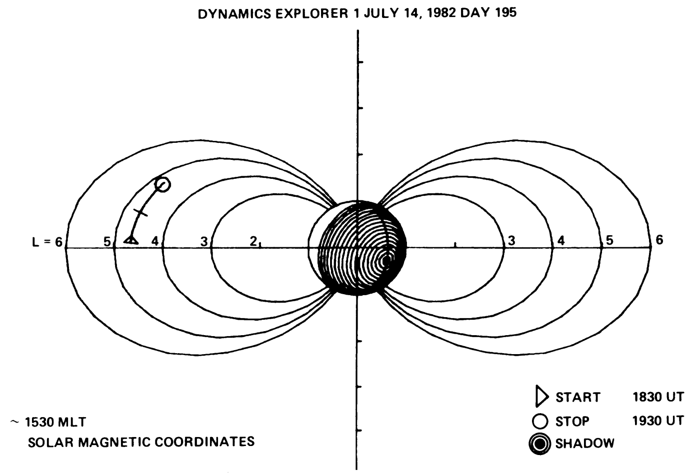

Fig. 1. Orbital segment of the Dynamics Explorer 1 satellite plotted in the orbit plane, in geomagnetic coordinates.

1200 UT and reached a peak with a 3-hour Kp value of 9 near 2000 UT on July 13. The sum of Kp on July 13 was 50 and on July 14 reached 56. RIMS observed particle pulsations on almost every apogee pass during this magnetic storm period culminating in the July 14, 1982, event at 1830 UT, which is reported here.

Cahill et al. [1984] found that the Pc 5 event between 1830 and 1930 UT was a fundamental, toroidal, resonant oscillation of the L = 4.5 magnetic field shell [see *Cahill et al., 1984*; Figure 8]. In the same study, polarization hodograms show changes from left- to right-hand polarization across the Pc 5 event [see *Cahill et al., 1984*; Figure 10], consistent with the theory of *Southwood [1974]* and *Chen and Hasegawa [1974]* for a single pulsation event of Kelvin-Helmholtz surface waves on the magnetopause. Inconsistent with the interpretation of this as a single event is the minimum in intensity of the wave event at the time of polarization reversal. Cahill et al. [1984] resolve this inconsistency by interpreting the amplitude variations as due to more than one event or due to temporal variations in the wave source [see Cahill et al., 1984; Figure 14]. In what follows, the particle observations are analyzed and compared to the electric field observations, resulting in a more complete description of the observed Pc 5 event.

2. OBSERVATIONS

Figure 1 shows the DE 1 orbital segment for the time interval 1830 to 1930 UT. The spacecraft is at 1500 LT, near apogee, and traveling in a northward direction a few degrees north of the magnetic equator. Note that the spin axis is perpendicular to the orbit plane shown, with the spin axis pointing in an antisunward direction (+Z axis pointing sunward).

2.1 Particle Observations

Plate 1 is a three-panel spectrogram of He+ data for the RIMS radial, +Z, and -Z heads on July 14, 1982, from 1830 to 1930 UT. The top panel shows a spin phase angle versus time spectrogram of He+. The data are sorted by time and the radial head view direction with respect to the local spacecraft velocity vector; ram angle of zero means that the radial detector is viewing into the direction of motion of the spacecraft. The maximum (180°) and minimum (0°) magnetic pitch angles are indicated by the white dashed and dotted lines, respectively. Clearly, there is an indication of an oscillation in the low-energy He+ fluxes with a period of around 3 min. During the first portion of the oscillation from 1830 to 1850 UT the 3-min period enhancements correspond to the detector viewing spin phase or pitch angles around +90° and are in antiphase to the enhancements corresponding to the detector viewing -90° phase angles. Although the enhancements initially have spin phase angles of + 100° and -80°, these angles close in toward the field-aligned direction (150° pitch angle) by 1850 UT, giving a "wave packet" appearance to the flux modulation and indicating that throughout this period (1830 to 1850 UT) the ratio of E x B velocity to field-aligned flow velocity is constantly decreasing. During the 1830 to 1848 UT period the ion flow is field-aligned coming out of the northern hemisphere. At around 1848 UT a second "wave packet" grows out of the first at pitch angles near 90° and moves toward smaller pitch angles. We interpret this flow as a counter-streaming field-aligned flow from the direction of the southern hemisphere. The movement of the flow toward smaller pitch angles is again consistent with a decreasing ratio of the E x B to field-aligned flow velocities. Therefore, the region from 1850 to 1900 UT is characterized by slowed convection or increased field-aligned velocity and bidirectional field-aligned flows in He+ and even more distinctly in the O+ and N + ions (not shown). After 1900 UT the ion flux enhancements are seen principally in the positive half of the instrument spin plane and indicate that in addition to Pc 5 oscillation motion and field-aligned flow motion (now only from the northern hemisphere direction), there is also a substantial component of magnetospheric convection in the sunward direction.

The middle and bottom panels of Plate I show energy-time spectrograms for the same time interval as the top panel but for the +Z and -Z head, respectively, which look at directions orthogonal to the magnetic field and to the radial head look directions. The modulation is seen in both the +Z and -Z heads, but with opposite phases. At the beginninng of the event, the plasma flow does not

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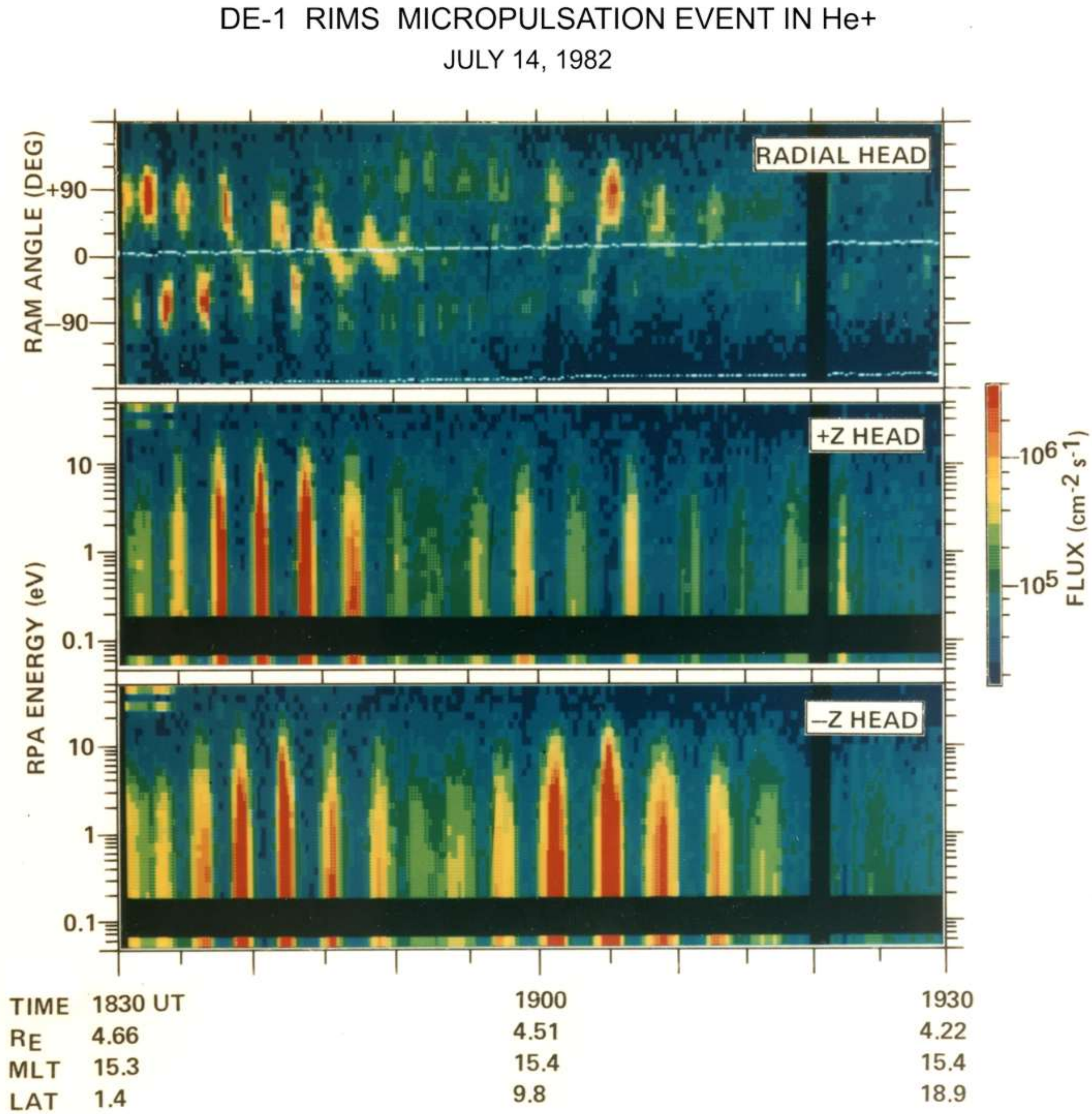

Plate 1. He' data for the RIMS instrument. The top panel is a spin-time spectrogram from the radial head detector. The spacecraft ram direction is in the center of the panel, and the 180° and 0° pitch angle directions are marked by the dashed and dotted white lines, respectively. The middle panel is an energy-time spectrogram from 0 to 50 eV for the +Z head, and the bottom panel is an energy-time spectrogram for the -Z head.

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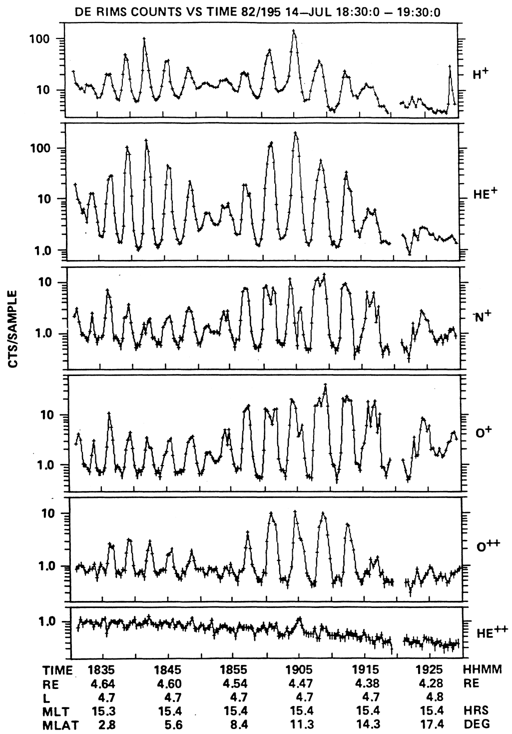

Fig. 2. Count rates versus time for the -Z head for the micropulsation event from 1830 to 1930 UT. All ion species except He++ measured by RIMS indicate a substantial oscillation due to magnetic pulsations. Notably, there are significant amounts of O+ and N+ ions present in the thermal plasma during the event.

leave the -90' pitch angle plane (determined from radial head data and the Z head data taken together). There are phase differences in the flux modulation between the four orthogonal look directions of the radial and Z head detectors, which indicate that the plasma has a vortical or elliptical motion. As one approaches 1850 UT, the field-aligned flow component begins to become more important relative to the Pc 5 oscillation E x B convection, as noted by the change in pitch angles in the radial head data (top panel) and in the decrease in flux intensity in the Z heads. After 1900 UT the -Z head flux enhancements intensify. This flux increase is greater than the out of phase +Z head flux enhancements. This reflects the increased influence of sunward magnetospheric convection during this latter time period. Note that the Pc 5 modulation is formed into three distinct segments. We see that there is a fundamental difference between the character of the He+ "wave" before 1850 UT, between 1850 and 1900 UT, and after 1900 UT.

All of the observed ion species participated in the convective motion. Figure 2 shows the hydrogen, helium, nitrogen, and oxygen fluxes from one of the end heads (-Z). Although hydrogen is the dominant ion by density, the modulation is greatest in He+. This larger modulation of He+ as compared to H + is a result of the positive charging of the spacecraft and the larger flow energies of the heavier ion He + . The hydrogen flow energy is comparable to the spacecraft potential, so that many of the H+ ions have insufficient energy to pass the potential barrier, thereby lowering the observed H+/He+ flux ratio. Such arguments also hold for the larger modulations of the heavier ions O+ and N+. Consistency of the plasma parameters and the dc electric field data determine the spacecraft potential, which must be carefully considered in deriving plasma parameters from the raw RIMS data of Figure 2. The heavy ions, N+, O+ , and O+ + , are minor species by density but form important contributions to mass loading due to their large relative masses. Their kinetic energies tend to rise above the RIMS energy range at peak flow velocity, resulting in a slight underestimate of heavy ion fluxes from RIMS which is confined to the time near 1842 and 1903 UT where the convection velocity reaches a maximum.

The RIMS observations of the particle oscillations are complemented by the higher-energy measurements provided by EICS. The sensitivity of the RIMS experiment to oxygen drops significantly near 50 eV, while EICS provides an integral measurement from 10 to 100 eV, which is the energy range of the O+ flow at its peak. Plate 2 shows the EICS data from H+ and O+ (the latter probably including N+) in four panels. The top two panels are spin-averaged, energy-time spectrograms; the bottom pair are spin-time spectrograms for data from 10 eV to 1 keV. The color-coded flux is in $(cm^2\ keV\ s\ sr)^{-1}$ for the top two panels, and in $(cm^2\ s\ sr)^{-1}$ in the bottom two panels. The Pc 5 wave appears most clearly in the O+ spin-time spectrogram, where the 90° pitch angle data are clearly modulated in the same manner as the RIMS data.

The O+ data show the largest flux in the EICS instrument because of the 10-eV low-energy limit of that instrument, which excludes the thermal H+ and He+ measured by RIMS. The O+ ions extend up in energy to several hundred electron volts, where they become the dominant ions. The peak oxygen flux is 3 to 5 x 10^7 $(cm^2\ s\ sr)^{-1}$ in the 10- to 100-eV energy range. In addition, there appears to be a hot O+ component with a temperature of about 120 eV that has a significant effect on the wave propagation characteristics during this Pc 5 event.

2.2 Reduced Plasma Parameters

The plasma density, temperature, and drift velocity are deter-mined from the EICS and RIMS particle data using a variety of techniques. For the RIMS data set the plasma density, temperature, and drift velocity are determined using a thin sheath model representation of a drifting Maxwellian distribution derived by Comfort et al. [1982], by means of the methods described by Comfort et al. [1985]. Due to the uncertainty in the spacecraft potential, there are many combinations of the available model parameters which can be adjusted to best fit the data. Basically, as spacecraft potential is assumed to be more positive, the corresponding drift velocity required to fit the data increases. Figure 3 shows this relationship for data from the + Z head for He+ at 1840:23 UT. Equivalent quality fits to the data are obtained over a range of spacecraft potentials from 2 to 20 V with a corresponding range of drift velocity values ranging from 20 to 34 km s- l as shown in Figure 5. To eliminate this ambiguity between the drift velocity and the spacecraft potential, we have (1) used the E x B drift calculated from the electric and magnetic field data to specify the plasma drift velocity, and (2) required self-consistency in the drift speeds and spacecraft potentials for both H+ and He+ ions. The results of such fits to the H+ and He+ ion data at the peak of each pulsation envelope (1842 and 1905 UT) are shown in Figures 4a and 4b, respectively.

The drift velocity, as derived from the static electric field and magnetometer instruments, increases slightly from the first peak to the second peak, 21.6 km s-I and 25.0 km sr1, respectively. The required spacecraft potential is + 5 V. The temperature of the

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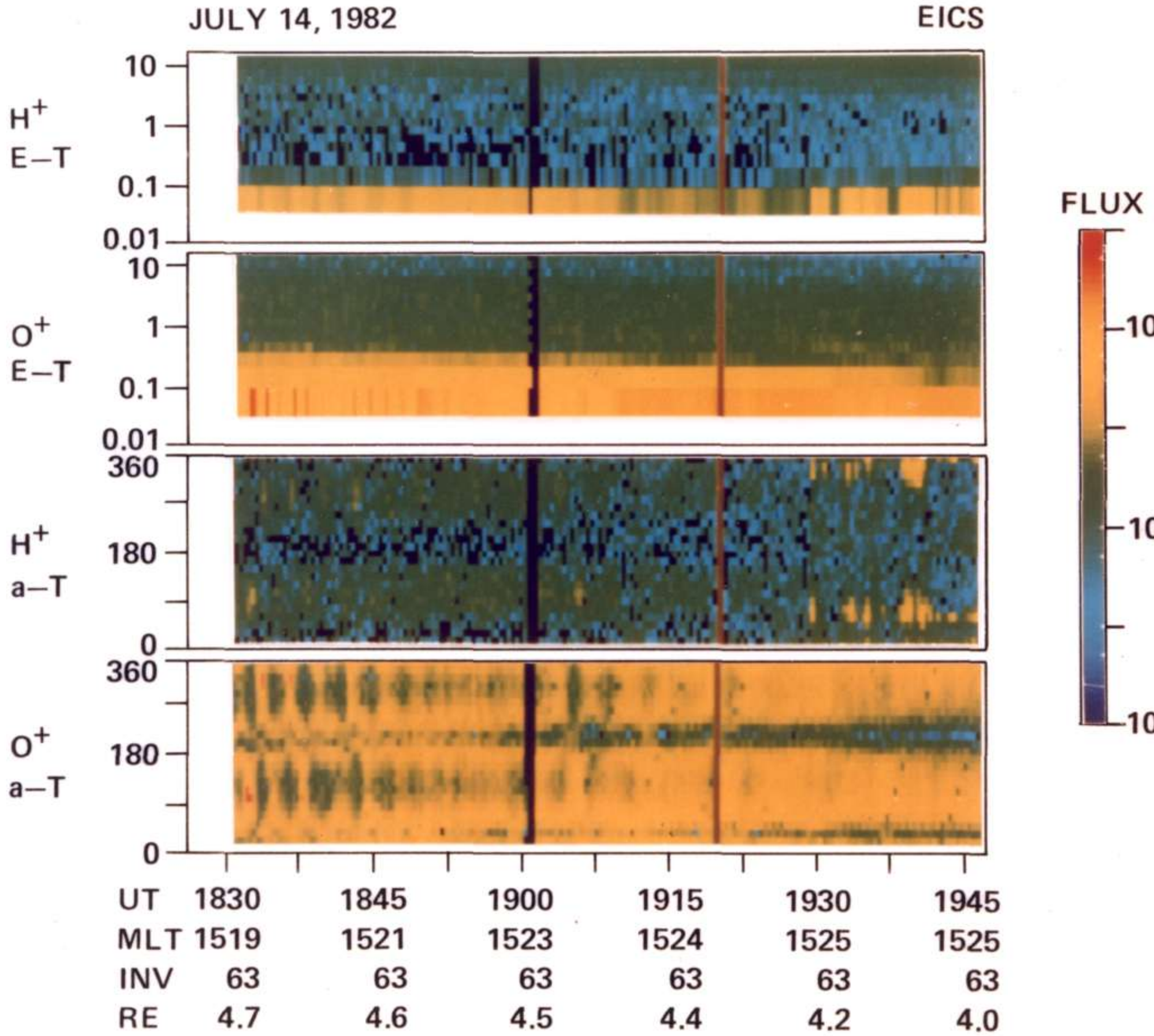

Plate 2. The EICS data set during the pulsation event. The top two panels are energy-time spectrograms for H+ and O+. Data for each 24-s measurement cycle have been averaged over all pitch angles, and the average flux color coded using the color bar on the right. The units are $(cm^2\ keV\ s\ sr)^{-1}$. The bottom two spin-phase angle-time spectrograms are the integral flux from 10 eV to 1keV, and the flux units are $(cm^{-2} s\ sr)^{-1}$ encoded with the same color bar. The spin phase angles are shown with respect to the satellite velocity. The two loss cones are easily identified near 0+ and 180+ spin phase angle.

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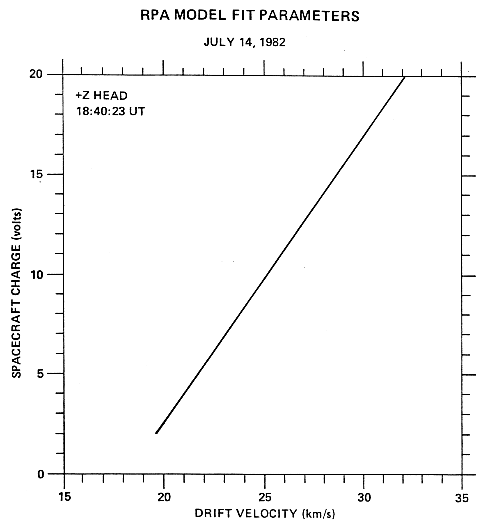

Fig. 3. Dependence of drift velocity on the assumed spacecraft potential for a drifting Maxwellian model fit to data.

thermal H + plasma remains nearly constant at 0.85 eV, and the He+ temperature goes from 0.85 to 2.0 eV from the first to the second half of the event.

The fact that one also sees a measurable flux of H+ and He+ when the drift velocity vector is pointed away from the detector (see Plate 1) indicates that there is also a relatively warm thermal plasma component present with sufficient thermal energy to partially overcome the positive spacecraft potential. Indeed, there appears to be a two-temperature distribution. The bulk of the low-energy plasma has a 0.85-eV temperature and, as a result of the positive spacecraft potential, can only be seen when the detector looks into the drifting ions. There is also a less dense, intermediate temperature population at higher energy (<10 eV) which can be seen at all times in the + Z and -Z heads in H+ (see Figures 4a and 4b) with a density of <0.1 cm^{-3}.

Densities for the heavy ions are more difficult to obtain since drifts of 20 to 25 km s I result in 0+ and N + ions which are near the upper energy range of the RIMS instrument. Therefore, the RIMS ion fluxes were corrected using the EICS 0+ ion data in the 10- to 100-eV energy channel, and a ram flux approximation was then used to obtain densities for the heavy ion species O+, N+, and O++.

An estimate of the energetic O+ component (temperature approximately ~140 eV) was obtained by fitting a Maxwellian in the plasma frame of reference to the EICS O+ data. The warm H+ temperature and density could not be determined with the same technique used to obtain the warm 0+ temperature and density because of the low H+ signal levels. An estimate on the magnitude of the warm H+ density can be made by using the measured H+/O+ flux ratios and assuming the H+ temperature is the same as the O+ temperature. These assumptions lead to an estimate that the warm H+ density is ~3% of the warm O+ density, consistent with the earlier RIMS analysis of the superthermal H+ population.

The cold plasma density increases slightly between the two segments of the event from 33 to 46 cm-3 (see Table 1). The fractional concentration of the cold, heavy ions (He+, O+, O++, and N+) remains about the same from the first half of the event to the second half (see Figure 2). However, in addition to the cold plasma there is a significant concentration of warm 0 + with a temperature of --140 eV and a density of about 6 cm-3 for the 1842 UT time period and a temperature -1 10 eV and a density of 4 cm-3 for the 1905 UT time period. Therefore, this hot component makes up 10 to 20% of the total plasma and has a considerable effect on the calculated mass loading factor, which is simply the plasma density times the composition-weighted average mass of the plasma (see Table 1). The addition of the more dense hot 0+ at the 1842 UT time period results in a slightly larger mass loading factor for this time period as compared to the later 1905 time period, but the relative effect is moderated by the increase in total plasma density in the later time period.

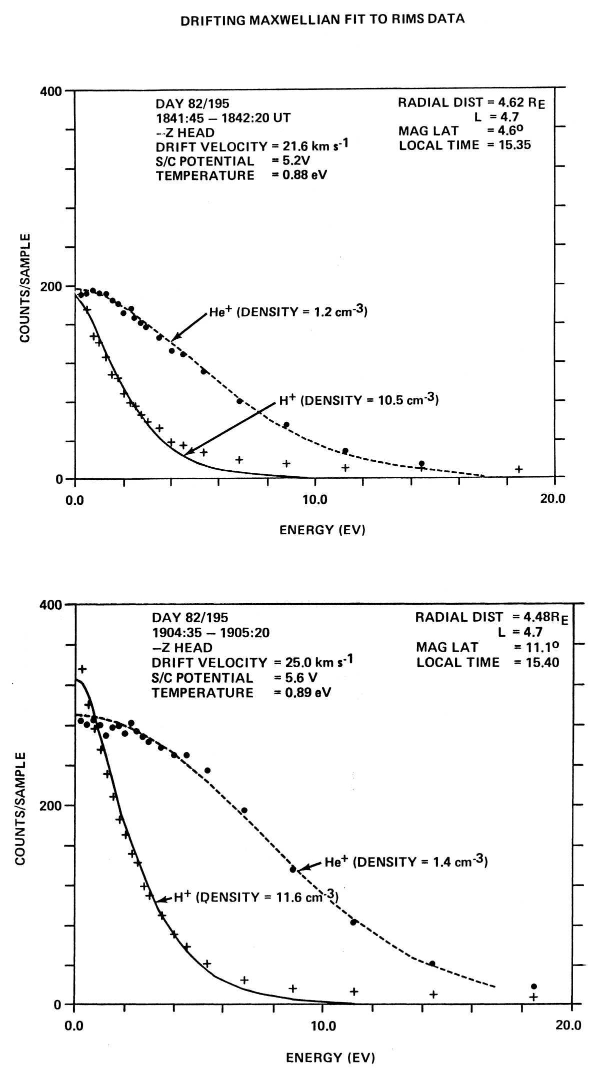

Fig. 4. (a) Drifting Maxwellian fits to the RIMS data for H+ and He+ during the peak of the first "pulsation packet" at 1842 UT. The drift velocity values have been constrained by the E x B drift velocities given by the wave data. (b) Same as Figure 4a, but the fit here is for the second "pulsation packet" at 1905 UT.

TABLE 1. Reduced Plasma Parameters

	1842 UT		1905 UT	
	Cold Plasma Only	With Hot O^+ and H^+	Cold Plasma Only	With Hot O^+ and H^+
Total density, cm^{-3}	33	39	46	50
Composition ratios, %				
H^+	83	70	84	77
He^+	9	8	10	9
O^+	4	19	4	12
N^+	2	2	2	2
O^{++}	1	1	~0	~0
Average mass, amu	2.2	4.4	2.2	3.3
Mass loading factor, amu cm^{-3}	72	172	99	167

2.3 Pc 5 Polarization Determination From the Particle Data

One other source of information is contained in the particle data set, the polarization of the wave. Figure 5 shows the count rate for He+ at low energy (less than 10 eV) for the + Z head (top trace), the radial head viewing positive ram angles (+45° to + 135° phase angles; second trace), the -Z head (third trace), and the radial head viewing negative ram angles (-135° to -45° phase angles; bottom trace), which are four look directions perpendicular to the magnetic field direction and separated by phase angles of -90°. The flux is given as counts per instrument sample (12 ms). It is evident that the enhanced flux occurs in sequence in the four traces, each trace representing a quasi-periodic variation, but phase shifted by 90° from the adjacent trace. The enhancement goes in the sequence +Z, radial positive phase angles, -Z, radial negative phase angles. Circles are drawn at the center of each peak and along the 10 count/ sample lines for each trace in Figure 5. Times of flux maxima in the particle modulations which indicate phase differences between the peaks in adjacent traces are marked by the dashed lines.

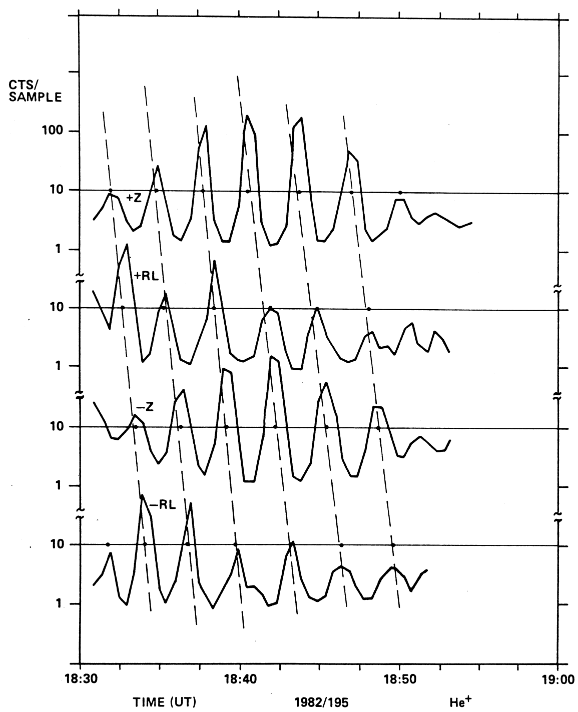

Fig. 5. The count rate as a function of time for He+ for (from top) the +Z head, radial head viewing positive ram angles, -Z head, and radial head viewing negative phase angles for the time interval 1830 to 1850 UT.

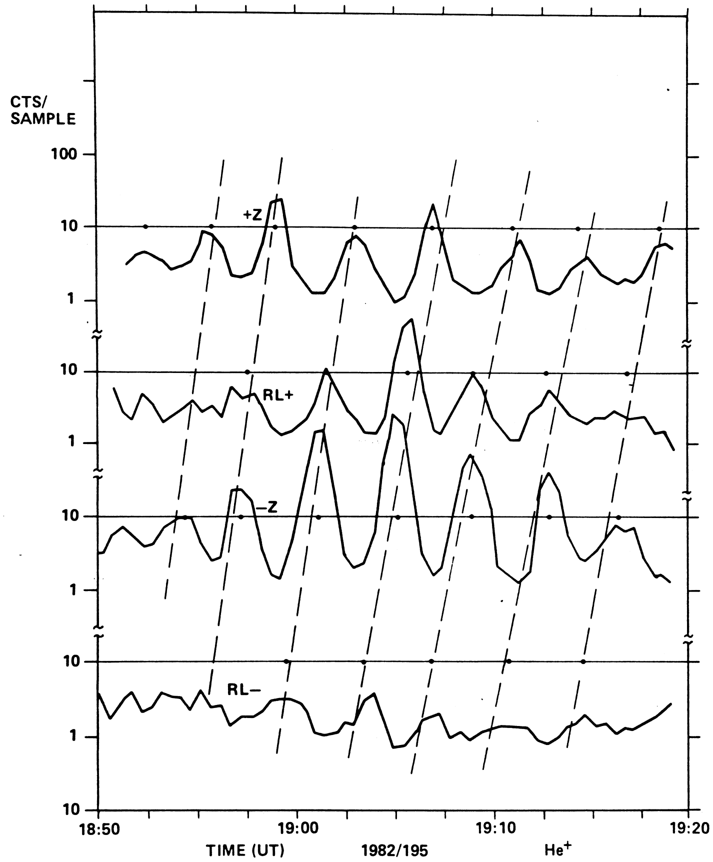

Fig. 6. Count rates as a function of time for He+, but for the time period 1850 to 1920 UT.

This phase shift in the flux enhancement in the four viewing quadrants, which are perpendicular to the magnetic field, suggests an elliptical polarization of the ion particle drift vector, consistent with the earlier analysis of the magnetometer data from this event by Cahill et al. [1984].

Figure 6 is a similar format covering the time period from 1850 to 1920 UT. Here we see that the peak count is in the sequence radial negative angles, -Z, radial positive angles, and +Z. This is the opposite sense to that seen in the first time interval. (Also note the increased period from 190 s in Figure 5 to 230 s in Figure 6.) This again suggests an elliptical polarization of the ion drift vector in the plane perpendicular to B, but now instead of the left-hand polarization rotation of the plasma as in the earlier example, a right-hand polarization is present.

2.4 Quasi-Static Electric Field Data

Although particle motions [Cummings et al., 1975] and electric fields [Junginger et al., 1983] during Pc 5 events have been studied separately, seldom has there been the opportunity to directly compare both particle and field-derived flow velocities. From static electric field and magnetic field measurements from DE 1, the spacecraft Z axis component of the E x B drift velocity is plotted in the upper panel of Figure 7. The V x B electric field induced by spacecraft motion is removed before computing the drift velocity. In the bottom panel of Figure 7 is plotted the flux from the -Z head RIMS detector for He+. The similarity in phase and structure between the two curves in Figure 7 is striking. In addition, analysis of the RIMS RPA data for H+ and He+ (see Figures 4a and 4b) requires flow velocities which are self-consistent with the magnitude of the flows found in the upper panel of Figure 7. All of the observed ions display fluctuation in counting rates similar to He+; however, none follow the electric field-derived flow velocity as closely as He . Also evident in Figure 7 is an offset in the zero axis of the Pc 5 flow velocity oscillation. This offset (—3-4 km s-') is comparable to that expected due to corotation at the DE 1 location during the first half of the event and increases by about a factor of two in a sunward convection direction during the second half of the event.

The electric field polarization sense and eccentricity have been examined in detail for this Pc 5 event. Cahill et al. [1984] describe the event as being primarily left-hand polarized from 1832 to 1852 UT and right-hand from 1852 to 1925 UT in agreement with the RIMS data shown in Figures 5 and 6. Using the quasi-static electric field data from PWI we have carefully reexamined the polarization and eccentricity over the first half of the event. The first half of the event from 1832 to 1852 UT is detailed in Figure 8. The top panel shows the field-derived drift velocity along the spacecraft spin axis which has been band pass filtered from 85 to 256 s (the E, measurements are similarly filtered to remove intereference). The middle panel shows the relative amplitude of the electric field eccentricity and the sense of polarization.

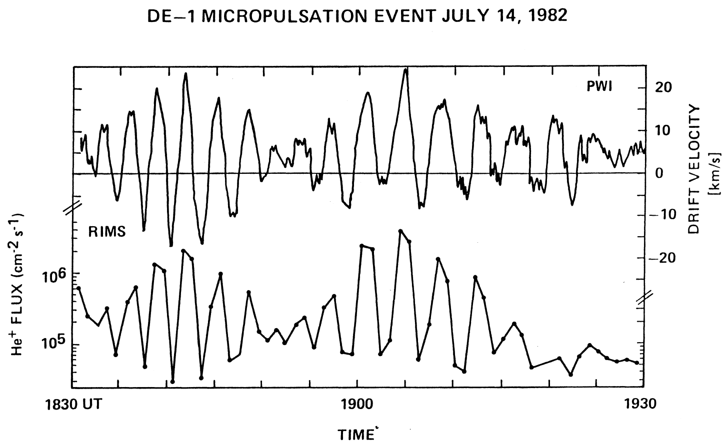

Fig. 7. Comparison of field-derived flow velocity and measured He' flux along the DE I spin axis for the Pc 5 event of July 14, 1982. The drift velocity component along the DE 1 spin axis is plotted in the upper panel. Drift velocity is derived from E x B, where the electric and magnetic fields are measured by the static electric field (PWI) and magnetometer instruments, respectively. The flux of He+, plotted in the bottom panel, is determined from measurements by the -Z head of the retarding ion mass spectrometer (RIMS).

Eccentricity is obtained by fitting an ellipse to each cycle of the wave event, where the error bars represent one standard deviation of the wave measurements from the fitted eccentricity. The magnitude of the eccentricity is shown only as a relative quantity with an overall variation of about 10%. Due to the short length of the electric field antenna along the spacecraft Z axis, measurements from this antenna are susceptible to spacecraft and Debye sheath effects. Although measurements of the existence and variation in electric field plasma oscillations are generally reliable, the absolute amplitude of the nearly static Pc 5 electric field cannot presently be deter-mined. However, it is believed that relative variations in the measured eccentricity accurately account for an increase, followed by a decrease in Pc 5 wave eccentricity across the first half of the event, since the overall variation substantially exceeds the error in deter-mining the eccentricity.

The sense of the PC 5 wave polarization is also obtained during the eccentricity calculation. The wave is clearly left-hand polarized at the beginning and end of the event interval as shown in Figure 8. However, the analysis of Pc 5 wave polarization becomes confused by the presence of other waves in the plasma and/or the proximity of the center of wave resonance in the interval from 1840 to 1845 UT. All that can be determined during this 5-min interval is that the Pc 5 wave is linearly polarized to the extent that its polarization can be measured.

The bottom panel gives the period of each cycle of the wave, determined by the time between peaks, as measured by PWI and the +Z and -Z head RIMS detectors. The solid curve through the wave period measurements is a free hand sketch.

The second half of the event from 1852 to 1925 UT is much more difficult to analyze with the static electric field measurements. When the sense of polarization can be unambiguously determined, it is consistent with the right-hand polarization seen in the RIMS particle measurements and also reported by Cahill et al. [1984]. However, during much of this interval the polarization appears to be linear. Just as for the time interval from 1840 to 1845 UT, wave energy at other than Pc 5 frequencies obscures the evaluation of the polarization when the Pc 5 is highly eccentric.

3. DISCUSSION

The observations of the previous section represent a comprehensive new wave particle data set from DE 1 which can be used to study the structure of micropulsation events in the earth's magnetosphere. The important new composition and ion velocity information for this event enable a careful check between model and theory to be carried out with respect to the period and the polarization of the oscillation.

3.1 Polarization of the Micropulsation Event

The micropulsation theories of Southwood [1974] and Chen and Hasegawa [1974] predict a particular relationship between the amplitude, phase, and eccentricity of a Pc 5 field line resonance. For an eastward propagating resonance at low latitudes in the local afternoon, the wave will exhibit left-hand polarization at L values just greater than the resonant field line, and right-hand for L values less. The eccentricity of the Pc 5 fields is expected to be the greatest at the resonant field line and more circular away from resonance. Although the observation of a field line resonance is complicated by the expected motion of the resonance, spacecraft, and temporal variations in the wave source, the interrelationship of the characteristics of Pc 5 resonance suggests that the relative position of a spacecraft to a resonant field line might be found by a close examination of these resonant characteristics.

The sense of the rotation of the thermal ion distribution with respect to the spacecraft is summarized in Figure 9. This is a view from above the earth (north pole), looking onto the equatorial plane. The upper half represents the situation in the first half of the event, 1830 to 1850 UT. Consistent with Figure 5, the peak flux is observed first in the +Z head and then the RL+, -Z, and RL-"heads," consecutively. This identifies the sense of the rotation of the plasma flow vector about the spacecraft to be in a direction opposite to the earth's rotation viewed in the same coordinate system. There is a net bulk motion of the plasma as well as this periodic variation, but the periodic flow clearly dominates.

By contrast, the lower half of Figure 9 shows the situation for the second half of the event, 1855 to 1930 UT.

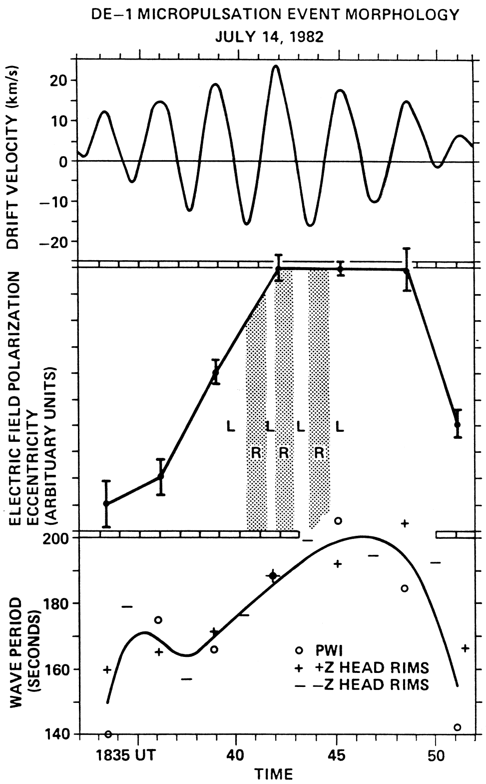

Fig. 8. Detailed plots of the drift velocity, polarization, and wave period for the first 20 min of the July 14, 1982, Pc 5 event. The top panel shows the drift velocity and consequently the wave fields peaking near 1842 UT using a low-passband filter. The center panel shows the field polarization eccentricity peaking near the same time as the peak drift velocity, along with a fluctuation in the sense of polarization. The wave is polarized in the left-hand (L) sense around the background magnetic field at the beginning and end of the event. Polarization reversals to the right-hand (R) sense occur near the center of the Pc 5 resonance, suggesting a near-linear polarization, and are marked by the shading. The error bars represent the standard deviation of the measured field eccentricity from the fitted value. The bottom panel shows the period of each cycle of the Pc 5 wave event as measured by the static electric field instrument (PWI) and the + Z and -Z heads of the retarding ion mass spectrometer (RIMS).

Here the plasma drift vector rotates about the spacecraft in the same sense as the earth's rotation; however, the magnetospheric convection bulk motion dominates the plasma and makes the eccentricity very difficult to determine.

The quasi-static electric field and magnetometer data agree with this general polarization change; however, these measurements allow a more detailed analysis than with the particle measurements. As shown in Figure 8, there is a marked change in eccentricity, as determined by the quasi-static electric field, over the first lobe of the Pc 5 event. Figure 14 of Cahill et at. [1984] shows phase relationships between ground-based and DE I magnetometer observations. Their interpretation of these data is that the oscillations are in phase across the event and that the 20-min lobe structure is due strictly to temporal variations. If a zero phase difference exists between DE 1 and ground-based magnetometer meassurements, then spatial variations would not appear to account for the variation in the wave amplitude and eccentricity shown in Figure 8. Examination of Figure 14 in the work by Cahill et at. [1984] suggests that a quantitative evaluation of phase differences may be difficult to obtain. Although zero phase difference appears to exist near 1840 UT, by 1849 UT the DE 1 magnetometer trace seems to lead the ground-based measurements by as much as 1 to 1.5 min. If true, the corresponding phase difference would approach 90°. As a consequence, it is possible that there are spatial as well as temporal variations that might be explained by the motion of the resonance past DE 1.

The coincidence of the peak in eccentricity with the peak wave amplitude of the portion of the event between 1832 and 1852 UT, accompanied by essentially linear fluctuations in the polarization direction near the peak, suggests that the measured peak wave amplitude corresponds to a near encounter of the spacecraft with the center of the wave resonance. If the reversals of the sense of polarization are due to excursions of the resonating field of the toroidal wave, then DE 1 must have passed within 540 km [Cahill et at., 1984] of the center of the resonance. There is, however, an apparent inconsistency between the change in eccentricity over the lobe and the absence of a polarization reversal when the spacecraft passes through the wave resonance. In the afternoon sector, the

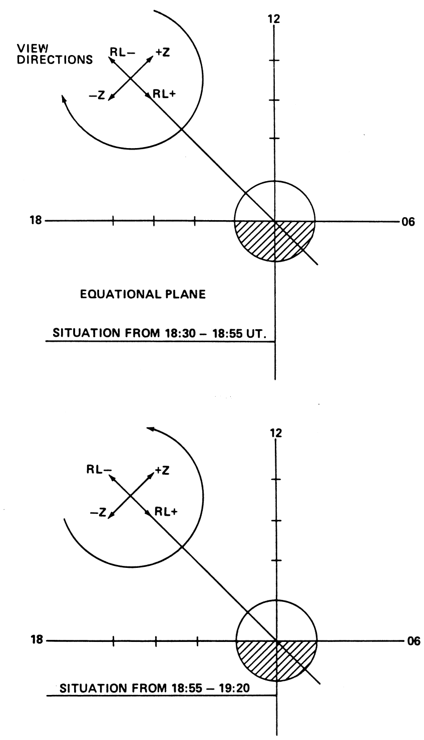

Fig. 9. Sketch showing plasma rotation in equatorial plane. The upper half represents the situation before 1855 UT, showing the sense of the rotation of the plasma drift vector about the spacecraft. The lower half shows the situation after 1855 UT.

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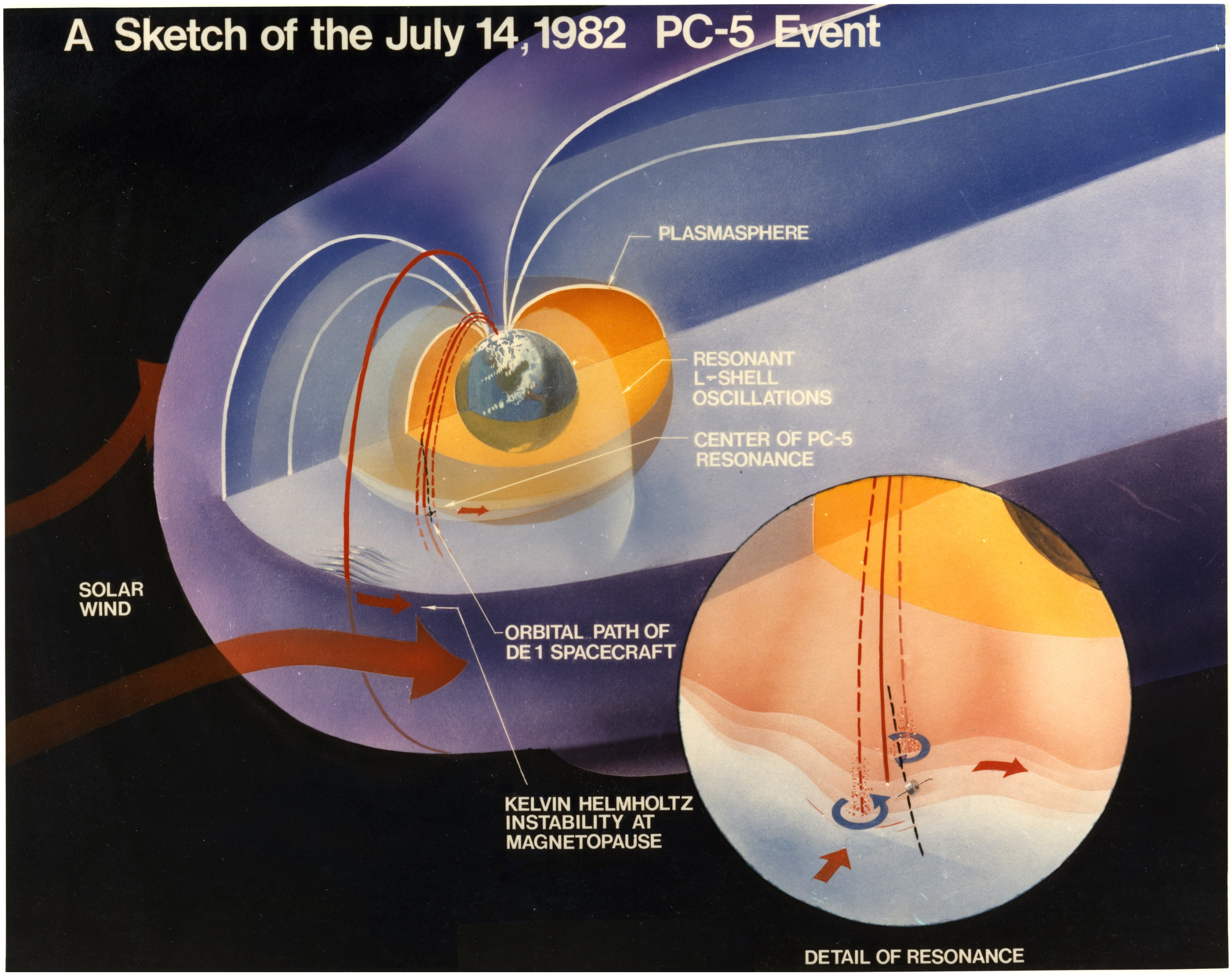

Plate 3. Schematic figure showing the encounter of the DE 1 spacecraft with the traveling Pc 5 resonance region during the first half of the event described herein. The resonance receives energy from the propagating disturbance at the magnetosheath. It is not clear from the data whether this scenario explains the behavior in the second half of the event.

theoretically predicted polarization reversal would be expected to go from left to right [Southwood, 1974; Chen and Hasegawa, 1974] as the spacecraft moves radially through the peak of the first component of the event at 1842 UT.

The absence of a polarization reversal at the resonance can be explained if the resonance structure and its associated wave source at the magnetopause boundary are moving tailward at a velocity of 200 km s 1 and with a scale size of 15 to 25 RE. We postulate that the location in longitude of the center of resonance is controlled by the source of the wave energy. If the observed standing wave is driven by a Kelvin-Helmholtz instability on the magnetopause, then the magnetopause turbulence and the resulting standing wave near the plasmapause would move tailward with the magnetosheath plasma flow, thereby explaining the apparent tailward motion of the resonance region (see Plate 3).

Singer et al. [1982] found a resonant region width of about 1.6 RE for Pc 5 micropulsations. For the event studied here, Cahill et al. [1984] suggest that the event subtends an azimuth of 120°, centered at the earth. At the DE 1 radial distance of -4.6 RE, this Pc 5 event may have an azimuthal extent of --16 RE. Hones et al. [1981] reported a Pc 5 resonance near dawn local time moving tailward at about 640 km s^{-1} with a scale size between -20 and 40 RE. Since the DE 1 spacecraft velocity is much less than this reported motion of Pc 5 field line resonance, the time for the passage of the current event past DE 1 will be roughly 10-20 min. The 20-min duration of the Pc 5 oscillation centered at 1842 UT is consistent with the passage of a single field line resonance past DE 1. The alternative is a simple temporal variation in pulsation amplitude as suggested by Cahill et al. [1984].

3.2. Period of the Micropulsation

Using the model for standing Alfven waves derived by Orr and Matthew [1971], it is possible to relate the observed plasma density to a predicted period and then compare that predicted period to the observed period. The work by Orr and Matthew solves both the poloidal and toroidal modes, and does so for density distributions which fall off as $(1/\text{radius})^n$, where n varies from 0 to 6. Choosing n = 4 (which corresponds to constant flux conditions during refilling), and assuming the fundamental of the toroidal mode, the cold plasma mass density of 72 amu cm^{-3} at 1842 UT gives a period of 115 s. Adding in the effect of the warm O+ leads to a mass loading factor of 172 amu cm^{-3} and a corresponding period of 192 for the 1842 UT time period. The mass density of 99 amu cm^{-3} found at 1905 UT gives a period of 145 s. However, adding in the warm O+ component modifies the result with a mass loading factor of 167 amu cm^{-3} and a period of 189. It is interesting to note the effect of the N+ and O+ on the mass density here. An important implication of this comparison of theory and data is that it is not correct to measure the electron density and then assume that protons are the only ion species present in calculating resonance periods [e.g., Cummings et al., 1969]. Careful considerations of the overall plasma regime including the cold and hot plasma composition must be included to determine the proper wave propagation characteristics during Pc 5 events.

RIMS determined a wave period of 190 s from the spacing of the ion peaks in the + Z and -Z head data for the time period 1842 UT. This is consistent with the period derived from the quasi-static electric field and the magnetometer instruments reported by Cahill et al. [1984]. Theoretical calculations using the measured ion densities and assuming a constant flux field-aligned plasma density profile (n = 4) suggest a period of 192 s when the composition and density of both the hot and cold plasma components are taken intoconsideration. The excellent agreement in period is again consistent with a near encounter with the center of resonance by DE 1 near 1842 UT. The RIMS particle data indicate a period of 233 s, whereas theoretical calculations using the measured ion densities and an assumed field-aligned plasma density profile result in a period of 189 s when all components of the plasma are taken into consideration. The disagreement of the theoretically determined period with the measurements in the second half of the event can be affected by many factors the most notable of which are listed below: (1) A field-aligned plasma density profile which is inconsistent with the constant flux profile that is assumed may be present during this time. Evidence for large field-aligned plasma density irregularities during storm recovery times has been observed in the RIMS data (P. M. E. Decreau, private communication, 1984). The clear increase of magnetospheric convection in this half of the event as well as changes in composition clearly distinguishes this as a different plasma regime from that of the first half of the event. (2) Since the oscillation is a nonlocal phenomenon spread over at least 1500 km or more, sharp radial or longitudinal gradients in the plasma will affect the period of the oscillation. In fact, according to DE 2 observations (L. Brace, private communication, 1984) the plasmapause is at L = 4 at this time. Therefore, oscillatory motion brings the spacecraft within 2000 to 3000 km of the plasmapause during a Pc 5 wave cycle. (3) Uncertainties in the determined plasma composition and densities will affect the results. However, care has been taken to minimize this uncertainty as much as possible. Cross-calibration of the RIMS and EICS instruments and internal RIMS electrometer cross-calibration checks have been carried out on this data set.

Finally we note again that the period of the first half of the event (1842 UT) measured by RIMS is 190 s and the period of the second half of the event (1905 UT) is 230 s. This is roughly the difference in period that would be expected if the Pc 5 oscillation was a fundamental mode that changed from a toroidal to a poloidal mode during the event [Cummings et al., 1969]. However, the magnetometer observations show that if there is a change in mode, the tendency was from poloidal to toroidal, opposite to that suggested by the period change. This observation is another piece of puzzling evidence during this complex Pc 5 event.

4. CONCLUSIONS

This paper reports the particle detector and electric field measurements for a Pc 5 event encountered by the DE 1 spacecraft between 1830 and 1930 UT on July 14, 1982. These measurements (which have a "double-lobed" drift velocity variation over the event) for the first time show simultaneously measured E x B and particle-derived drift velocities during a Pc 5 event. The measurements indicate a rotation of the plasma in the direction normal to the magnetic field. The drift velocity modulation reaches peak values of 20 to 25 km s^{-1} in both lobes, but shows a change in the direction of rotation of the plasma from left- to right-hand polarized between the two lobes of the event. Both regions extend over a 20-min period with Pc 5 oscillations within each lobe of 190 and 233 s, respectively. This "double-lobed" structure is present both in the low-energy particle data and in the quasi-static electric field data. The data in the first half of the event also indicate a relative increase in the eccentricity of the wave over the first lobe which is well correlated with the wave amplitude structure of the lobe. This suggests that the lobe structure is indicative of an encounter with a localized Pc 5 resonance structure in the afternoon magnetosphere. Since the observed electric field polarization was left-handed on both sides of the resonance and became essentially linear at the peak of the lobe, the 20-min period of the lobe structure can be interpreted as a resonance region (10 to 20 RE) traveling past, but radially within the orbit of DE 1, with a velocity of approximately 200 km s^{-1} The second lobe is more complicated, and a predominance of highly eccentric right-hand polarization of the plasma suggests that the location of the traveling resonance was just radially outside of the location of the DE 1 spacecraft. Alternatively, the double-lobed structure and eccentricity changes may be interpreted as simply temporal variations in the pulsation.

Thermal plasma measurements show a variety of ions (H+, He+, O+, and N+) in the region of the event. The dominant ion through-out both lobes was H+ with a density variation over the event from 27 to 38 cm-3. Significant quantities of He+, O+, and N+ were also observed to be present and rotating together in a plane normal to the magnetic field direction due to the Pc 5 E x B drift. An appreciable component of hot O+ ions of between 6 and 4 cm-3 was also observed. The plasma parameters for the two lobes have been determined and used in theoretical calculations to predict the period of the observed resonance. The results give periods of 192 and 189 s, which are to be compared to the observed periods of 190 and 233 s for the peak amplitude of the first and second components of the event, respectively. The excellent agreement in derived and observed periods during the first half of the event is consistent with near-linear eccentricity of the electric field measurements at this time, which suggest a near encounter of DE 1 with the center of wave resonance. The apparent discrepancy of periods in the second half of the event may be explained by plasma irregularities in either the radial (i.e., a near plasmapause encounter), longitudinal, and/ or field-aligned directions, yet it remains puzzling.

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