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STUDIES OF ULF WAVES WITH AMPTE CCE SPACECRAFT: REVIEW OF SPACECRAFT OBSERVATIONS AND OUTLOOK ON GROUND/SPACE STUDIES

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Abstract: Studies of ULF pulsations based on observations with the AMPTE CCE spacecraft are reviewed and suggestions are made for future ground/satellite studies of ULF waves. CCE is an elliptically orbiting satellite with an apogee of 8.8 R_E and a low-inclination of 4.8°. These orbital characteristics make the spacecraft very useful for examining the spatial variation of ULF wave properties. Wave types reviewed in this paper include transverse Pc 3–5 waves, compressional Pc 5 waves, and Pi 2 waves. Possible subjects of future ground/satellite studies include giant pulsations and Pc 1 waves. Some preliminary results are presented using data from Syowa and other ground-based stations.

1. Introduction

Since launched in August 1984, the AMPTE CCE spacecraft has provided a wealth of data suited for studying ULF waves in the magnetosphere. In this paper we will review the highlights of the published results from the CCE experiments and will make suggestions for future studies involving CCE and ground-based data sets.

The uniqueness of the CCE data set comes from the orbit of the spacecraft itself. Figure 1 shows examples of CCE orbits plotted at ~50-day intervals from September 1984 to May 1988. The spacecraft has an orbital period of 15.7 h, a perigee of 1.2 R_E geocentric, an apogee of 8.8 R_E, and an inclination of 4.8°, covering magnetic latitudes of ±16°. The orbit precession is 0.8°/day. Previous studies of magnetospheric ULF waves used geostationary satellites and other earth-orbiting satellites, but not many spacecraft covered the radial distances of 4–8 R_E at the near-equator latitudes. The magnetic equator is the site of particle trapping, weakest magnetic field, high-β, and therefore the likely region of wave excitation. The fact that the magnetic equator is repeatedly crossed by CCE makes the spacecraft very useful for studying the latitudinal structure of ULF waves and plasma instabilities localized near the equator. CCE has completed three rotations in local time and we now have a comprehensive data base for statistical studies and ground-satellite correlations.

The scientific instruments carried by the spacecraft and used for studies of ULF waves include the fluxgate magnetometer (POTEMRA *et al.*, 1985), the medium energy-particle analyzer (MEPA) (MCENTIRE *et al.*, 1985), the hot plasma composition experiment (SHELLEY *et al.*, 1985), the charge-energy-mass spectrometer for 0.3–300 keV/e ions (GLOECKLER *et al.*, 1985), and the plasma wave detector (SCARF, 1985). While

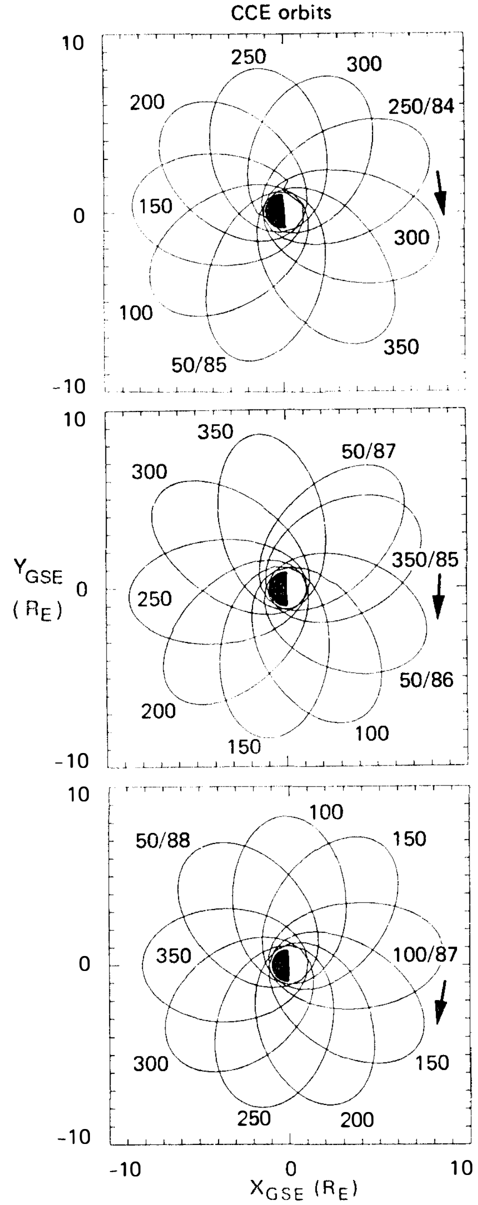

Fig. 1. Orbits of AMPTE CCE at 50-day intervals projected into the geocentric solar ecliptic x-y plane. The orbit precesses in the direction shown by an arrow, at a rate of 0.8°/day.

ULF waves are identified primarily from the magnetic field data, the other experiments provide information on the ambient plasma. For some cases, it is possible to use the particle data for inferring the electric field and the spatial structure of the waves.

2. Review of CCE Results

The magnetometer data have been plotted as time series and dynamic spectra have been generated on a routine basis. Different types of ULF waves are found in this process and the following results have been obtained.

2.1. *Alfvén resonances generated by external sources*

AMPTE CCE has observed multiharmonic toroidal Alfvén resonances previously

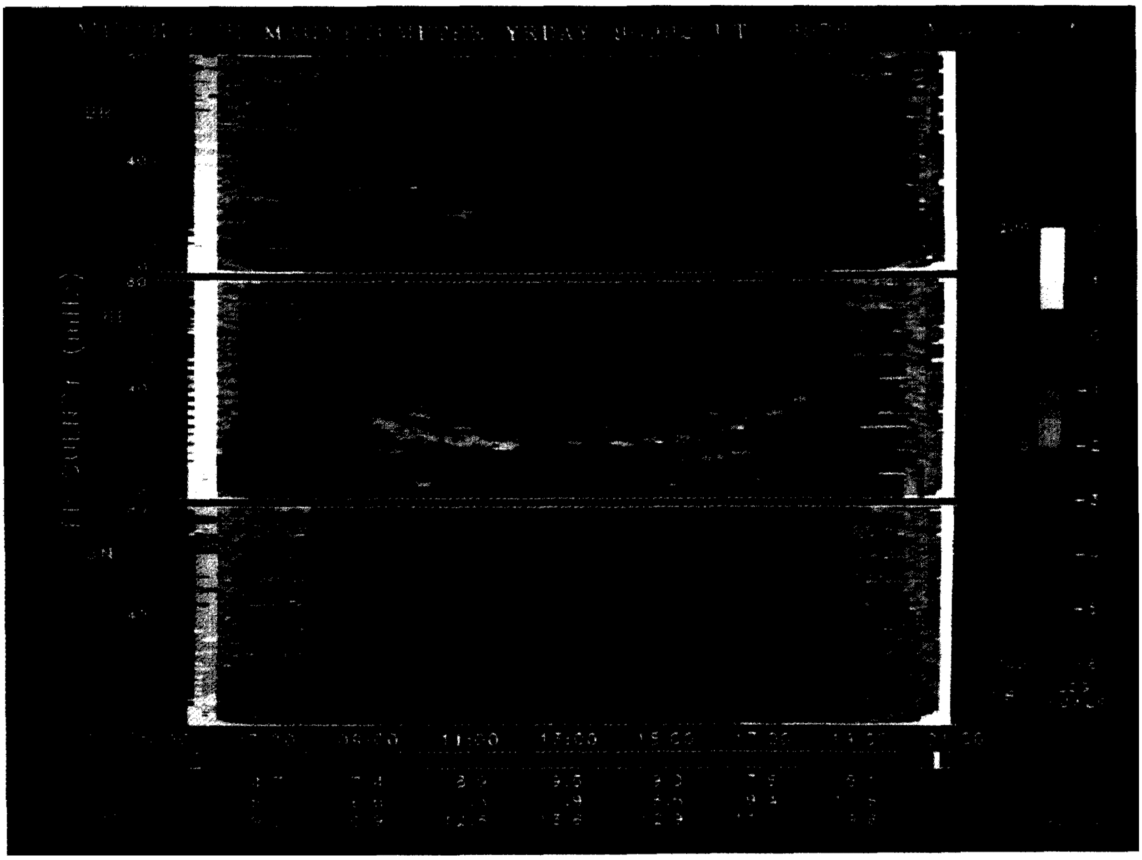

Fig. 2. Representative dynamic spectra for the magnetic field data from AMPTE CCE. The vertical scale is linear frequency from 0 to 80 mHz, and the three panels give the radial (top) azimuthal (middle) and the magnetic field-aligned (bottom) components. See ENGEBRETSON *et al. (1986) for the calculation of the spectra.*

observed near geostationary orbit (TAKAHASHI and MCPHERRON, 1982; CAHILL *et al.*, 1986) and firmly established that they are the most commonly excited Pc 3–5 ULF waves in the dayside magnetosphere form inside the plasmapause to the magnetopause (ENGEBRETSON *et al.*, 1986, 1987; ZANETTI *et al.*, 1987). One example of a dynamic spectrum for a full orbit of CCE magnetic field data is shown in Fig. 2. The distinctive structure in the azimuthal component, consisting of several frequency components, corresponds to the fundamental and the harmonics of the local toroidal Alfvén resonances. The L-dependence of the frequency and the latitude dependence of wave amplitude are unambiguous evidence for local standing Alfvén waves.

Regarding the excitation mechanisms of these pulsations, ENGEBRETSON *et al.* (1987) studied three orbits of CCE data for which simultaneous solar wind data were available from AMPTE IRM. They found that both the direction of the interplanetary magnetic field and the velocity of the solar wind control the amplitude of the harmonically structured pulsations. Also a comprehensive statistical study of the resonant harmonic waves was done by ANDERSON *et al.* (1988). They categorized the pulsations into several classes, depending on the strength of different harmonics. Their results are reproduced in Fig. 3. At the top is the coverage of magnetic field obser-

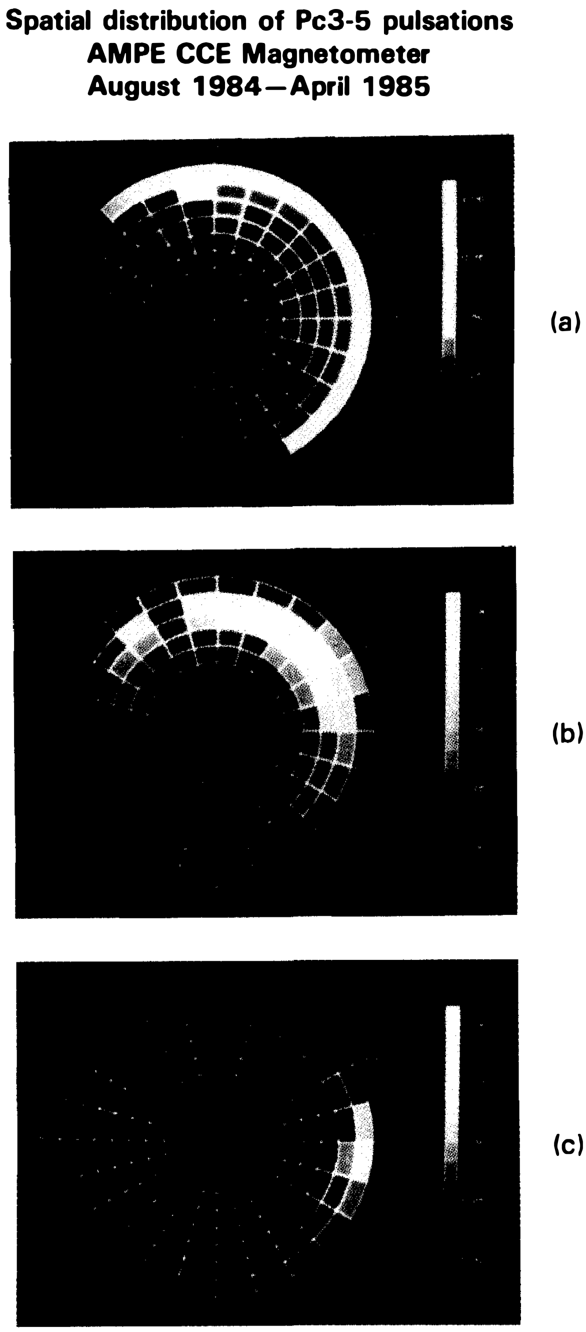

Fig. 3. Statistical summary of the local time and L dependence of the amplitude of multiharmonic toroidal oscillations (modified from ANDERSON *et al., 1988). Three quantities are shown using a gray-scale key given on the right. (a): Distribution of the spacecraft location. (b): Distribution of multiharmonic resonances with weak fundamental power. (c) Distribution of multiharmonic resonances with strong fundamental power.*

vations in the local time-L space, and at the center and bottom, respectively, are the occurrence frequencies of harmonic resonances with weak and strong fundamental. Higher occurrence probability is indicated by a brighter key of the gray scale. Near noon, the fundamental mode has a weak power whereas at the flank (0600 MLT), the fundamental mode has a strong power. On these observational bases it was suggested that although the pulsations usually consist of several harmonics of local toroidal resonances within the local time range covered in the study, there can be two different source mechanisms generating different harmonic modes at different local times. The dayside source may be related to the bow-shock-associated upstream waves while the flankside strong fundamental waves may be generated by the Kelvin-Helmholtz instability.

A semi-statistical study of Viking magnetic field data and CCE magnetic field data also demonstrated that the fundamental toroidal mode Pc 3–5 waves are commonly generated in the morning sector (POTEMRA *et al.*, 1988). In this study, it was further shown that the ULF waves are localized at the interface between the region 1/region 2 field-aligned current systems. The result supports the Kelvin-Helmholtz instability as the source mechanism, since the interface is considered to be a region of strong velocity shear.

In the above-mentioned studies, the energy sources for the toroidal resonances are considered to be present in a continuous fashion. Recently, much attention has been paid to impulsively excited toroidal resonances (*e.g.*, KIVELSON and SOUTHWOOD, 1985). There are two major questions addressed in this subject. One is whether impulses represent convected plasma structures in the solar wind or something generated near the bow-shock or the magnetopause. POTEMRA *et al.* (1989) showed an example of a

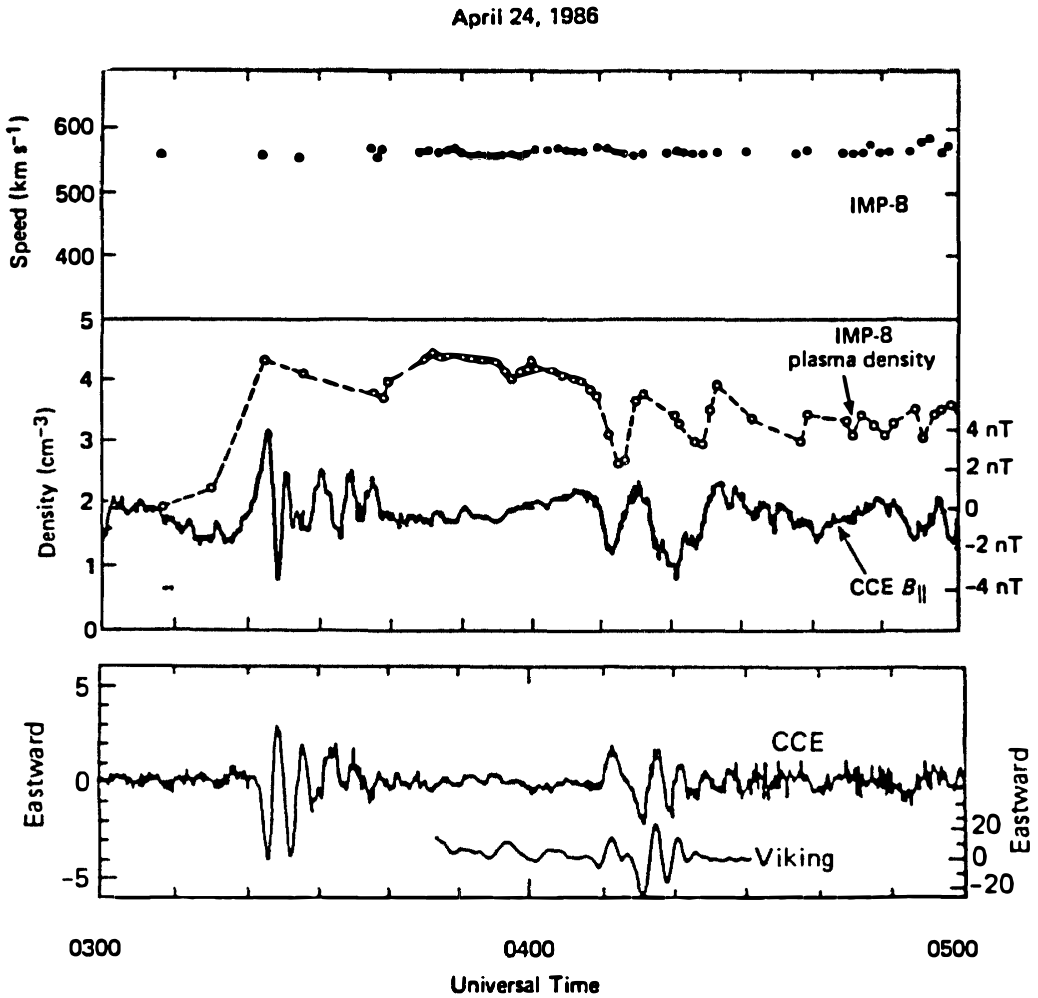

Fig. 4. The relationship between solar wind bulk velocity (top) and solar wind plasma density (middle) measured by the IMP-8 satellite, and magnetospheric field variations as observed by CCE and Viking (middle and bottom). The figure is a modified version from POTEMRA *et al. (1989).*

magnetic pulsation unambiguously excited by a dynamic pressure change imbedded in the solar wind. The relation between magnetospheric ULF pulsations and the changes in the solar wind density (*i.e.*, the major factor for the changes in the dynamic pressure in that particular circumstance) in their work is reproduced in Fig. 4. Note that transient toroidal oscillations follow solar wind density changes at 0320 and 0410 UT. In another study SIBECK *et al.* (1989) observed large-amplitude dynamic pressure variations near the bow shock, which were correlated with magnetospheric magnetic field pulses on a one-to-one basis. The pressure variations appear to have been generated in the vicinity of the bow shock. Other examples of dynamic pressure variations near the bow-shock and their correlation with magnetospheric magnetic field variations have been found, and it has been suggested that an unsteady interaction of the solar wind with the magnetopause/bow shock may account for many of magnetic pulses observed in the magnetosphere (FAIRFIELD *et al.*, 1988). Thus some doubt has been cast on the interpretation of transient ULF pulsations as the result of patchy reconnection on the magnetopause (RUSSELL and ELPHIC, 1979).

The other question is whether the impulses first generate global resonance modes and then couple to local standing Alfvén waves (*e.g.*, KIVELSON and SOUTHWOOD, 1985). The question of the coupling was critically examined by ENGEBRETSON *et al.* (1986) and by TAKAHASHI *et al.* (1988b). ENGEBRETSON *et al.* (1986) concluded that there was no evidence of the global mode in the dynamic spectra of the CCE magnetic field data. That is, no dynamic spectrum showed a frequency component in B_{Total} that remained constant across L shells. TAKAHASHI *et al.* (1988b) reported a coexistence of a compressional magnetic pulsation and a toroidal Alfvén resonance. However, they concluded that these two waves cannot be coupled because of frequency mismatch. They suggested that the toroidal resonances represent transient oscillations caused by external pressure variations. Thus we have been unable to find direct evidence of the global mode.

2.2. *Substorm-associated pulsations*

Impulsive excitation of Alfvén waves is not limited to the dayside magnetosphere. In fact, it has been suggested that standing Alfvén waves are generated at the onset of magnetospheric substorms (ROSTOKER, 1967). This idea has been verified by a recent CCE observation (TAKAHASHI *et al.*, 1988a). In this study ion data from MEPA were used to infer the $\boldsymbol{E}\times\boldsymbol{B}$ drift motion of the plasma associated with magnetic pulsations (see also LOPEZ *et al.*, 1986). Figure 5 shows a sequence of magnetospheric ULF waves associated with substorms. Immediately following the injection of energetic ions at 0136 and 0219 UT, there is an oscillation in the dawn-dusk anisotropy of the ion flux. This oscillation originates from a dawn-dusk oscillation of the local flux tube. The inferred flux tube motion and the observed magnetic field oscillation had an amplitude and phase relation which is consistent with a fundamental mode standing Alfvén wave. The period of the oscillation at CCE is found to be longer than that observed at Syowa ($L\sim6$), when CCE was at $L>6$. This supports the view that CCE observed a local resonance.

In another case study of a substorm event, TAKAHASHI *et al.* (1987c) found a large-amplitude 13-s compressional oscillation in the magnetic field at $L\sim8$ and near mid-

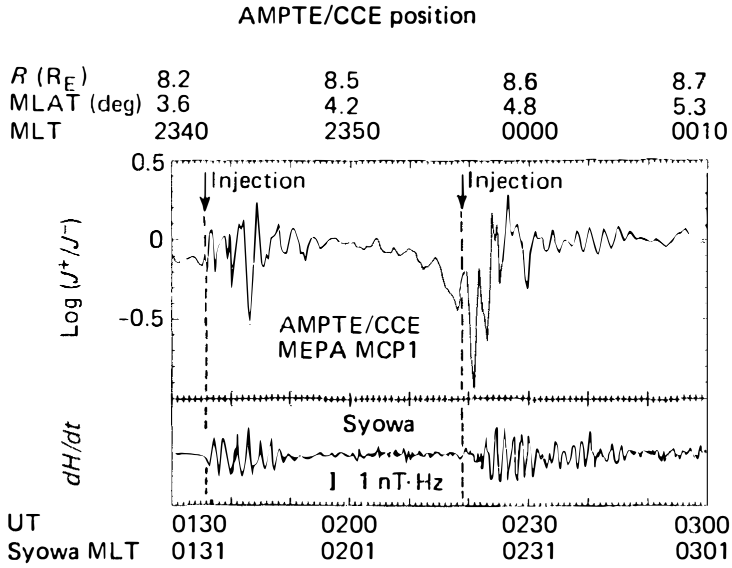

Fig. 5. Examples of substorm-associated ULF waves observed in the near-earth magnetotail by CCE and on the ground at Syowa. Injection of energetic ions observed in CCE signals at the onset of a magnetospheric substorm (after TAKAHASHI et al., *1988a). The dusk/dawn anisotropy of J^+/J^- is caused by an azimuthal oscillation of the flux tube at the local Alfvén resonance frequency. Pi 2 pulsations are seen at Syowa, starting nearly simultaneously with the oscillations at CCE. However, the wave frequencies in the magnetosphere and on the ground are different.*

night. Magnetic pulsations of a nearly identical period were simultaneously observed on the ground at low latitudes (YUMOTO *et al.*, 1988) as shown in Fig. 6. For this case, it has been argued that the low-latitude pulsation is due to field line resonance caused by a distant monochromatic source wave.

2.3. *Pulsations excited by local plasma instabilities*

So far, we have discussed magnetic pulsations whose origin can be attributed to external disturbances or waves. In this section we describe pulsations which are generated by local plasma instabilities. One good example is compressional Pc 5 waves, which have previously been studied with geostationary satellites (*e.g.*, BARFIELD and MCPHERRON, 1972). The combined magnetic and particle observations from CCE have led to a new understanding of the wave properties at L=8–9. The upper panel of Fig. 7 shows magnetic field and ion data for a compressional Pc 5 wave observed in the postmidnight sector (TAKAHASHI *et al.*, 1987b). The compressional component (δB_Z) oscillates at the second harmonic frequency of the transverse components. From a survey of CCE magnetic field data obtained at magnetic latitudes ranging from $-16°$ to 16°, we confirmed that the second harmonic is observed at the magnetic equator (TAKAHASHI *et al.*, 1987a). The origin of the second harmonic has been attributed to a nonlinear effect associated with an antisymmetric linear mode drift-mirror wave (CHENG and LIN, 1988).

A new observation made by CCE on compressional Pc 5 waves is that they propagate eastward in the dawn-sector, when seen from the spacecraft. An ion remote sensing technique has been used for determining the direction of the wave propagation

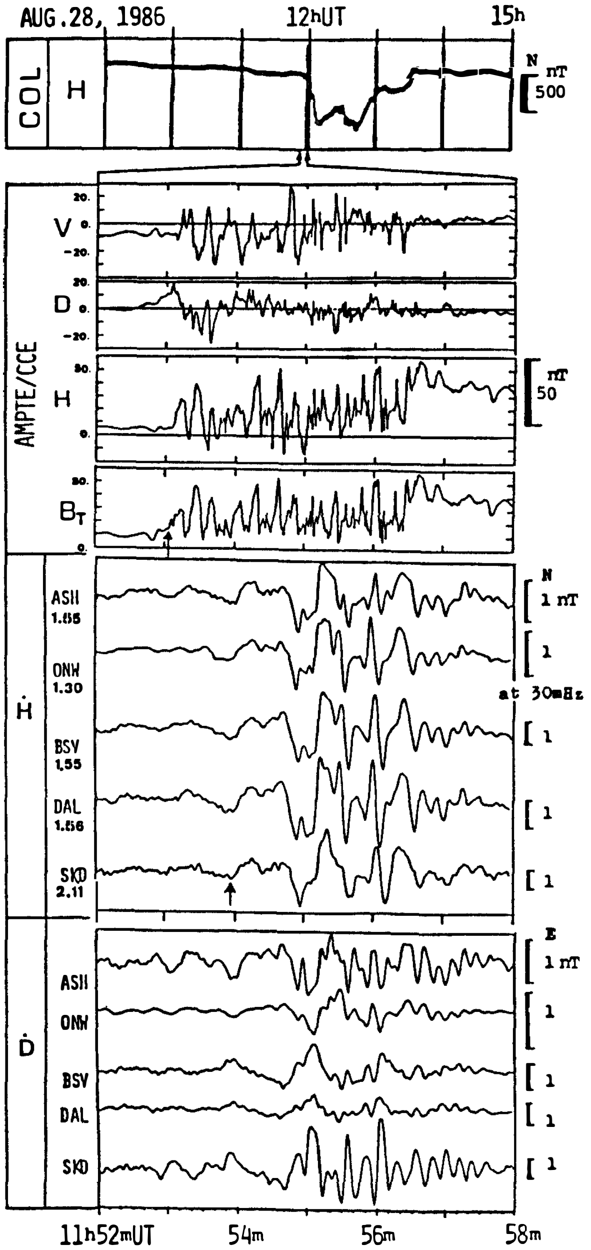

Fig. 6. Thirteen-second magnetic field oscillations observed simultaneously at CCE at L∼8 and on the ground at L=1.6–2.1 at the onset of a substorm (after YUMOTO *et al., 1988).*

(TAKAHASHI *et al.*, 1987b). The lower left panel of Fig. 7 illustrates how this technique works. Since the spin axis of the spacecraft is within 10–30° of the sun-earth line and the particle detector has a look direction perpendicular to the spin axis, the guiding center of ions entering the detector are at the "X" locations in the figure. Thus flux oscillations observed at CCE carries information on the spatial phase of the wave. If the perpendicular wavelength of a ULF wave is comparable to the Larmor radius of the observed ions, then the phase of ion flux oscillations measured at different gyrophases must be different. This actually occurs for compressional Pc 5 waves. As can be seen in the lower right panel of Fig. 7, there is a time lag between oscillations westward and eastward of the spacecraft, and the result has been taken as evidence for eastward propagation. Our interpretation of this result is that the waves are west-

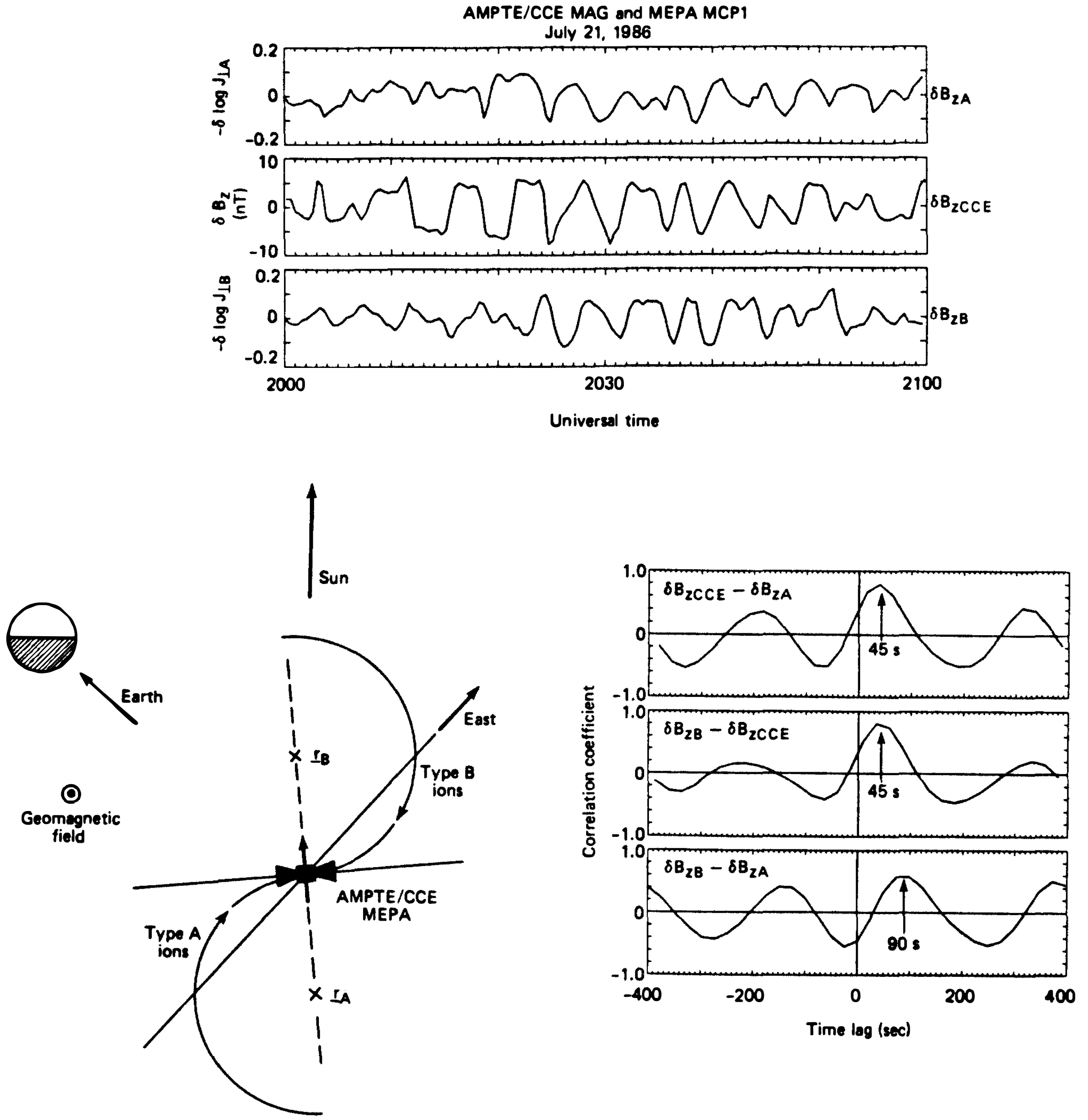

Fig. 7. Magnetic field and ion flux perturbations for a compressional Pc 5 wave event (top), the geometry of ion flux measurements (bottom left), and the cross correlations between ion fluxes and magnetic field (bottom right) (after TAKAHASHI *et al., 1987b). The positive time lag 45 s, or 90 s, implies that the phase front of the wave propagated eastward.*

ward-propagating in the plasma rest-frame but the $\boldsymbol{E}\times\boldsymbol{B}$ drift of the plasma causes a strong Doppler shift.

Another type of pulsations, which are probably excited internally, have been studied by ENGEBRETSON *et al.* (1988). The waves are almost purely transverse, radially polarized, and are observed near the magnetic equator. The waves are consistent with the second-harmonic standing Alfvén waves excited on a local field line, with a possible latitudinal localization of the wave amplitude by equatorially trapped warm plasma. It has been suggested that these waves are excited by drift instabilities or bounce resonance mechanism when freshly injected energetic ions enter the region of trapped warm ions.

3. Future Studies

In this section we comment on studies which are currently undertaken or planned for the future. Preliminary results are presented and suggestions made on how ground based observations should be used in conjunction with CCE data. One advantage of CCE is that it is not geostationary, but it crosses L shells at various local times. Thus a given ground-based station has a high possibility of having CCE nearly in the same magnetic meridian sometime during the operation period of CCE.

An example of the occurrence of such near-conjunction condition is illustrated for Syowa Station in Fig. 8. The definition of near-conjunction in this case is $\Delta L=\pm 1$, ΔMLT$=\pm 1$ hour.

3.1. Pi 2 pulsations

Preliminary results have already been obtained on the relationship between Pi 2 pulsations on the ground and substorm-associated ULF distrurbances in the near-earth magnetotail (TAKAHASHI *et al.*, 1988a; YUMOTO *et al.*, 1988). One question on Pi 2 pulsations is how they propagate from the nightside to the dayside, especially at mid- and low-latitudes. To answer the question, one may look for Pi 2 signals in CCE data taken within geosynchronous orbit at various local times at substorm onsets. The nature of Pi 2 pulsations at $L<6$ is little known except for several cases reported by LIN and CAHILL (1975).

3.2. Giant pulsations

In spite of a long history of research, the origin of giant pulsations remains unidentified. One major reason for this is lack of observations in space. There are only two Pg events observed so far simultaneously on the ground and in space (LANZEROTTI and TARTAGLIA, 1972; HILLEBRAND *et al.*, 1982). It will be of great importance to use CCE data to study the excitation mechanism of giant pulsations. Because the pulsations are identified from their unique sinusoidal waveforms observed on the

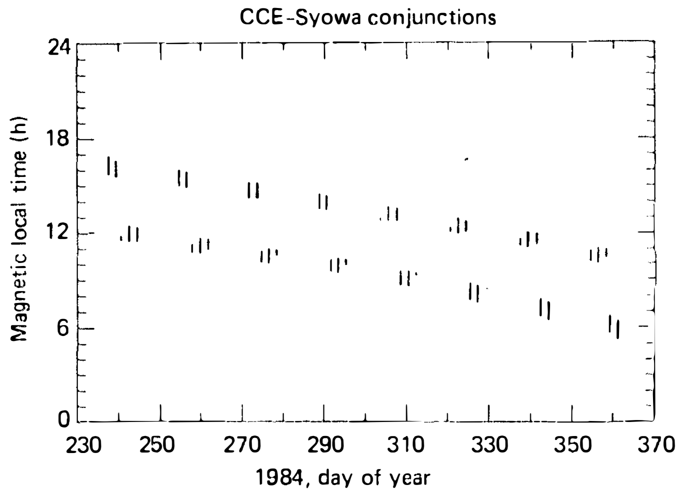

Fig. 8. A diagram showing near-conjunctions of Syowa and CCE in 1984. The plotted segments of CCE orbits correspond to the intervals when the spacecraft was within 1 hour of magnetic local time and within 1 in L value with respect to Syowa.

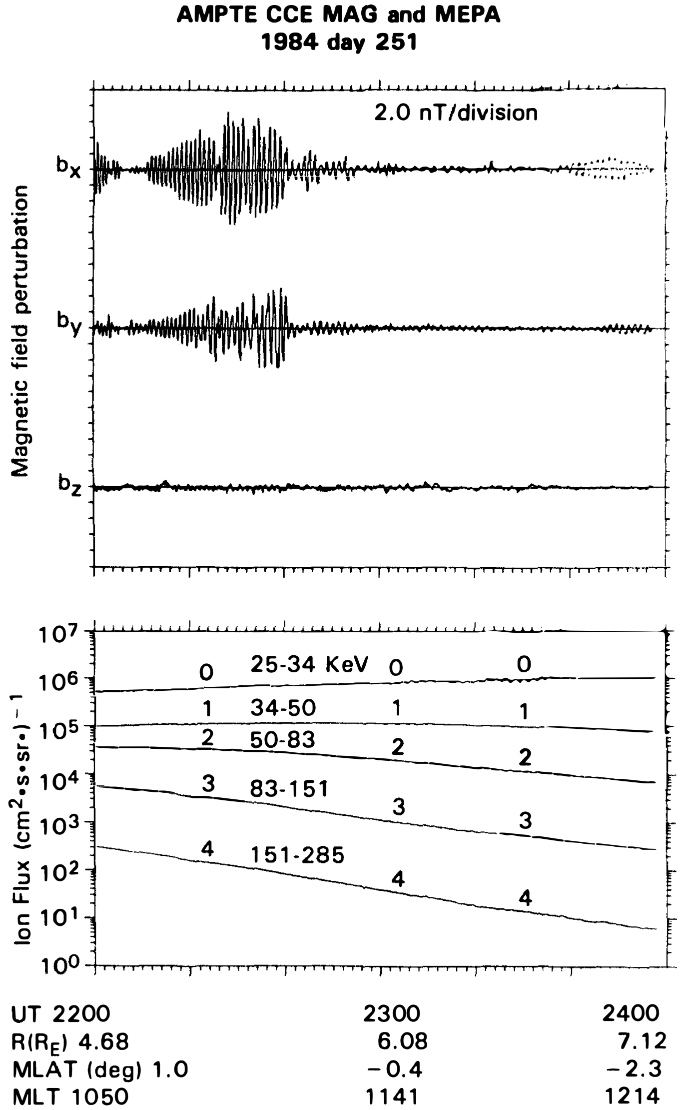

Fig. 9. Magnetic field (top) and ion fluxes (bottom) for a 2-hour interval of Pc 4 activity. The particle data are the spin-averaged flux of ions at various energies for the five energy bands of the MEPA energy channels, 25–34 keV (ECH0), 34–50 keV (ECH1), 50–83 keV (ECH2), 83–151 keV (ECH3) and 151–285 keV (ECH4). The magnetic field data consist of the radial (R), azimuthal (A), and the field aligned (P) components in the mean-field aligned system. An ion flux fluctuation is present between 2300 and 2340 UT, most clearly in the 25–34 keV. There is no clear magnetic pulsation in this interval. However, transverse Pc 4 magnetic pulsations are present before and after the ion flux pulsation. These magnetic pulsations have been studied by ENGEBRETSON *et al. (1988).*

ground, we must first look for giant pulsations in ground-based data and then examine spacecraft data to see if there is a corresponding oscillation. Since a number of pulsation types give a fairly sinusoidal waveform, it is not appropriate to start the survey from the satellite data.

Figure 9 shows an example of an ion flux pulsation potentially related to a giant pulsation. In the lower panel, a flux oscillation with a 110-s period was present at 2300–2340 UT in the 25–34 keV channel. In this interval there was no obvious mag-

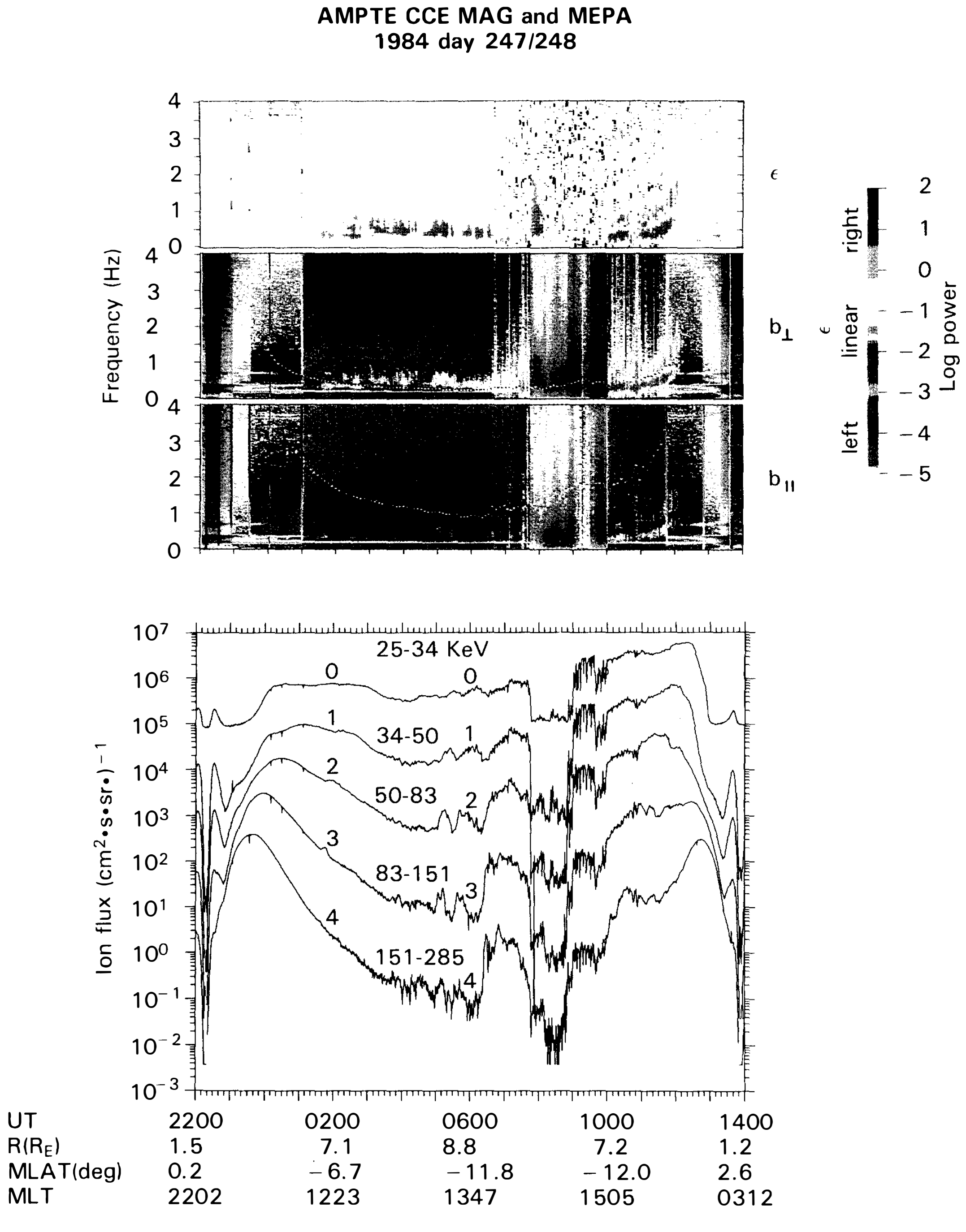

Fig. 10. Dynamic spectra showing intermittent Pc 1 waves over a large portion of the CCE orbit (top) and the spin-averaged ion fluxes for the same time interval (bottom). The format for the particle data is the same as in Fig. 9. The dotted lines in the panels for $b_\perp$ and $b_\parallel$ are the gyrofrequencies for H_e^+ and H^+. See text for the detail of the magnetic field spectra. The ion flux enhancement starting at 0400 UT is caused by a compression of the magnetosphere. The Ion flux dropout between 0740 and 0850 indicates that the spacecraft was outside the magnetosphere.

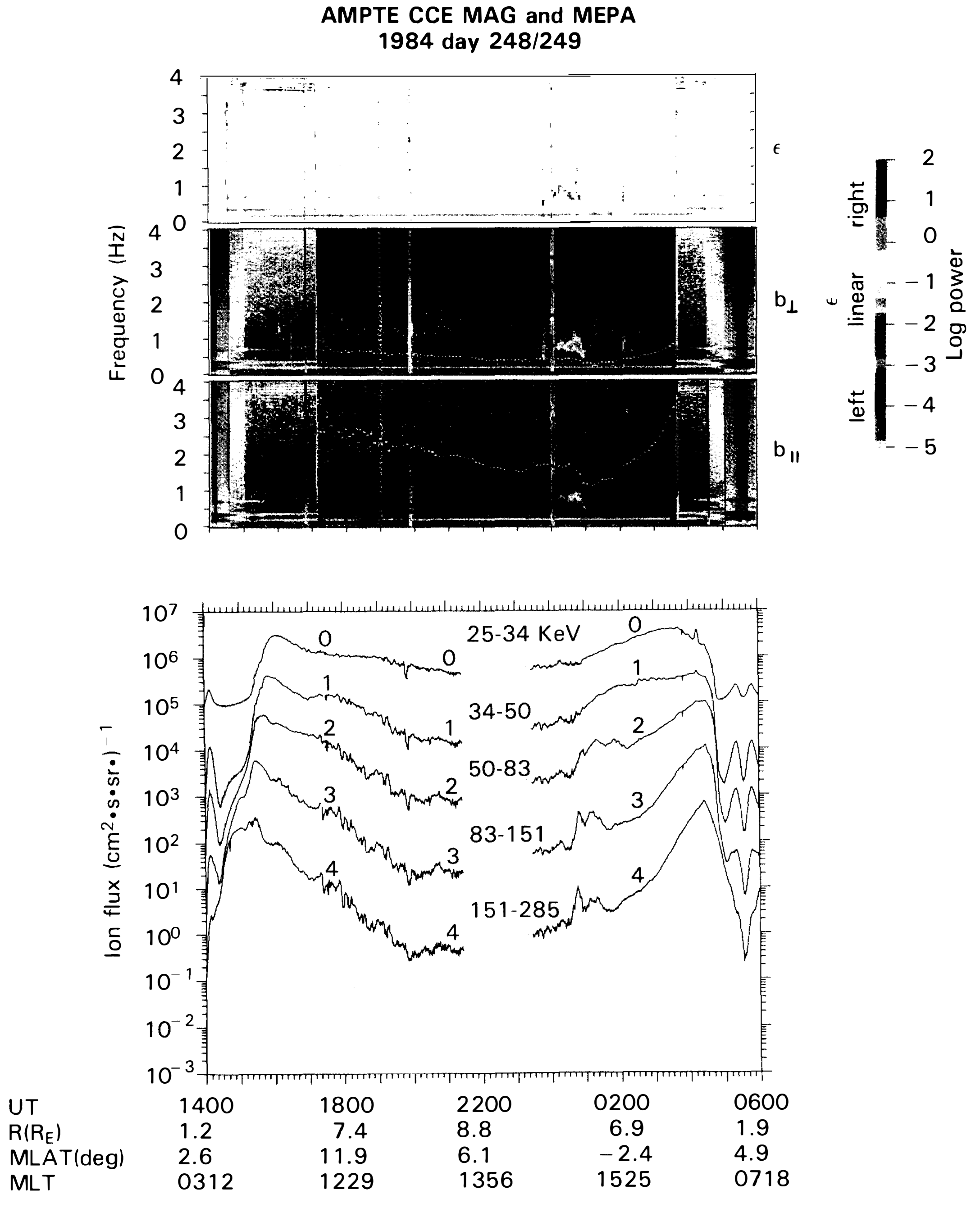

Fig. 11. Dynamic spectra showing isolated Pc 1 waves. The format is the same as in Fig. 10.

netic pulsation, as shown in the upper panel. The magnetic field data are characterized by 60-s transverse oscillations before and after the ion flux oscillation. The magnetic pulsations have been identified as the second harmonic standing Alfvén wave (ENGEBRETSON *et al.*, 1988). Interestingly, a giant pulsation was observed at Syowa and at its conjugate stations at the same local time and L value as the CCE ion flux event, but

12 hours earlier in universal time (TONEGAWA and SATO, 1987). Although we are unable to identify the exact physical mechanism of the flux oscillation, it appears to be caused by a radial convection of a flux density gradient. TONEGAWA and SATO (1987) have concluded that their event had an odd-mode standing wave structure, and we wish to determine whether the ion flux oscillation is consistent with the standing wave.

3.3. *Pc 1 pulsations*

Satellite observations of Pc 1 activity have been made previously by several groups. The geosynchronous satellites ATS-1, ATS-6, and GEOS 2 as well as GEOS 1 and OGO 5 have all observed ion cyclotron waves (ICW) in the Pc 1 band. Data from ATS-1 was used to make a statistical survey of ICW events at geosynchronous orbit (BOSSEN *et al.*, 1976). Subsequent work using ATS-6 data (FRASER and MCPHERRON, 1982; FRASER, 1985) has shown that a source region of the pulsations is located in the equatorial region near the plasmapause. The proximity of the source region to the plasmapause was inferred by these workers from a diurnal variation strongly favoring the afternoon and early evening when the afternoon bulge in the plasmasphere extends out to and beyond 6.6 R_E during low to moderate geomagnetic activity. Pc 1–2 events have been observed by OGO 5 in the afternoon sector from 0° to 30° magnetic latitude and over a wide range of L shells (L=7.1 to 13.7) (KAYE and KIVELSON, 1979). GEOS 1 and 2 data were used by YOUNG *et al.* (1981) and ROUX *et al.* (1982) to investigate details of the wave particle interaction and propagation characteristics of ICW's in several events. Data from the AMPTE CCE satellite will allow us to characterize the equatorial source region of Pc 1 pulsations from L=3–9 at all local times. Such a comprehensive picture of Pc 1 activity in the equatorial magnetosphere is needed since the majority of previous observations were made using geosynchronous spacecraft.

Figures 10 and 11 present examples of dynamic spectra for two orbits of the CCE satellite together with plots of the corresponding MEPA particle data. The magnetic field experiment obtains complete vector measurements every 0.124 s yielding a Nyquist frequency of just over 4 Hz. Data is despun and transformed into a local coordinate system in which one component, $b_{\parallel}$, is directed along the average magnetic field direction, the other two directions, $b_{\perp}$, being transverse. Six 256 point FFT power spectra are averaged for each horizontal pixel so that each pixel corresponds to a 190 second average. The three panels in the figure are from top to bottom: ellipticity in the plane transverse to $\boldsymbol{B}$ (red=$\varepsilon>0.2$, yellow=$-0.2<\varepsilon<0.2$, blue=$\varepsilon<-0.2$), transverse power, and parallel power. When the pulsations are large, the average field direction becomes less well defined and transverse power appears in the parallel component as an artifact of the analysis.

Figure 10 shows Pc 1 activity occurring intermittently beyond $L\sim6.5$ on the outbound pass. The activity between 0300 UT and 0700 UT is just above Ω_{He^+} and is predominantly left hand polarized. A strong compression occurs during the inbound pass and CCE is located outside the magnetopause from 0730–1000 UT as evidenced by intense broadband power spectra and a dropout in high energy particle fluxes. From 1000–1200 UT intense Pc 1 pulsations with a distinct gap at Ω_{He^+} are observed and are left hand polarized both above and below this gap. The high energy particle fluxes are also enhanced during this time. Figure 11 shows a second example in which several intervals of activity are observed. A very short event occurs at 1600 UT on the outbound pass and a more sustained and intense event occurs from 0000–0100 UT which is preceded and followed by several minor events. Note that MEPA observed a dispersive injection at about the same time, 0030–0130 UT but that the arrival of energetic particles occurs after the pulsations begin.

To date, 89 orbits of magnetometer data from day 248 to day 308 of 1984 have been processed in this way and the two examples presented here are typical of the data as a whole. Pc 1 pulsations are common in the outer magnetosphere, particularly for $L>7$, and occurred on 87 orbits. Outer magnetosphere pulsations appear to correlate with periods in which MEPA observes elevated fluxes and injections, but there is not a one to one correspondence between Pc 1 events and injections, suggesting that the plasmatrough Pc 1's are related to substorms but not directly to the arrival of injected particles. The relation of Pc 1's to substorm onset has been observed previously with Pc 1's occurring within and at geosynchronous orbit ~1 h after substorm onset (BOSSEN *et al.*, 1976). In addition to the plasmatrough events, pulsations have been observed by CCE near the plasmapause well inside geosynchronous orbit, with 11 observed in the morning and 12 in the evening. Plasmapause pulsations tend to be more intense than those in the plasmatrough. We have not yet found out a correlation between these plasmapause events and particle fluxes. Intense pulsation were also observed on the inbound passes after compressions on days 248, 280, 292, and 306. These compression associated events were observed throughout the outer magnetosphere from the magnetopause to near the plasmapause. In addition, these events exhibit a gap at Ω_{He^+} more clearly than the other events.

The prevalence of Pc 1 pulsation activity suggests that a reasonable number of events will be observed during AMPTE CCE-Syowa Station conjunctions providing a basis for ground-satellite coordinated studies.

4. Summary

In summary we have reviewed the highlights of ULF wave studies with CCE. It is emphasized that the orbital characteristics of the spacecraft make it unique for studying the spatial structure and occurrence of ULF waves in the magnetosphere. We also emphasize that the data coverage, especially that of the magnetometer, is very good for the entire mission of the spacecraft. This allows us to make comprehensive statistical studies of ULF waves in general, as well as to have many cases of ground-satellite conjugate observations. We have illustrated the potential of obtaining the CCE/ground data set using a few examples of wave events. We believe that a great deal will be learned about the propagation of waves from analysis of simultaneous data from ground and CCE.

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