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Field and Thermal Plasma Observations of ULF Pulsations During a Magnetically Disturbed Interval

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ULF pulsations were observed by DE 1 between 1600 and 1830 UT, October 31, 1982, during a magnetically disturbed interval. Ground observations suggested that the pulsations were excited by a sudden increase in the solar wind velocity and pressure. During the pulsation interval DE 1 traveled near apogee from -55 to -20° geomagnetic latitude and from $L \sim 13$ to $L \sim 4$ at about 0900 LT. The waves observed were azimuthal oscillations preceded by gradually decaying long period compressional waves which lasted for more than 1 hour. Phase relations between magnetic and electric field oscillations and calculated Poynting flux indicate that in the outer magnetosphere ($L >$ 8) DE 1 observed propagating waves which contained strong poloidal components, while the quasi-sinusoidal toroidal waves seen later for $L < 10.3$ were standing along field lines. The toroidal waves appeared as four wave packets, each of which corresponded to a region with a distinct plasma distribution. The observed wave periods decreased with L over an extended magnetospheric region. The seemingly weak interaction between magnetic shells suggests that the source was a broadband one. Magnetometer data from several high latitude observatories located near the footpoints of the magnetic shells crossed by DE 1 were also examined. The magnetic pulsations on the ground contained many frequency components, and the waves seen most strongly in space were often not the strongest signals seen on the ground near the same field lines. The broadband nature of the ground pulsations indicates that the stations also detected oscillations of the adjacent field lines. The major frequencies seen at ground stations seemed to be roughly constant for about 2 hours but L dependent. This suggests that the changing periods seen in space by DE 1 were clearly L related and not temporally varying.

INTRODUCTION

ULF pulsation studies have been very helpful in understanding the processes of basic plasma physics in the magnetosphere. Analysis of these waves has revealed important aspects of energy coupling between the solar wind and the magnetosphere and ionosphere. Earlier work [cf. *Chen and Hasegawa*, 1974; *Southwood*, 1974], proposing that surface waves on the magnetopause excite field line resonances in the magnetosphere, has been widely applied to interpretation of observed long period (above 10 s) ULF wave phenomena. In recent years, continuing efforts have been made to solve the problem of mode coupling between externally excited compressional waves and magnetospheric field line resonances [e.g., *Kivelson and Southwood*, 1986; *Zhu and Kivelson*, 1988; *Lee and Lysak*, 1989, 1990; *Allan et al.*, 1986]. Spacecraft observations have provided further evidence of toroidal oscillations of resonant field lines occurring throughout the dayside magnetosphere [*Engebretson et al.*, 1986*b*; 1988; *Takahashi et al.*, 1988; *Anderson et al.*, 1990; *Cahill et al.*, 1990; *Zanetti et al.*, 1987]. AMPTE CCE observations of the dayside outer magnetosphere [cf. *Engebretson et al.*, 1986a] displayed an essentially continuous variation in resonant period as a function of L, implying that adjacent L shells can oscillate in the azimuthal direction with very little interaction.

In exploring the external source of long- period ULF waves (in the Pc 3 to 5 range), the long-proposed Kelvin-Helmholtz instability at the magnetopause has been further investigated [*Pu and Kivelson*, 1983, and the references therein; *Miura*, 1987; *Ogilvie and Fitzenreiter*, 1989] and more observational evidence favoring the mechanism was found [e.g., *Potemra et al.*, 1988; *Mitchell et al.*, 1990; *Anderson et al.*, 1990]. Recently, more attention has been paid to the role of the variation of the solar wind dynamic pressure in generating ULF waves in the magnetosphere [*Song et al.*, 1988; *Sibeck et al.*, 1989; *Potemra et al.*, 1989; *Southwood and Kivelson*, 1990]. Harmonic Pc 3,4 waves in the outer dayside magnetosphere associated with a quasi-parallel geometry at the subsolar bowshock have also been reported [*Engebretson et al.*, 1987, 1991; *Lin et al.*, 1991]. They found that, in addition to ever strong evidence that small solar wind cone angles favored the occurrence of the harmonic pulsations, disturbances of magnetic field which contained significant transverse fluctuations and energized turbulent plasma in the subsolar magnetosheath correlated closely with the harmonic oscillations in the magnetosphere.

Multi-instrument and multipoint observations have more and more been used in pulsation studies. The use of particle data and electric field data as well as magnetic measurements is vital in determining wave modes, wave propagation, and other properties of the waves [e.g., *Cahill et al.*, 1986; *Takahashi et al.*, 1988; *Potemra et al.*, 1989]. *Waite et al.* [1986], using particle detector and electric field measurements, revealed the drift motion of the plasma near resonant field lines in a Pc 5 event. *Lin et al.* [1988] using a multichannel energetic ion detector determined the propagation of Pc 5 waves in both the radial and the azimuthal direction. In this study we have used particle and electric and magnetic field measurements from the DE 1 spacecraft to investigate a pulsation event. The polar orbit of DE 1 has been utilized to observe wave structure along field lines and across field lines [*Cahill et al.*, 1984, 1986; *Lin et al.*, 1986; *Engebretson et al.*,

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1986*b*]. Some of the observations were made a few tens of degrees away from the magnetic equator [cf. *Cahill et al.*, 1986], covering a region infrequently observed in comparison with the near equatorial region. The event reported here was observed in space covering a large range of L shells (from $L \sim 13$ to $L \sim 4$) and magnetic latitudes (from ~-55° to -19°). The spacecraft observations are then compared with ground observations near the footpoint of the DE 1 trajectory during the period.

DE 1 Orbit and Instrumentation

DE 1 magnetic field data presented here were taken by a three-axis flux gate magnetometer on board the spacecraft [*Farthing et al.*, 1981]. The data were originally recorded at 16 vector samples per second, but we used 6-s averages of the data in this paper. Electric field measurements were obtained with the University of Iowa plasma wave instrument (PWI), which has two 100-m probes perpendicular to the spin axis and a 9-m double probe along the spin axis [*Shawhan et al.*, 1981]. Particle measurements from DE 1 were obtained by the retarding ion mass spectrometer (RIMS) [*Chappell et al.*, 1981]. Three nearly identical ion mass spectrometers of the RIMS instrument are denoted +Z (pointing west), -Z (pointing east), and *RL* (pointing radially outward), respectively. The radial head (*RL*) rotates in the spin plane and is perpendicular to the spin axis which is pointing east.

The wave event was observed by DE 1 between 1600 and 1830 UT October 31 (day 304), 1982. (The pulsations might have started earlier, but no DE 1 data are available for several hours before 1600 UT.) During the interval, DE 1 was traveling near apogee between 0912 MLT, -55° geomagnetic latitude at 1600 UT, and 0836 MLT, -19.1° geomagnetic latitude at 1830 UT. It reached apogee at about 1652 UT. The trajectory of the DE satellite during the 3-hour interval is sketched in Figure 1 which is plotted by rotating the meridian planes that DE 1 crossed during the event onto a meridian plane on the paper.

Solar Wind and Geomagnetic Conditions

The day of the observations is recorded as the third most disturbed day of the month (*Kp* indices of the day are 4-, 4+, 3+, 1-, 4+, 4, 6+, 5). Solar wind data measured from ISEE 3, which was approximately at GSM coordinates (-100, -75, 38) tailward of the Earth at 1600 UT, are displayed in Figure 2*a* for the magnetic field *Bx*, *By*, *Bz*, and the total magnetic field in GSM coordinates and Figure 2*b* for plasma bulk velocity, density, and temperature. Figure 2a shows that at about 1345 UT there was a sharp increase in the magnetic field magnitude from ~ 8 nT to ~ 20 nT. At the same time, the solar wind velocity also increased sharply from ~ 500 km/s to ~ 700 km/s, and remained at a high level until the end of the day (Figure 2*b*). The velocity increase was accompanied by sudden increases in the plasma density and temperature. The above changes in plasma parameters at 1345 UT implied a sudden increase in the solar wind pressure, which, as will be shown later, initiated magnetic pulsations observed on the ground.

At ~ 1500 UT the solar wind magnetic field turned southward. There was probably another dramatic change in the solar wind parameters at about 1530 UT, accompanying a northward turning of IMF *Bz*. Unfortunately, there are data gaps between 1522 UT and 1545 UT in both magnetic field and plasma data. Comparison of the plasma data before and after the gap, however, shows that fluctuations of the solar wind velocity, density, and temperature and thus the solar wind dynamic pressure intensified during the gap period. We will show later that this intensification of the variation of the solar wind dynamic pressure is coincident with the occurrence of a negative bay in the *H* components of some ground stations and an intensification of magnetic pulsations on the ground.

At ~1700 UT the solar wind magnetic field started to rotate its direction from originally northward and slightly dawnward (-*By*) to duskward and gradually southward. At ~1750 UT, *Bz* became negative. This southward turning of *Bz* is probably associated with the substorm signatures observed at about 1800 UT at some ground stations.

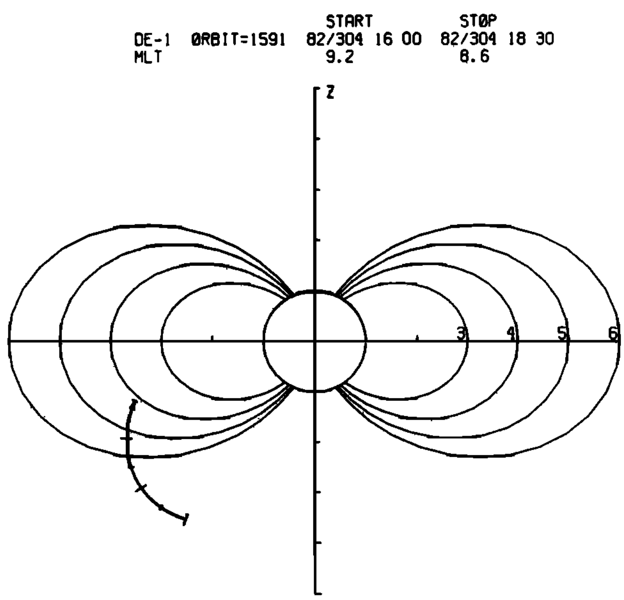

Fig. 1. The trajectory of DE 1 from 1600 UT to 1830 UT, October 31, 1982, plotted by rotating the meridian planes that DE crossed during the event onto a meridian plane on the paper.

DE 1 Magnetic Field Observations

Figure 3*a* shows the difference between DE 1 measurements of the magnetic field from 1600 UT to 1900 UT and the Magsat model field [*Langel et al.*, 1980] in three components of a spherical coordinate system: dBr points radially outward, $dB\theta$ points southward, and $dB\varphi$ points eastward. The $dB\varphi$ component was negative during the entire 3- hour interval, indicating that the magnetic field lines were bent westward, or tailward, since DE 1 was at about 0900 local time. The positive $dB\theta$ component throughout the interval indicates field lines at DE 1 were stretched outward and oriented more southward than usual. The large increase in the $dB\theta$ component starting at about 1740 UT was probably caused by the southward turning of IMF *Bz* observed by ISEE 3 at 1750 UT. In the subsolar magnetosheath this southward turning of *Bz* was observed by ISEE 1 and 2 at ~ 1737 UT (M. Cao, private communication, 1991).

In order to examine the compressional and transverse components of magnetic pulsations we rotate the magnetic field data used in Figure 3*a* into a field-aligned coordinate system with orthogonal unit vectors $\hat{\mu}$, $\hat{v}$, $\hat{\varphi}$. The vector μ is parallel to the background magnetic field, B_0, which is defined as the 151-point (906 s) running average of the original data, and thus $\hat{\mu} = B_0 / |B_0|$. The azimuthal component $\hat{\varphi} = \hat{\mu} \times \hat{r} / |\hat{\mu} \times \hat{r}|$, where $\hat{r}$ is the radial unit vector in spherical coordinates and the transverse poloidal component $\hat{v} = \hat{\varphi} \times \hat{\mu}$. Figure 3*b* displays the variation of the magnetic field projected to the above coordinates, $b\mu$, bv, $b\varphi$.

Figure 3*b* shows that before 1715 UT, compressional oscillations with decaying amplitude were seen in $b\mu$. The period of the compressional waves was not constant. It decreased with L values from ~ 700 s to ~ 450 s as DE 1 travelled inbound from $L \sim 13.3$ to 7.5. Between

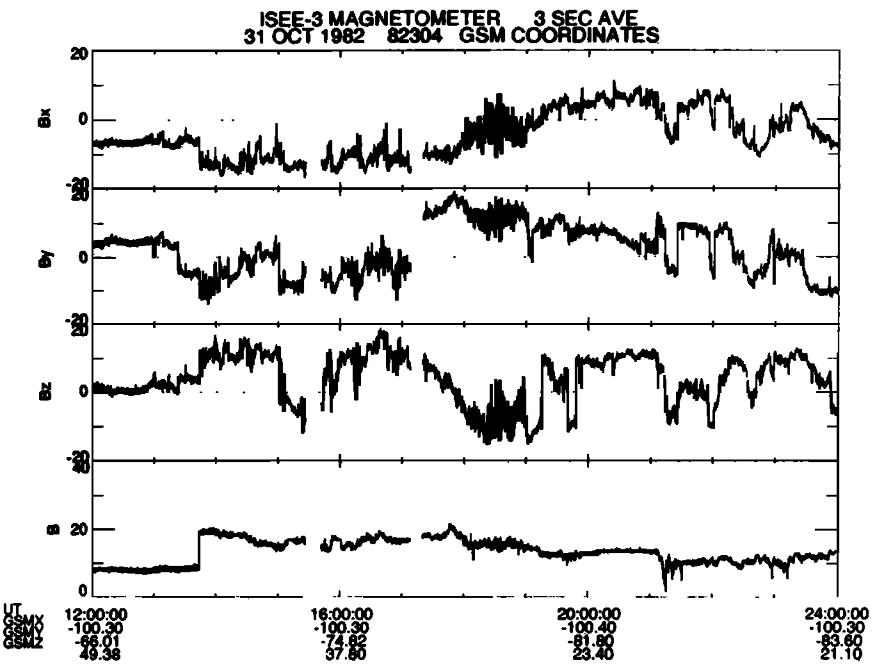

Fig. 2*a*. Solar wind magnetic field data measured from ISEE 3: *Bx*, *By*, *Bz* and the total magnetic field in GSM coordinates.

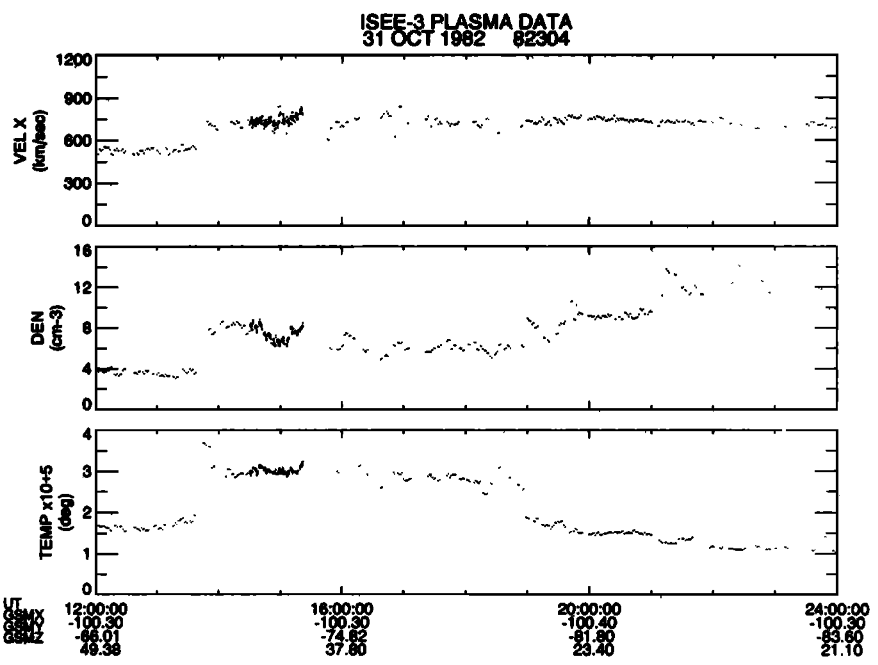

Fig. 2*b*. Solar wind plasma data measured from ISEE 3: plasma bulk velocity, density, and temperature.

1605 and 1630 UT, as DE 1 travelled from $L \sim 12.6$ to 10.3, a 110-s poloidal wave with a maximum amplitude of about 5 nT was seen mainly in the bv component before 1620 UT. After 1630 UT the observed magnetic pulsations were mainly in the azimuthal component, $b\varphi$. The wave period clearly decreased from ~400 s at 1630 UT ($L = 10.3$) to ~150 s at 1820 UT ($L = 4.7$) as the spacecraft moved to lower L shells. The azimuthal waves may roughly be divided into four wave packets: 1630 - 1700 UT, 1700 - 1740 UT, 1740 - 1805 UT, and 1805 - 1820 UT. A summary of Fourier analyses of subintervals of the 3-hour data is shown in Table 1. Note that although Fourier transforms for each subinterval give a certain value of peak frequency for each component, the real frequency in a wave packet may still vary with L. In some subintervals (for example, the one from 1630 to 1700 UT) the wave frequency varies significantly, so that the calculated frequency for the interval has little meaning. The polarization of the waves on the v-φ plane is listed in the last column of Table 1. Except for the transverse waves between 1630 and 1700 UT (2.2 - 5.0 mHz) which exhibited alternately left-handed and right-handed polarization, long-period transverse waves ($T > 100$ s) in other subintervals were left-handed or linearly polarized.

TABLE 1. Summary of Magnetometer Observations of DE 1

Time Period, UT	L	GM latitudes deg	Wave Frequency, mHz	Main Components	Polarization bv-$b\varphi$
1600—1700	13.3—8.3	-55.0 — -41.4	1.5–2.9	$b\mu$	
1600—1630	13.3—10.3	-55.0 — -48.0	9.1	bv	left
1630—1700	10.3—8.3	-48.0 — -41.4	2.2–5.0	$b\varphi$	left-right
1700—1740	8.3—6.4	-41.4 — -32.6	3.9	$b\varphi$	left
1740—1805	6.4—5.3	-32.6 — -26.4	3.9	$b\varphi$	linear
1805—1820	5.3—4.7	-26.4 — -22.2	6.5	$b\varphi$	left
1820—1840	4.7—4.0	-22.2 — -15.7	37.0	$b\varphi$	

PARTICLE SIGNATURES OBSERVED BY THE RIMS INSTRUMENT

Plate 1 shows proton count rate measurements from the radial head of the RIMS instrument in a spin angle versus time spectrogram format. The dashed line in each panel indicates the angle at which the look direction of the instrument is parallel to the measured magnetic field, while the dotted line indicates the antifield direction. Zero degree ram angle in the plots means that the radial detector is viewing into the direction of motion of the spacecraft.

The first panel of Plate 1 shows that at about 1606 UT the radial head of the instrument observed a transition from unidirectional flow out of the southern hemisphere (count rate enhancements along the dotted line before ~ 1606 UT) to gradually increasing bidirectional flow after 1606 UT (L ~ 12.5). Data (not shown) from the DE 1 energetic ion composition spectrometer (EICS), courtesy of W. K. Peterson, indicated clear signatures of alpha particles before 1607 and none thereafter. These observations indicated that DE 1 probably moved from open field lines to closed field lines. The bidirectional flow was not symmetric, however, with the flow streaming away from the southern ionosphere apparently stronger than the one in the opposite direction. The asymmetric flow after 1606 UT is commonly seen when the spacecraft is well into the southern hemisphere (DE 1 was between -53.5° and -42.7° geomagnetic latitude from 1606 UT to 1654 UT), and the further into the southern hemisphere the stronger the flux may appear from the southern ionosphere than the northern ionosphere. After 1654 UT, the fluxes parallel and antiparallel to the magnetic field apparently became equally strong. However, we note that, since the flow from the northern hemisphere is closer to the ram direction than the plasma flow from the southern hemisphere, the observed antifield flow will be artificially enhanced. Thus it is possible that the bidirectional flow remained asymmetric after 1654 UT.

The magnetic signature which coincided with the transition seen at ~ 1606 UT in the plasma data was the beginning of the 110-s poloidal oscillation in the bv component. In fact, the plasma data also show the 110-s wave signature between 1606 and 1620, which appears as a fluctuation in the pitch angle of the otherwise field-aligned outflowing hydrogen ions. The above proton signature was probably caused by the oscillation of field lines in the poloidal direction. The compressional wave in $b\mu$ at the beginning of the interval seemed to start at about the same time, too, since a large amplitude of the compressional wave was seen after ~ 1605 UT. Unfortunately, no DE 1 data are available before 1600 UT to confirm this.

At ~ 1742 UT and ~ 1749 UT the RIMS instrument observed two brief periods of isotropic ion fluxes with slightly larger intensity, each lasting for only 1 to 2 min. This might suggest that DE 1 encountered detached plasmaspherelike plasma. At ~1753 UT (L ~ 5.8), DE 1 encountered a rammed hydrogen distribution characteristic of the plasmasphere. The magnetic signature that is coincident with the entering of the spacecraft into the plasmasphere is the transition between two wave packets from 1740 UT to 1750 UT which can be clearly seen in the $b\varphi$ component. Note that the transition time is also coincident with the time when $dB\theta$ began to increase (Figure 3a), which is probably associated with the southward turning of the interplanetary magnetic field (IMF) and magnetosheath magnetic field. It seems that the southward turning made the field lines at the location of DE 1 tilt more southward so that DE 1 encountered the plasmapause region at that time. The waves seen on both sides of the plasmapause (the waves before and after 1740 UT) are similar: they are mainly in the azimuthal component and have a period of about 256 s. The amplitude of the waves inside the plasmasphere (~ 5.5 nT) is slightly larger than outside (~ 4 nT), and the inside waves are linearly polarized while the outside ones are left-hand polarized.

From ~1753 UT to ~1814 UT the RIMS instrument observed a series of quasi-periodic enhancements of ion densities near the ram direction (see the second and third panel of Plate 1). The corresponding magnetic signature during this interval is the development of two wave packets in $b\varphi$: one occurred between 1750 UT and 1805 UT, and the other started at ~ 1805 UT, reached its maximum (~ 8 nT) at ~ 1815 UT, and then decayed rapidly.

DE 1 ELECTRIC FIELD MEASUREMENTS

The DC electric field data for the event are available for the interval between 1600 UT and 1812 UT in three components: Epar and Eperp, which are the spin-plane field components parallel and perpendicular to the projection of the magnetic field vector in the spin plane, respectively, and Ez, which is the average component of the DC electric field along the spin axis. The DC output is sampled at 16 samples per second. Computations are performed with segments of the DC data spanning 6 s of time (one spin period). These data segments are "centered" on times which are 4 s apart, so there is a 2-s overlap between segments. In this event the parallel, perpendicular, and +z directions in electric field measurements correspond to +μ, +v, and -φ in the field-aligned coordinates we have used to present the magnetic field data.

To see the variation of the wave electric field, we have high-pass filtered the data by subtracting the running average over about 900 s from the original data. We then compared the E field variation with the magnetic variation. Field line oscillations in the azimuthal direction ($b\varphi$) result in the variation of the electric field in the transverse component (Eperp) in the magnetic meridian plane where the oscillating field line is located. The poloidal oscillation (bv) produces electric field variations in the azimuthal direction (Ez).

In Figure 4 we compare the toroidal component $b\varphi$ (solid lines) with Eperp (dashed lines). This figure shows that between 1630 UT and 1655 UT, when DE 1 was in the outer magnetosphere (L > 8.5), higher-frequency (less than 1-min period) variations in Eperp were seen superimposed on the long-period waves (200 - 450 s) which were also clearly seen in $b\varphi$. Between 1700 UT and 1735 UT, when

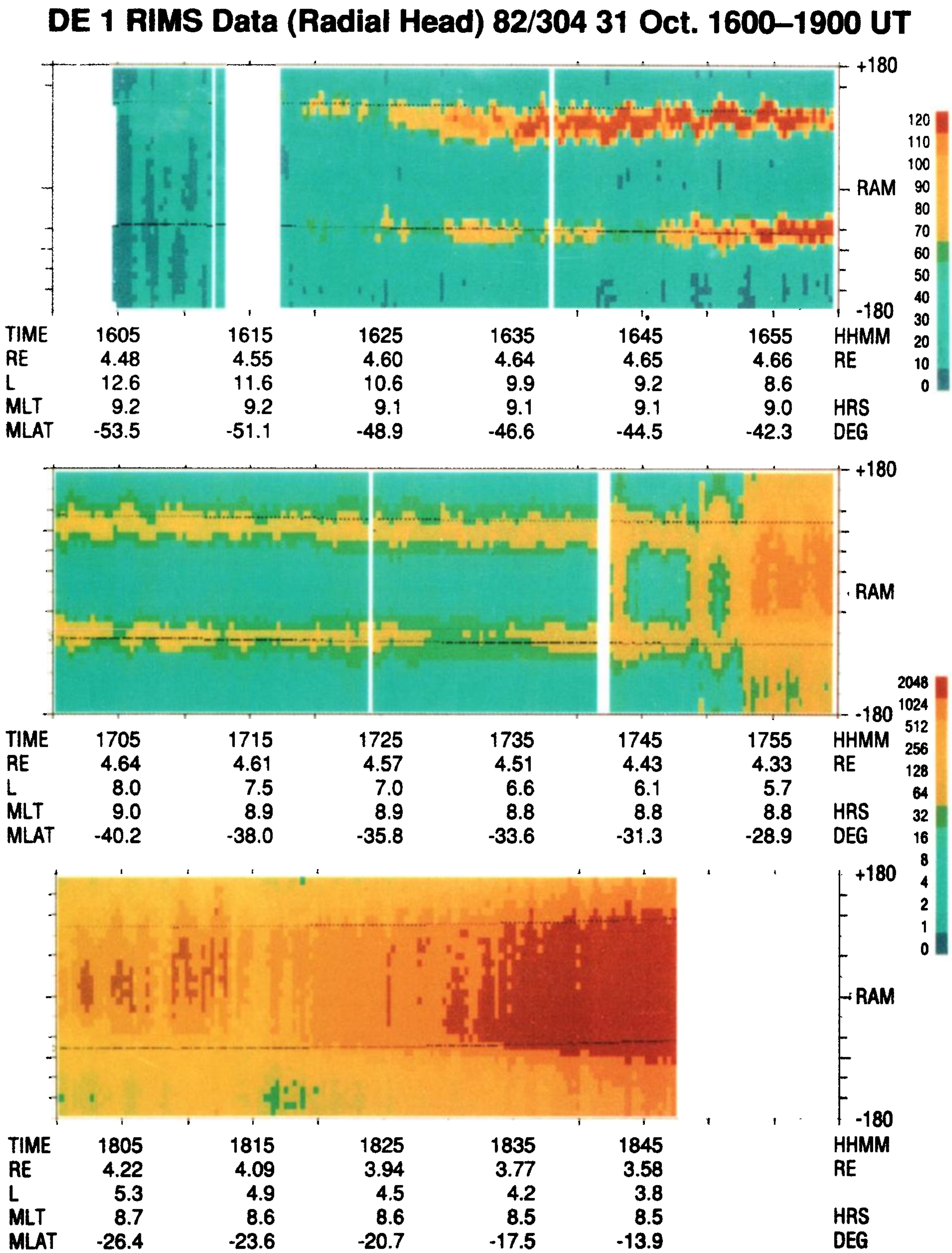

Plate 1. Proton count rate measurements from the radial head of the DE 1 Retarding Ion Mass Spectrometer (RIMS). The dashed line in each panel indicates the look direction of the instrument which is parallel to the measured magnetic field, while the dotted line indicates the antifield direction. Zero degree ram angle in the plots means that the radial detector is viewing into the direction of motion of the spacecraft.

there were strong oscillations in $b\varphi$ (about 250 s in period and a maximum amplitude of about 5 nT), *Eperp* was very weak (almost zero). At about 1748 UT the variation of *Eperp* intensified to an amplitude of about 1.5 mV/m and remained in quadrature with magnetic pulsations in $b\varphi$. Actually, the 90 deg phase shift between $b\varphi$ and *Eperp* with $b\varphi$ leading *Eperp* can be seen for the transverse oscillations after 1630 UT, even during the interval when electric pulsations were weak. This phase relation between $b\varphi$ and *Eperp*

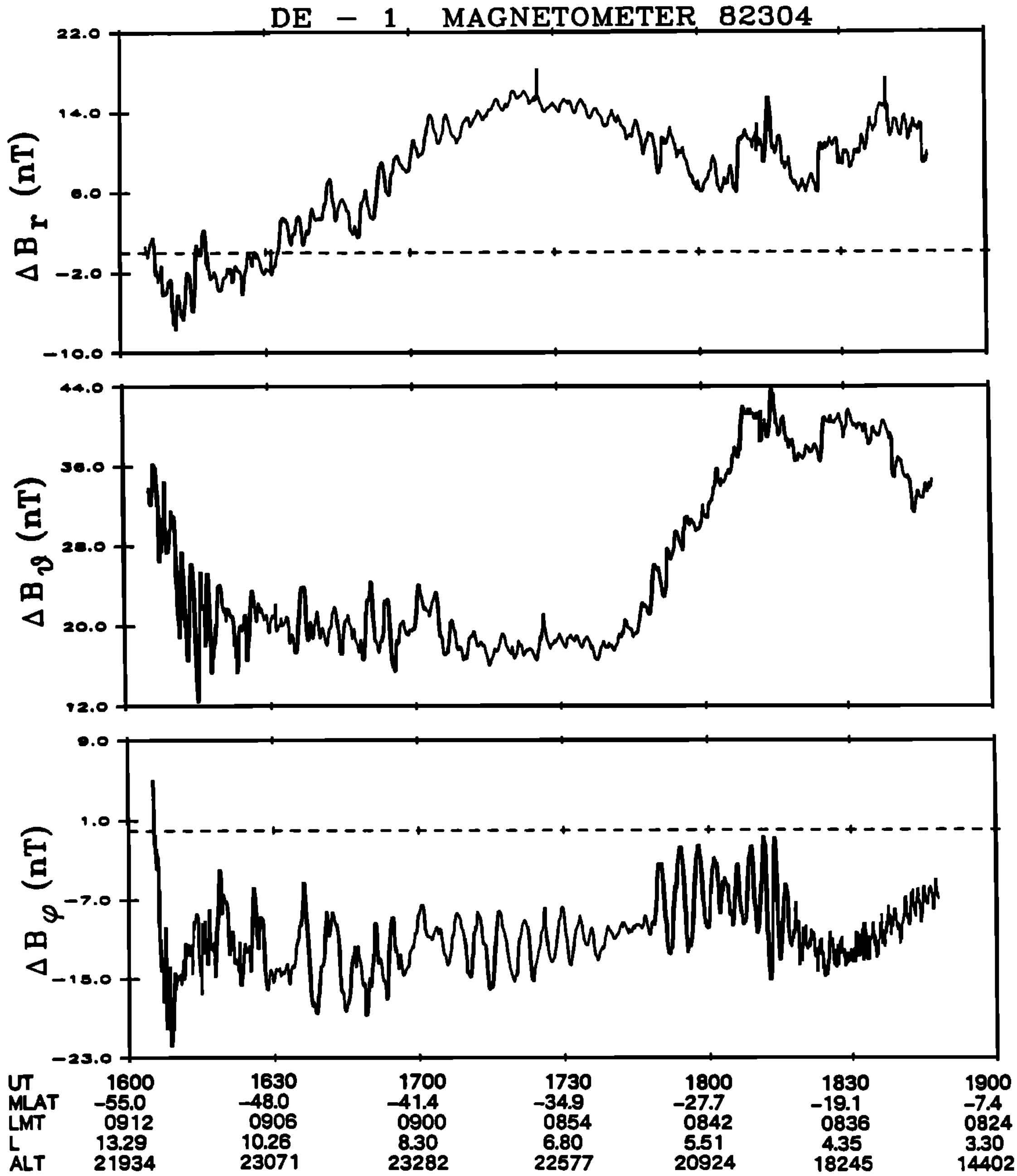

Fig. 3*a*. The difference between DE 1 measurements of the magnetic field and the Magsat model field in three components of a geomagnetic spherical coordinate system: ΔBr points radially outward, $\Delta B\theta$ points southward, and $\Delta B\varphi$ points eastward.

suggests that the transverse waves were standing Alfven waves along magnetic field lines.

The short tubular *Ez* antenna often detects spacecraft-generated noise which enhances the signal detected by the *Ez* antenna. Although the *Ez* amplitude values are contaminated, the high-pass-filtered *Ez* data (not shown) show a component remained which oscillated in antiphase with the *bv* component before 1655 UT, especially between 1605 UT and 1620 UT, when the poloidal oscillations were most clearly seen. This phase relation is a signature of propagating waves.

In order to examine the propagation of the wave energy we have calculated the Poynting flux of the waves, $S = (1/\mu_0)E \times b$, where $\mu_0 = 4\pi\ 10^{-7}\ s^2/m^2$. Because of the noise-contaminated *Ez* amplitude values, it is possible to calculate only an upper limit of the Poynting flux using the *Ez* data. Before calculation, we interpolated the electric field data to match the 6 s time resolution of the magnetic data. The calculated Poynting flux is displayed in Figure 5: the μ, ν, φ components in the the first three panels, and the total Poynting flux in the bottom panel. The large magnitude of the Poynting flux before ~ 1700 UT was due, in large part, to the noise contamination in the *Ez* data, but it is clear that the flow direction of the energy flux was mainly in the -μ direction, i.e., along magnetic field lines toward the southern ionosphere. After ~ 1700 UT, when the toroidal waves dominated, the Poynting flux oscillated around zero in the three components. These results show that the DE 1 spacecraft, travelling inbound, observed propagating waves in the outer magnetosphere.

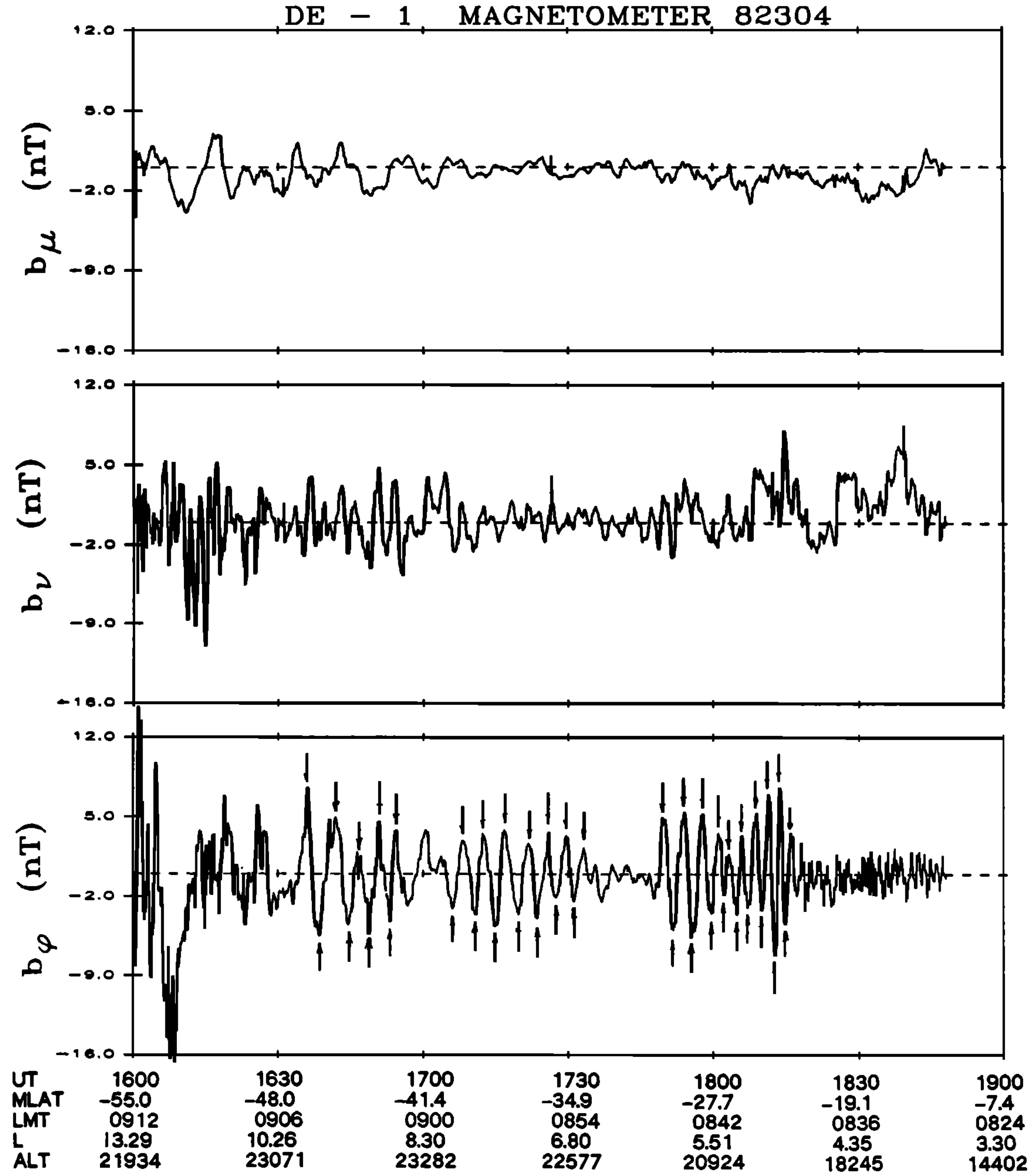

Fig. 3*b*. Magnetic field data in a field-aligned coordinate system with orthogonal unit vectors μ (parallel to the background magnetic field), the transverse poloidal component ν, and the azimuthal component φ.

As it moved further into the magnetosphere, the spacecraft entered regions where magnetic field lines oscillated in the form of standing waves.

GROUND OBSERVATIONS

The DE 1 satellite trajectory was magnetically conjugate to western Canada during the interval of pulsation activity from 1600 UT to 1900 UT. Figure 6 shows the footprint of the DE 1 trajectory for the time interval being studied, and includes the locations of several Alaskan and Canadian magnetic observatories. The coordinates of the stations are summarized in Table 2. The ground magnetometer data are available for three components: the north-south component, *H* or *X*, with +*H* or +*X* pointing north, the east-west component, *D* or *Y*, with +*D* or +*Y* pointing east, and vertical component Z, with +Z downward. In this paper we will show the north-south component only. The available data have 1- min time resolution, with the exception of College search coil data which have 10-s resolution. The data are grouped into two sets. The first set (Figure 7) covers the period of 1300 UT to 2100 UT from the stations at Sachs Harbor (SAH), Cape Parry (CPY), Inuvik (INK), Fort Yukon (FYK), College (COL), and Talkeetna (TLK) and thus gives the magnetic field components for decreasing geomagnetic latitude and *L* values, approximately along a magnetic meridian. The second set of data is from Fort Smith (FSM), Fort Simpson (FSP), Norman Wells (NOW), and College (COL), which, from east to west, follow the auroral oval approximately (Figure 8).

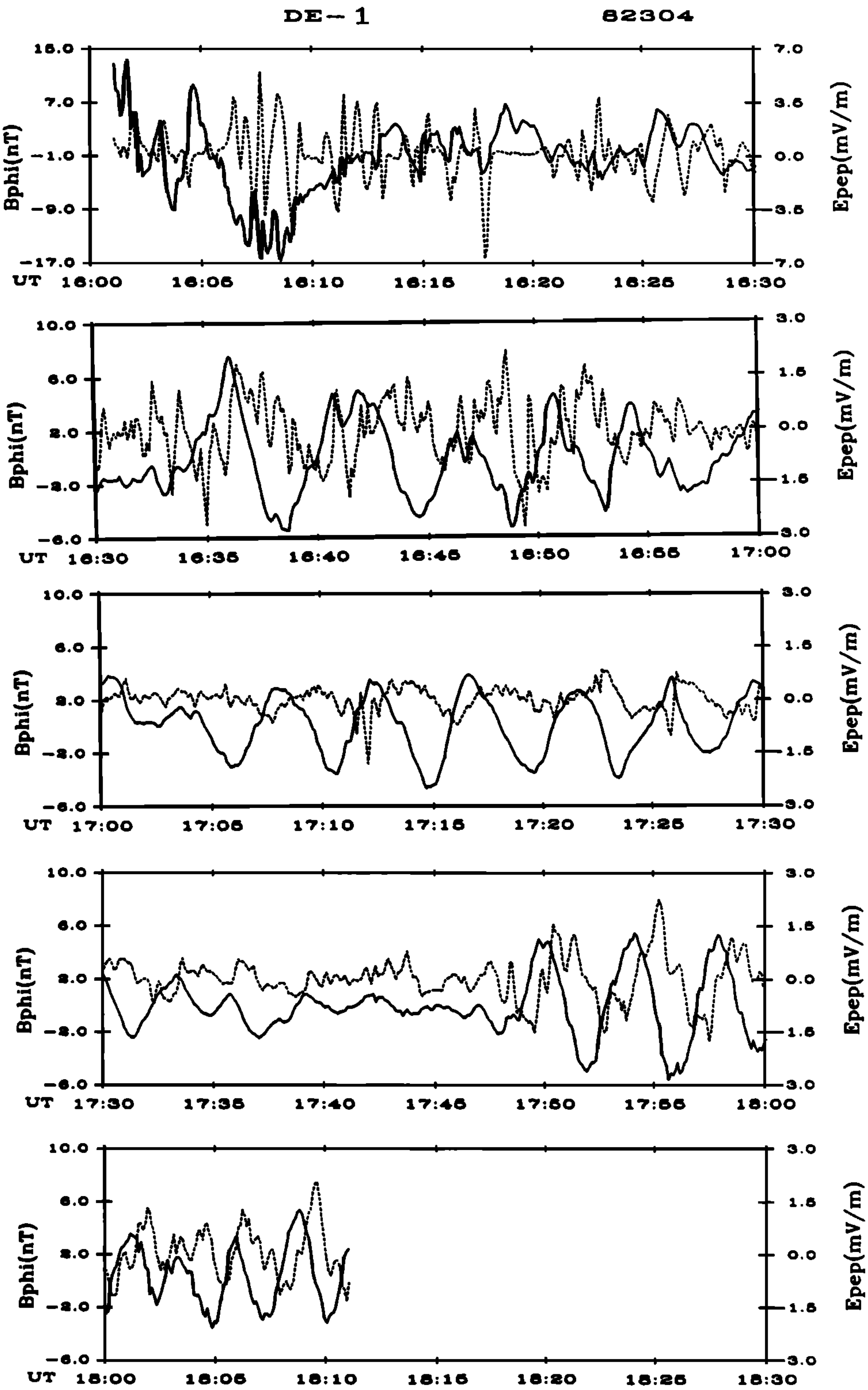

Fig. 4. Comparison between the azimuthal magnetic field variation, $b\varphi$ (solid lines), and the variation of the spin-plane component of the electric field which is perpendicular to the magnetic field, Epep (dashed lines).

The ground data show a series of magnetic disturbances. A signature which is probably associated with the sudden increase in solar wind pressure observed by ISEE 3 at ~ 1347 UT is the small spike clearly seen in the *H* component (first vertical dashed lines in Figure 7 and 8) from all stations at ~ 1339 UT. The second signature of magnetic disturbances occurred at about 1527 UT (marked by the second vertical dashed lines in Figure 7 and 8), when negative bays were seen in the *H* components of all stations, especially in the INK station. Corresponding signatures were also evident in the east-west and the vertical components (not shown). These negative bays simultaneously observed in the *H* components were probably caused by a westward electrojet, the center of which developed above INK

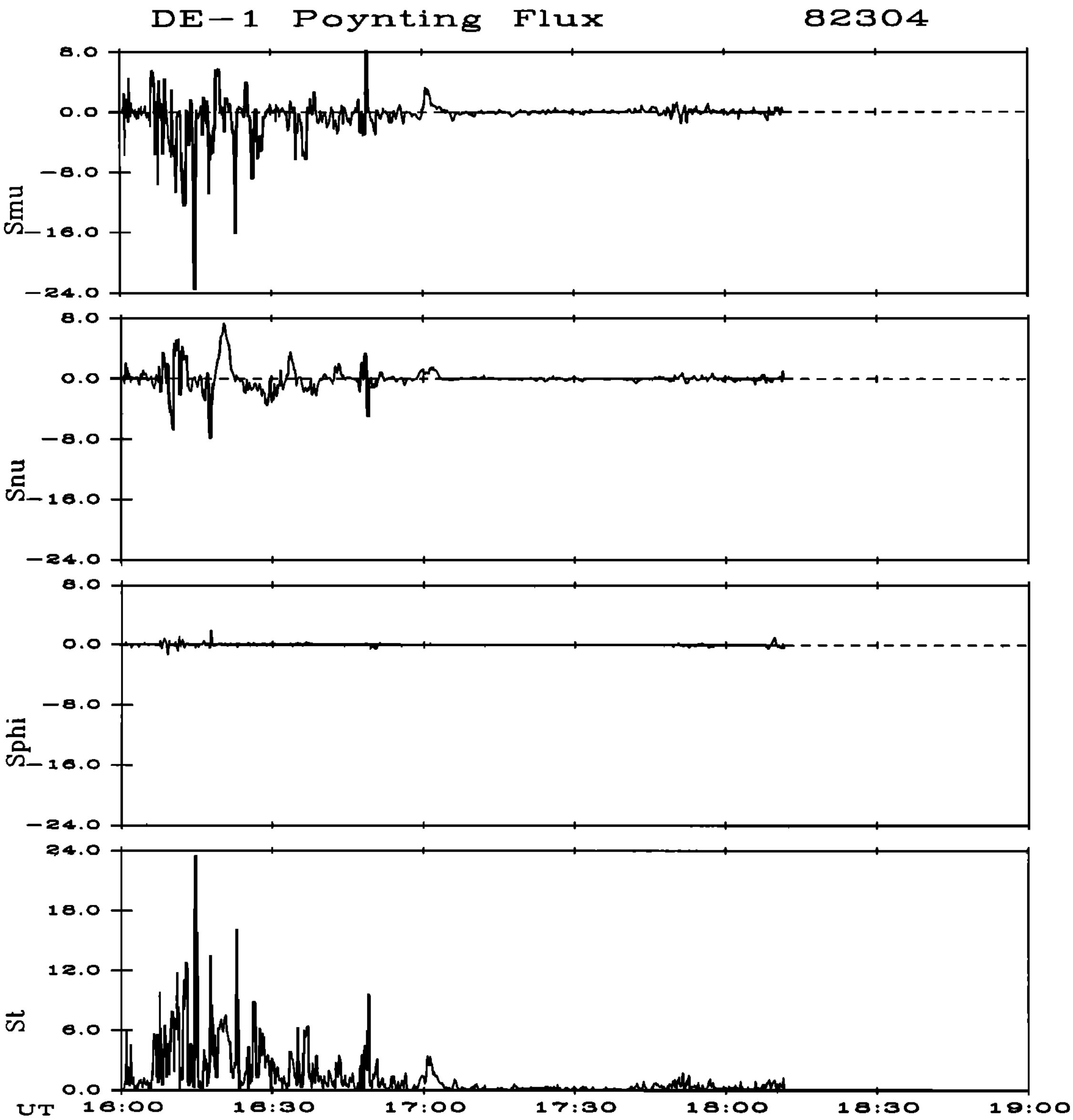

Fig. 5. The Poynting flux (in 10^{-5} Watts/m^2) for the interval 1600 to 1802 UT. The first three panels show the μ, ν, and φ components, and the bottom panel shows the total Poynting flux.

and thus reduced the *H* component of INK data most significantly. This electrojet also caused the *Z* components (not shown) of the stations to the north of INK (CPY and SAH) to increase forming positive bays, and those of the stations to the south of INK (FYU and COL) to decrease forming negative bays. This relatively weak westward electrojet seemed to be a precursor of much larger electrojets which occurred a few hours later. At about 1800 UT, large magnetic variations occurred, indicating development of a substorm. The signature was seen earlier in higher latitude (polar cap) stations. Figure 7 shows (marked by arrows) that the *H* component at SAH began to increase at about 1730 UT to a maximum of about 250 nT, then became negative at ~ 1843 UT. A few minutes later, similar variations occurred at CPY (beginning at ~ 1735 UT) and INK (beginning at ~ 1748 UT). Stations at lower latitudes (FYU, COL, and TLK) observed only large decreases (negative bays) after 1800 UT. At College the negative bay developed most intensely.

To see magnetic pulsations more clearly, we display in Figures 9 and 10 the magnetic data which are used in Figures 7 and 8 but after subtracting a 17 point (17 min) running average from the original data. Figures 9 and 10 show that magnetic pulsations began at all stations after the spikes at about 1339 UT which were associated with the solar wind pressure increase. The development of pulsations after 1339 UT is more clear at higher latitudes (Figure 9). The electrojet events described in the previous paragraphs seem to be associated with intensifications of ground pulsations. We have marked vertical lines and arrows in Figures 9 and 10, corresponding to the lines and arrows in Figures 7 and 8. Figures 9 and 10 show that, after ~ 1525 UT, when small bays in *H* began at all stations, the pulsations intensified and the amplitude of the fluctuations became larger. Associated with the substorm development around 1800 UT, which was characterized by first eastward and then westward electrojets, another intensification of magnetic fluctuations was seen at each station, especially those at lower latitudes (FYU, COL, TLK, FSM, FSP, and NOW). The onset times of this intensification in each station seemed to coincide with the time when the station began to feel the effects of the eastward or westward electrojets.

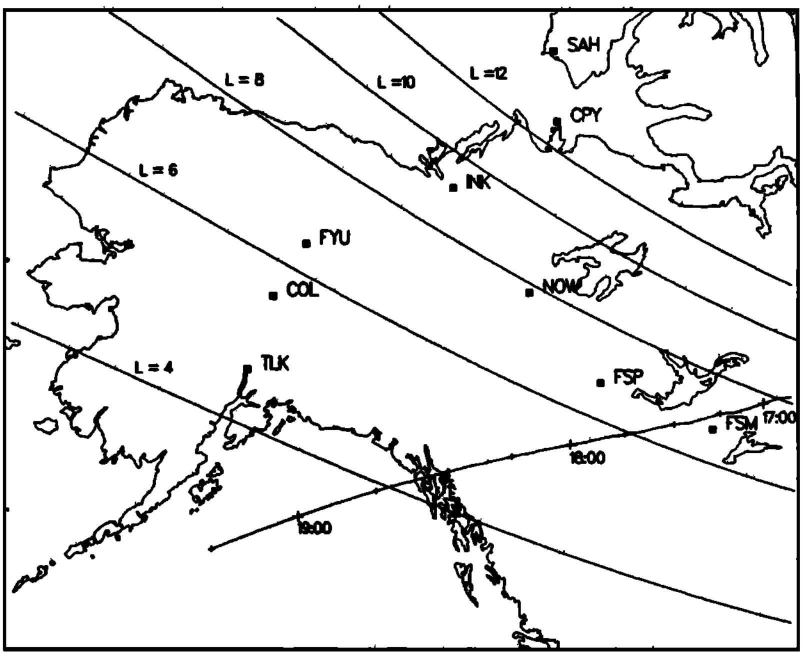

Fig. 6. A map indicating locations of the stations and the ionospheric footprint of the DE 1 trajectory for the time interval being studied.

TABLE 2. List of Station Coordinates

Station		*L*	Geomagnetic Latitude	Geomagnetic Longitude	Invariant Latitude
Sachs Harbor	(SAH)	16.99	77.3	268.0	75.96
Cape Parry	(CPY)	13.78	75.7	272.3	74.37
Inuvik	(INK)	9.39	72.7	264.9	70.95
Fort Yukon	(FYU)	6.60	69.2	253.8	67.09
College	(COL)	5.55	66.9	252.9	64.88
Talkeetna	(TLK)	4.82	62.2	258.6	62.90
Fort Smith	(FSM)	5.81	67.4	298.9	65.49
Fort Simpson	(FSP)	6.71	67.2	287.2	67.30
Norman Wells	(NOW)	8.00	69.4	276.9	69.30
College	(COL)	5.55	66.9	252.9	64.88

The waveforms observed at each station are not sinusoidal, implying that the waves consist of several frequency components. Fourier analysis was applied to the data to determine wave frequencies. Before performing the FFT, we calculated the time derivative of the original data to emphasize the short period variations. Since the data have 1-min resolution, the shortest period we could determine using Fourier methods is 120 s (8.3 mHz). For each FFT we took 128 points starting from 1600 UT. The results are listed in Table 3. The frequency peak values in each component at each station are listed in the table in descending order of their power. In general, the power is larger for longer-period components.

While the waves observed at DE 1 have a narrow frequency band, the waves on the ground have a broader frequency range. At each station the magnetic pulsations consist of several frequency components, including those observed in space. For example, between 1630 UT and 1700 UT, DE 1 was traversing *L* shells of $L \sim 10.3$ to

TABLE 3. Wave Frequencies at Ground Stations

Station		*L*	*H* or *X*	D or Y	*Z*
			Frequency, mHz		
Sachs Harbor	(SAH)	16.99	1.45, 2.0, 2.6, 3.2, 4.5, 5.5	2.0, 5.5	1.4
Cape Parry	(CPY)	13.78	1.4, 2.1, 3.0, 4.0, 4.7	1.9-2.5, 3.0, 3.8, 6.0	1.3, 2.4, 4.0
Inuvik	(INK)	9.39	2.3, 3.3, 4.4, 5.5	2.0, 2.9, 5.5, 4.0	1.3, 2.0, 3.0
Fort Yukon	(FYU)	6.60	2.0, 4.0, 5.5	5.5, 6.5, 3.7	2.0, 4.0 ,5.3, 6.0
College	(COL)	5.55	5.5, 6.5, 2.0, 3.9, 3.2	5.5, 6.7, 3.7	3.7, 2.2
Talkeetna	(TLK)	4.82	5.5 - 6.5	5.6	
Fort Smith	(FSM)	5.81	3.7, 4.5, 2.2, 5.6	3.1, 3.7, 5.5, 2.0	3.1-3.8, 4.5
Fort Simpson	(FSP)	6.71	3.8, 4.4, 5.4, 1.9 - 2.3	6.6, 3.2, 5.4, 2.1, 3.7, 4.4	3.9, 2.0, 3.1, 5.4
Norman Wells	(NOW)	8.00	4.5-5.4, 6.6, ~ 2.0, 3.8	6.6, 5.5, 6.0, 2.0, 3.0, 3.7	4.5, 2.4, 3.0, 3.7

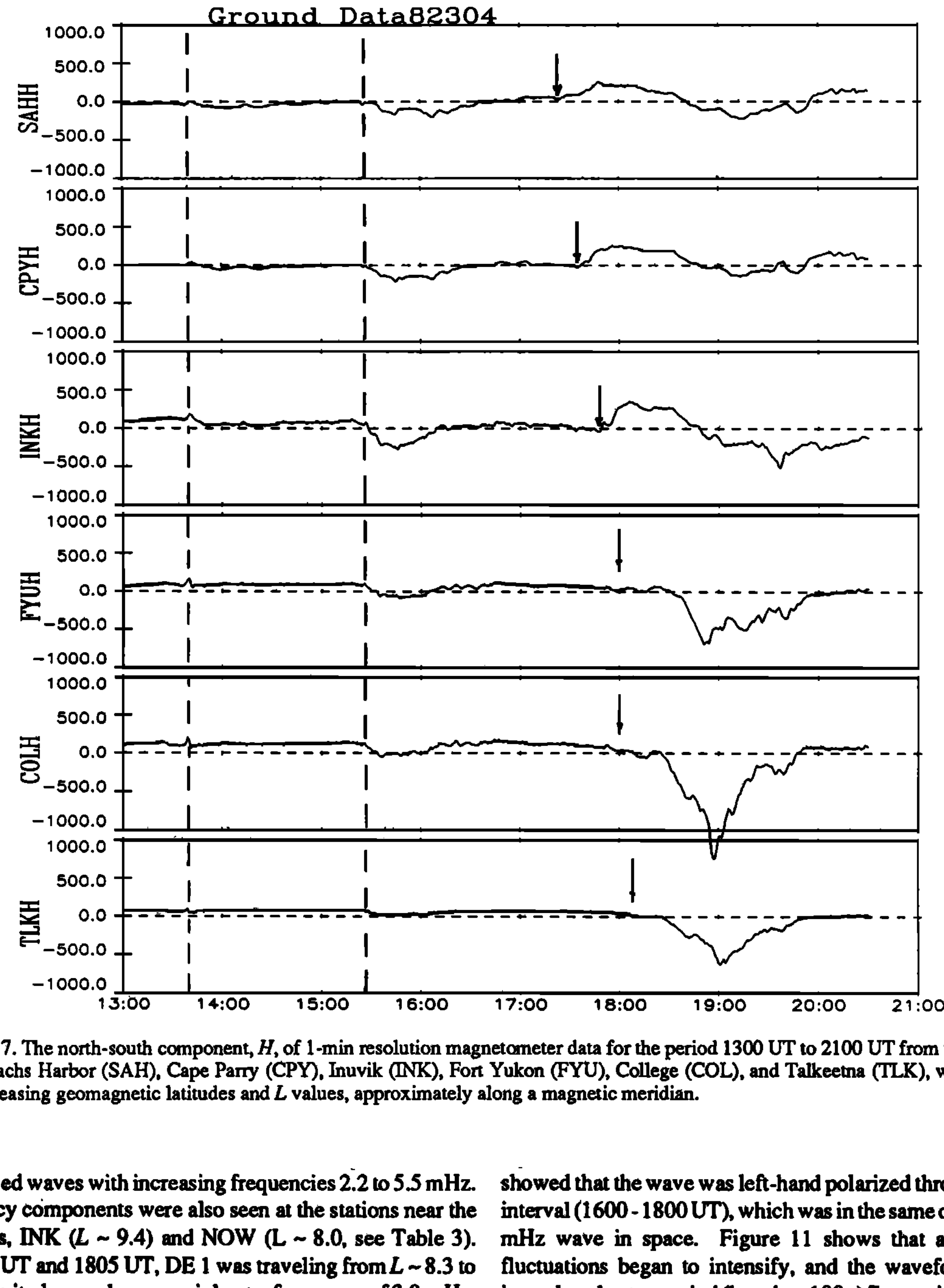

Fig. 7. The north-south component, H, of 1-min resolution magnetometer data for the period 1300 UT to 2100 UT from the stations at Sachs Harbor (SAH), Cape Parry (CPY), Inuvik (INK), Fort Yukon (FYU), College (COL), and Talkeetna (TLK), which are at decreasing geomagnetic latitudes and L values, approximately along a magnetic meridian.

8.3, and observed waves with increasing frequencies 2.2 to 5.5 mHz. These frequency components were also seen at the stations near the above L values, INK ($L \sim 9.4$) and NOW ($L \sim 8.0$, see Table 3). Between 1700 UT and 1805 UT, DE 1 was traveling from $L \sim 8.3$ to 5.3. The waves it observed were mainly at a frequency of 3.9 mHz. Similar frequencies (3.7 - 4.0 mHz) were observed at the stations near these L values, e.g., FSM, FSP, NOW, FYU, and COL. The last wave packet seen in space between 1805 and 1820 UT ($L \sim 5.3$ - 4.7) has a frequency of 6.5 mHz. This frequency component was also seen at COL ($L \sim 5.6$) and TLK ($L \sim 4.8$).

The time variation of the H and D components, measured by College search coils, is displayed in Figure 11 for the interval from 1600 UT to 1845 UT. Quasi-sinusoidal waves are seen in both components before 1800 UT. Fourier analysis of the data shows that frequency components at ~ 5.7 - 6.7 mHz (150 - 175 s period) consistently existed until about 1800 UT, when higher-frequency variations appeared and the longer-period waves gradually disappeared. The main frequency seen at the search coil data, about 6.5 mHz (154-s period), was very close to that observed by DE 1 between 1805 and 1820 UT. Hodograms produced using the above search coil data filtered in a frequency band between 5 and 10 mHz (not shown) showed that the wave was left-hand polarized throughout the 2-hour interval (1600 - 1800 UT), which was in the same direction as the 6.5-mHz wave in space. Figure 11 shows that after 1800 UT the fluctuations began to intensify, and the waveform became more irregular; shorter-period (less than 100 s) fluctuations appeared. This change is coincident with the development of the large negative bay seen at College. We note that a similar change was observed at DE 1: At 1815 UT the 150-s wave observed by DE 1 decayed rapidly, and shorter-period waves (37 mHz) appeared.

DISCUSSION

We have observed a ULF wave event during a magnetically disturbed interval. The onset of pulsations on the ground was coincident with a sudden increase in the solar wind velocity and solar wind pressure at ~ 1345 UT. Another change in solar wind parameters at about 1530 UT (a northward turning of IMF Bz, and intensification of the fluctuations of the solar wind dynamic pressure) was apparently associated with the second intensification of Pi pulsations on the ground which was coincident with small negative bays in the H components. Field line oscillations observed by DE 1 in space were

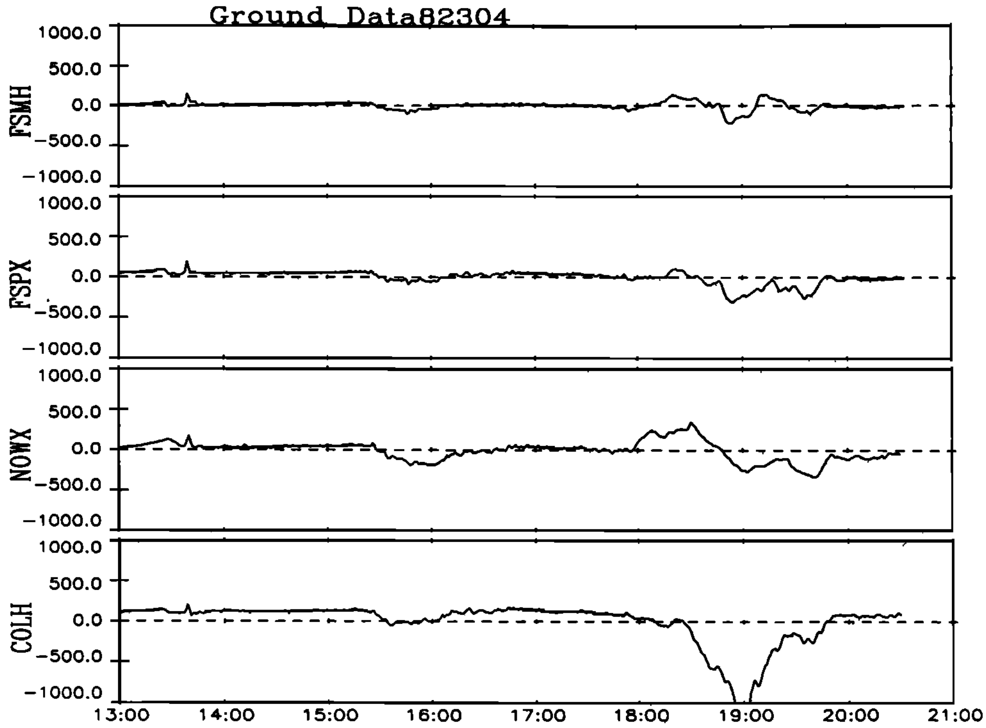

Fig. 8. The same as Figure 7, but for stations Fort Smith (FSM), Fort Simpson (FSP), Norman Wells (NOW), and College (COL), which, from east to west, follow the auroral oval approximately.

probably also associated with the above intensification of variations in the solar wind parameters around 1530 UT.

It has been reported that a sharp increase in solar wind dynamic pressure may initiate ringing of the magnetosphere [cf. *Sibeck et al.*, 1989]. *Southwood and Kivelson* [1990] have shown that a pressure perturbation at the magnetospheric boundary can excite fast mode and transverse mode eigenoscillations in the magnetosphere. The coincidence between the pulsation intensifications and the changes in the solar wind dynamic pressure in this event suggests that the magnetic pulsations were first excited by the increase of the solar wind dynamic pressure at ~ 1345 UT (the first vertical dashed lines in Figure 9), and another burst of pulsations at 1530 UT (the second vertical dashed lines in Figure 9) was the response of the magnetosphere to the intensification of the solar wind perturbation. DE 1, which entered the magnetosphere shortly after 1600 UT, observed the ringing of the magnetosphere.

RIMS and EICS data indicate that DE 1 might have entered a closed field line region from an open field line region at ~ 1606 UT. On entering the closed field line region, DE 1 observed a 110-s wave mainly in the poloidal component (bv). The antiphase relation between bv and Ez indicates that the wave was propagating. A Poynting flux calculation shows that the waves seen in the outer magnetosphere before 1700 UT ($L > 8.3$) had a significant component propagating along the ambient field lines toward the southern hemisphere.

Longer-period (~ 650 s) compressional oscillations with decaying amplitude were seen from the beginning of the available DE 1 data until about 1715 UT. The compressional waves preceded the transverse oscillations and lasted for more than one hour. *Cahill et al.* [1990] reported a toroidal Pc 4 wave preceded by rapidly damped compressional oscillations which were excited by a world wide storm sudden commencement. They suggested that the compressional pulsations were evidence of global cavity resonance oscillations and had coupled to the transverse oscillations. In our event the compressional oscillations might have been the oscillations of the magnetosphere in response to the variations of the solar wind velocity and pressure. The main frequency component (~ 1.5 mHz) is much lower than the toroidal oscillations seen by DE 1 after 1630 UT. However, Fourier analysis of the waves between 1600 UT and 1700 UT shows that there are minor peaks at ~ 2.9 and 4.5 mHz. It is possible that these compressional oscillations with frequencies matching the eigenfrequencies of magnetic field lines at lower L shells coupled with toroidal modes and produced strong azimuthal oscillations which were seen by DE 1 after 1630 UT.

It is interesting to note that the period of the azimuthal oscillations decreased continuously with L values in the first wave packet (1630 - 1700 UT). It seems that in this event adjacent magnetic shells in the outer magnetosphere region (L = 10.3 - 8.3) rang at their own eigenperiods with little interaction. This phenomenon has been observed previously (see, for example, the third event in the work by Lin et al. [1986]), and was commonly seen in AMPTE CCE observations [cf. *Engebretson et al.*, 1986*a*; Anderson et al., 1990]. The continuous variation of the wave period with L values suggests that the sources of the waves, presumably the variation of the solar wind dynamic pressure at the magnetopause, had a broad frequency bandwidth. Such sources may drive harmonic oscillations over an extended radial distance with each field line resonating at its Alfven resonance frequency [*Hasegawa et al.*, 1983]. This kind of source is likely to be spatially localized and have a large azimuthal wave number. In this case the global eigenmodes do not occur and the compressional signal decays away from the boundary [*Southwood and Kivelson*, 1990], as is observed in this case.

The azimuthal waves can be divided into several wave packets which correspond to different plasma regions: before 1655 UT, ions streamed along field lines predominantly in the direction of magnetic field lines. From 1655 UT to 1745 UT, field-aligned streaming ions still dominated but traveled in both directions. Soon after 1740 UT, DE 1 started to see isotropic ion distributions, and at about 1753 UT

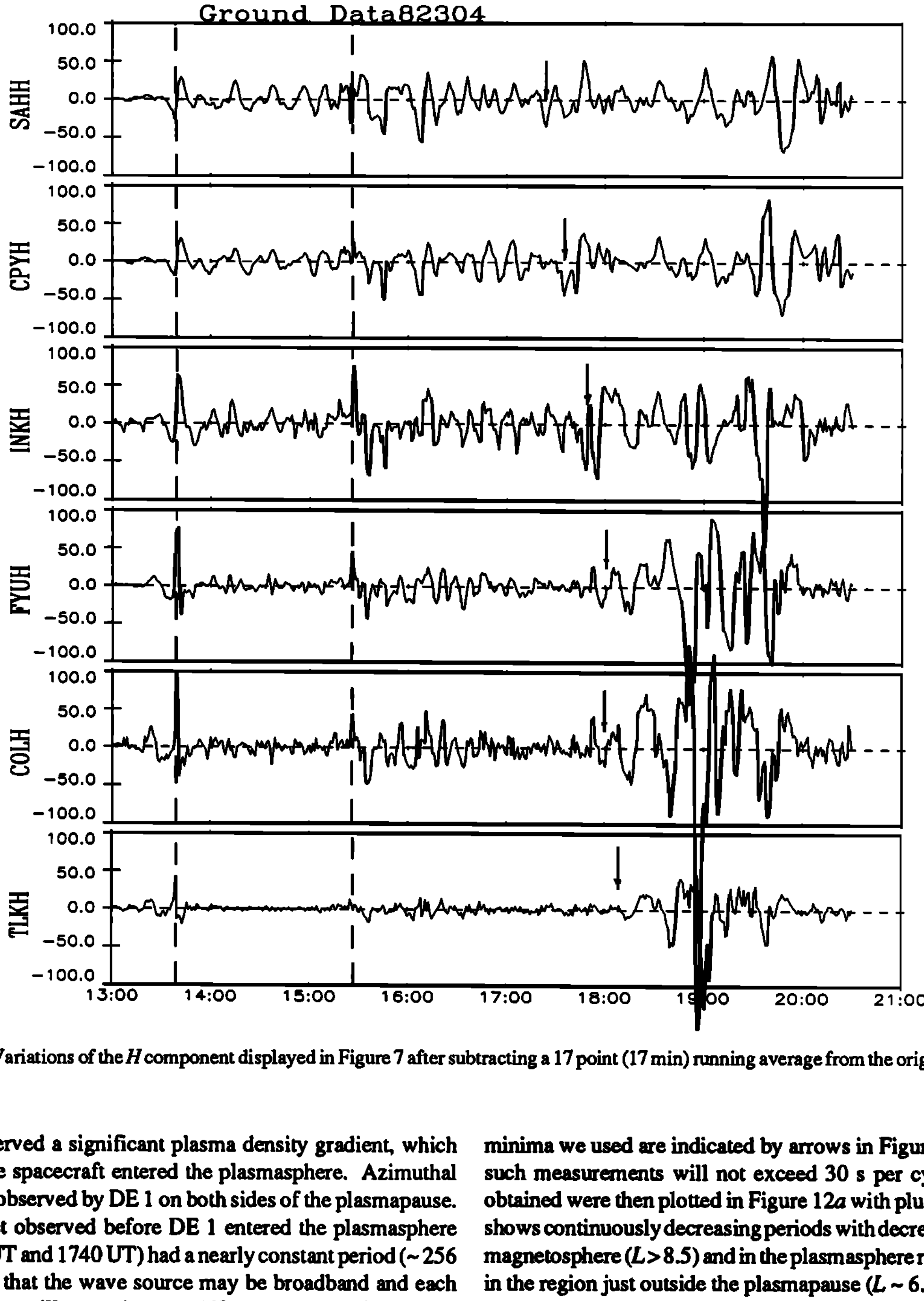

Fig. 9. Variations of the H component displayed in Figure 7 after subtracting a 17 point (17 min) running average from the original data.

the satellite observed a significant plasma density gradient, which indicates that the spacecraft entered the plasmasphere. Azimuthal pulsations were observed by DE 1 on both sides of the plasmapause. The wave packet observed before DE 1 entered the plasmasphere (between 1705 UT and 1740 UT) had a nearly constant period (~256 s). Considering that the wave source may be broadband and each ringing field line oscillates at its own Alfven resonance frequency, the constant wave period is consistent with the existence of a plasma density gradient near (outside) the plasmapause region. Theoretical models of the variation of the eigenfrequency of toroidal oscillations (see, for example, Figure 9 of *Yumoto and Saito* [1983]) predict a sharp increase in the wave frequency at the plasmapause. This was not observed in our event; instead, a transition between two wave packets was observed near the plasmapause crossing (1740 - 1750 UT).

To examine the changes of the wave period with L shells, we plotted the observed period versus L values in Figure 12*a*. In creating this diagram we took three intervals (1635 - 1700 UT, 1703 - 1735 UT, and 1745 - 1820 UT) when wave signatures were clear, measured the time difference between two successive maxima (or two successive minima), and then took this value as the wave period at the midtimes between the two maxima (or the two minima). The maxima and minima we used are indicated by arrows in Figure 3*b*. The error of such measurements will not exceed 30 s per cycle. The periods obtained were then plotted in Figure 12*a* with plus signs. The figure shows continuously decreasing periods with decreasing L in the outer magnetosphere ($L > 8.5$) and in the plasmasphere region ($L < 5.8$), but in the region just outside the plasmapause ($L \sim 6.7$ - 7.9), the period varied around 250 s.

We also show in Figure 12*a* three lines which represent variations of the eigenperiod of field lines versus L. The eigenperiod was calculated as [*Orr and Matthew*, 1971]

$$T = 0.05881\, L^4 (n_0/kC)^{1/2} \tag{1}$$

where n_0 is the equatorial mass density. The value kC is calculated using the formulae developed by *Taylor and Walker* [1984] for toroidal oscillations in a dipolar geomagnetic field with infinite ionospheric conductivity boundary condition. The plasma density distribution along a field line is assumed to be $n = n_0(r_0/r)^m$, where r_0 is the geocentric distance to the equatorial crossing point of the field line considered and r is the geocentric distance to a point on the field line. Inside the plasmapause, the density index m is chosen to be equal to 3, and

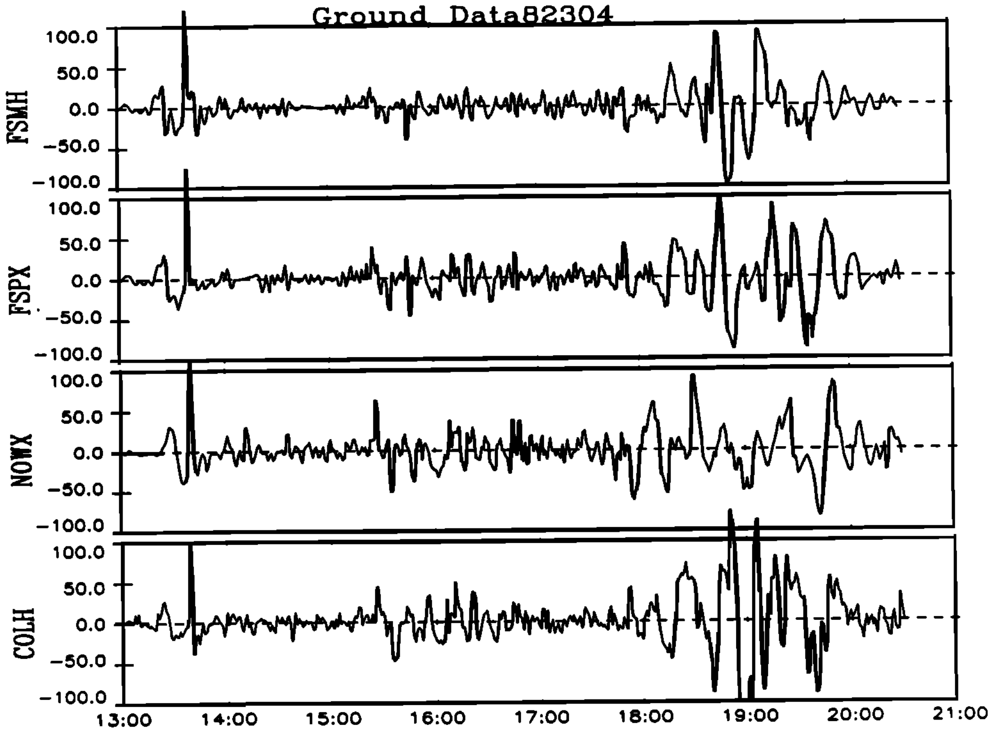

Fig. 10. Variations of the H component displayed in Figure 8 after subtracting a 17 point (17 min) running average from the original data.

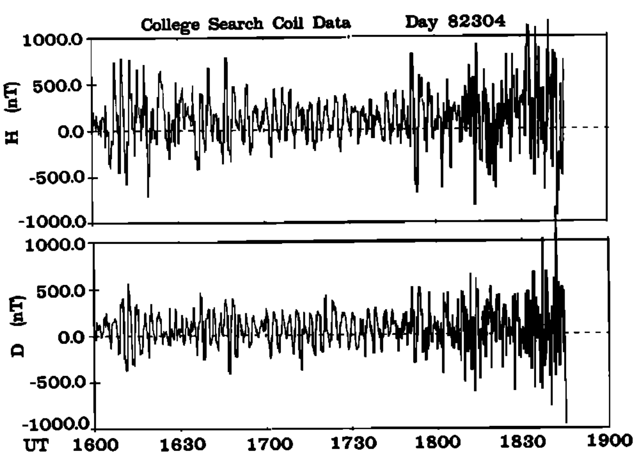

Fig. 11. Search coil magnetometer data from College, Alaska, at 10-s resolution. The search coil responds to dB/dt, so suppresses longer period components. *(a)* North-south component H, and *(b)* East-west component D.

$$kC = (\pi/S_o)^2/[1-(0.0980S_o^2-0.0077S_o^4+0.0003S_o^6)] \quad (2)$$

where S_o=2sinΛ, and Λ is the invariant latitude which can be calculated from L values using $L = 1/\cos^2\Lambda$. Outside the plasmapause m = 4, and

$$kC = (\pi/S_o)^2/[1-(0.0653S_o^2-0.0026S_o^4)] \quad (3)$$

In the calculation we have assumed that the pulsations were fundamental mode oscillations, and took the equatorial density to be 55 amu/cm^3 for L between 4.8 and 6.0; 9 amu/cm^3 for L between 6.4 and 8.0; and 1.5 amu/cm^3 for L between 8.5 and 9.8 in order to fit the data in each interval. It is shown from the figure that for the outer

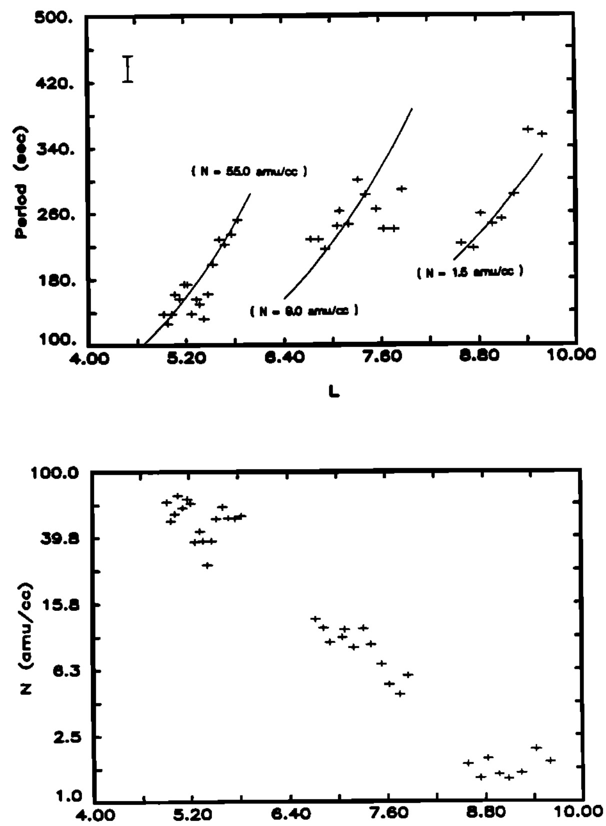

Fig. 12. *(a)* Wave periods observed by DE 1 versus L value. The periods (plus sign) were measured during three intervals (1635 - 1700 UT, 1703 - 1735 UT, and 1745 - 1820 UT) when wave signatures were clear. The three solid lines represent variations of calculated eigenperiods of field lines versus L, assuming that the pulsations were fundamental mode. *(b)* Equatorial mass densities derived from the observed period plotted as a function of L.

magnetosphere ($L > 8.5$), the calculated periods assuming a fixed equatorial density basically agree with the observed periods within the error range. For the region inside the plasmasphere ($L < 5.8$) the fit is reasonably good, while for the region outside the plasmasphere (between $L \sim 6$ and 8), the fit is quite poor, which suggests that the density in this region was not a constant.

In Figure 12*b* we plotted the equatorial mass density derived from the observed period versus L using the same model, and again assuming the waves were fundamental oscillations. The figure shows that the equatorial mass density was nearly constant (1 - 2 amu/cm^3) in the outer magnetosphere; from $L \sim 8$ to 6 the density gradually increased from ~4 to ~12 amu/cm^3, while inside the plasmasphere ($L < 5.8$) the calculated plasma density was fluctuating with an average of ~ 52 amu/cm^3. For the region far outside the plasmapause the assumption of fundamental mode oscillation seems to be justified, as we obtain a reasonable equatorial mass density. Immediately outside the plasmapause we obtain a gradual density ramp. For the region inside the plasmapause, this assumption again gives reasonable results, but we cannot be sure that the waves were in the fundamental mode. If they were not, the equatorial density could be higher. For example, at ~ 1812 UT DE 1 was at $L \sim 5$ and at ~-25° geomagnetic latitude. It observed a toroidal wave of 154-s period. A comparison of $b\varphi$ and *Eperp* (Figure 4) shows that $b\varphi$ led *Eperp* by 90°. This phase relation is consistent with that of both fundamental and second harmonic oscillations for a spacecraft at high latitudes [*Cahill et al.*, 1986]. If the wave was the second harmonic, then the equatorial density should be about 140 amu/cm^3 to produce a 154-s oscillation.

The phase relation between $b\varphi$ and *Eperp* with $b\varphi$ leading *Eperp* by 90° for the four toroidal wave packets indicates that the waves were standing along magnetic field lines. We have noted that during the second wave packet (1700 - 1740 UT), *Eperp* declined to ~ 0.1 mV/m in amplitude. This is unexpected, since the spacecraft was at -41° to -32° geomagnetic latitude (L ~ 8.3-6.3) and there are no nodes of *Eperp* at such high latitudes along field lines oscillating in the form of standing waves for the first few harmonics [cf. *Cummings et al.*, 1969]. We may estimate roughly the comparison of *Eperp* and $b\varphi$ using a model by *Allan and Knox* [1979] which considers finite conductivities of the ionosphere. First, we do the comparison for the E and b field at 1755 UT. The spacecraft at that time was at -29° geomagnetic latitude and at $L \sim 5.7$. The observed $b\varphi$ was about 5.5 nT in amplitude. From Figure 4 of *Allan and Knox* [1979], which is for the fundamental standing wave at $L = 4$ with conductivities of 10 S at both ends of the field line, the oscillation with 5.5 nT would produce an *Eperp* component with an amplitude of ~ 5.5 mV/m, which is about 2 times larger than the observed *Eperp* value. At 1715 UT the spacecraft was at -38° geomagnetic latitude and at L ~ 7.5. For the observed $b\varphi$ (about 4.5 nT) the model produces an *Eperp* value of about 3 mV/m, which is more than ten times larger than the observed *Eperp* value. Note that the model of *Cummings et al.* [1969] produces even larger *Eperp* values (see also *Cahill et al.* [1986]). Although the model of Allan and Knox we used is for $L = 4$, the observed *Eperp* for the wave packet between 1700 UT and 1740 UT is obviously much less than what field line resonance theory predicts and thus is puzzling.

Wave signatures on the ground are more complicated, containing more frequency components than those observed by DE 1. Although the spacecraft crossed magnetic shells at points roughly conjugate to several stations, the waves seen most strongly in space were often not the strongest signals seen on the ground. The broadband nature of the ground observations suggests that the ground stations also detected oscillations of the adjacent field lines, and during magnetically active periods, the effects of the adjacent field lines became stronger. This "spatial integration" of pulsation signals by ground magnetometers has been discussed in detail by *Poulter and Allan* [1985].

We note that the major frequencies of pulsations at ground stations were latitude dependent. Figure 9 shows, for example, that periods of pulsations after 1530 UT from stations SAH to TLK decreased with magnetic latitude and thus with L values. This can also be seen from Table 3. The first (the strongest) frequency component of H or X components for the first six stations tends to increase with decreasing L. However, the frequency components seem to remain nearly constant for more than 1 to 2 hours at each station, while the period of the waves seen in space decreased during this interval. This suggests that the changing periods seen in space by DE 1 were clearly L-related and not temporally varying. College search coil data, which have 10-s resolution and suppressed long-period components, have shown that magnetic field lines at College station ($L = 5.6$) had been oscillating for about 2 hours at 6.5 mHz, which was very close to the frequency observed by DE 1 when the spacecraft moved near the nominal L shell where College is located. DE 1 crossed $L = 5.6$ at about 1758 UT when it saw a wave packet at ~260-s period weakening, and at a slightly later time, saw another wave packet with a period of ~ 150 s (6.5 mHz). The latter is probably the one we saw the College data, and they are both left-handed polarized. The above observations support the idea that magnetic shells in the magnetosphere were oscillating independently while being driven by a broadband source. DE 1, traversing a large range of L shells, observed field lines oscillating at their eigenfrequencies, and the coupling between adjacent oscillating shells seems to be weak.

The small negative bays in H components seen at 1527 UT at ground stations are believed to be caused by a westward electrojet in the ionosphere. The associated bursts of the pulsations were seen to propagate westward. In Figure 13 we compare the signals between 1500 UT and 1800 UT recorded at Fort Simpson (solid line) and at

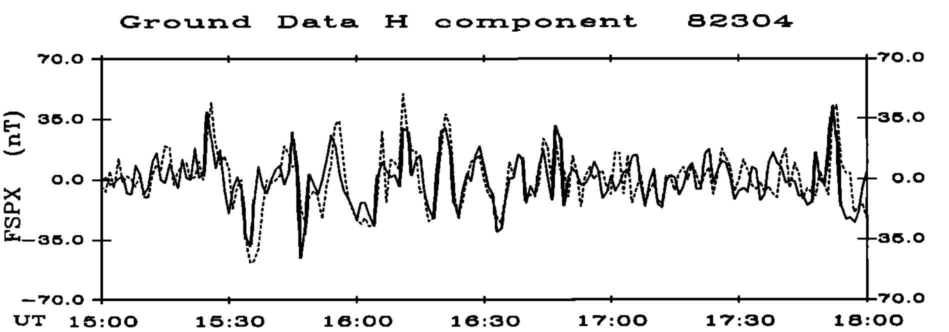

Figure 13. Comparison between north-south components of magnetic field variations at Fort Simpson (solid line) and College (dashed line).

College (dashed line) which are about 34° apart in longitude. The signal at FSP is seen to lead that of COL which means that the waves propagated westward. The time difference is not more than 1 min, the time resolution of the data. The two stations are at about 64° geographic latitude and are separated by about 1660 km. Thus the westward velocity of the wave structure was at least 27 km/s.

The substorm signatures on the ground (starting at the times marked by arrows in Figure 7) have been associated with the southward turning of IMF Bz. By examining geomagnetic indices AU and AL (shown in Figure 14 along with AE index) and geomagnetic records in Figure 7 and 8, it seems that the substorm in this study developed in two steps, a growth phase and an expansion phase. During the growth phase, between ~ 1730 UT and 1826 UT, the eastward Hall current developed at higher latitudes (invariant latitudes > 69°) at SAH, CPY, INK, and NOW, and the westward Hall current developed at lower latitude at COL, with the vortex center near FYU (INV ~67°). Starting from ~ 1740 UT, DE 1 observed a large increase in $dB\theta$, indicating an increased stretching out of field lines during this growth phase. The expansion phase (after about 1826 UT as seen from AL or AE indices) was manifested by the onset of a sharp intensification of the westward electrojet at COL. During this expansion phase, intensifications of long-period magnetic fluctuations were seen at all stations (Figures 9 and 10). However, such strong intensifications of pulsations were not observed in space. Instead, at about 1820 UT the last wave packet with 150-s period decayed rapidly. This may imply that the large fluctuations seen relatively worldwide on the ground were caused by the variation of an ionospheric current system which closed itself mainly on the ionosphere and thus had little effects on the current observed at DE which was in the conjugate magnetosphere.

SUMMARY

The pulsations we studied apparently were excited by variations of solar wind dynamic pressure and magnetic field. A sudden increase in the solar wind velocity and solar wind pressure at ~ 1345 UT and an intensification of fluctuations in the solar wind parameters at ~ 1530 UT initiated two bursts of pulsations on the ground; a southward turning of IMF Bz at ~ 1740 UT, which apparently triggered a substorm, excited another burst of long-period pulsations on the ground but not seen in space.

In response to the above solar wind variations, magnetic shells in the magnetosphere resonated at their own eigenfrequencies. DE 1, traveling inbound across a large range of L shells, thus observed azimuthal field line oscillations with periods decreasing with L values. The oscillating L shells seemed to interact very little with each other since the period changes occurred on closely adjacent field lines. The toroidal oscillations were preceded by decaying compressional waves seen in the outer magnetosphere. The compressional waves might have coupled with the transverse oscillations, transferring the energy to the resonating field lines.

Moving inbound, DE 1 appears to have entered a closed field line region from an open field line region at about 1619 UT and L ~ 11.2. On entering the closed field line region DE 1 observed propagating waves which had a strong poloidal component with a period of 110 s. The waves propagated along the ambient field lines toward the southern hemisphere. Azimuthal pulsations were observed by DE 1 on both sides of the plasmapause density gradient. The observed wave period before DE 1 entered the plasmasphere suggests that there was a gradual plasma density gradient just outside the plasmapause.

Pulsations on the ground were very irregular in contrast to those observed in space which were quasi-sinusoidal. The ground signals observed by the stations in regions conjugate to the path of DE 1 contained more frequency components than those observed by DE 1 but included those frequencies observed by DE 1 at the corresponding L shell. The broadband nature of the ground pulsations may have been the effect of the magnetometer sensing the oscillations of the adjacent field lines. The L-dependent but roughly constant major frequencies of pulsations at ground stations justified that the changing periods seen in space by DE 1 were L-related and not temporally varying.

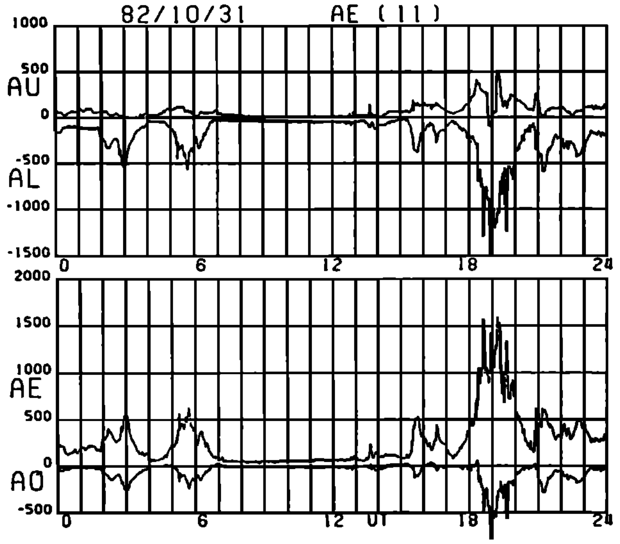

Figure 14. Geomagnetic indices for October 31, 1982. The upper panel shows the AU and AL indices. The lower panel shows the AE and A_0 (defined as $(AU + AL)/2$) indices.

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