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Ground observations of geomagnetic pulsations during a quiet magnetospheric interval correlated with satellite plasma measurements*

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Abstract. Using ground observations of Pi2, Pse, Pc5, Pc4 and Pc3 type pulsation events and simultaneous satellite plasma density and composition measurements, models of the natural eigenfrequencies of geomagnetic field lines have been compared with models of pulsation generation and damping. All the pulsations were recorded during a 10-h interval [0–10 UT on 28 November (day 322) 1977] on the Institute of Geological Sciences and University of Göttingen networks of magnetometer stations in northern Europe, which moved from approximately 0 to 12 LT. Plasma density and composition measurements were made in the plasmatrough and at the plasmapause of this region of the magnetosphere by the relaxation sounder experiment and Ion Composition Experiment on GEOS-1. The plasmapause was detected at two local times by the satellite during the selected interval, by both the plasma density measurements and the electric field experiment. Using the plasma density measurements, the variation of the natural eigenperiods of different wave modes with latitude in the plasmatrough and at the plasmapause have been calculated. The characteristics of the continuous pulsations generally corroborate the calculated eigenperiods. Oxygen ions in the plasmatrough made a significant contribution to the calculated eigenperiods. The Pi2 event provides evidence of a surface wave on the plasmapause with a period in close agreement with the calculated eigenperiod.

Key words: Eigenmode – Eigenfrequency – Eigenperiod – Plasma density – O^+ ions – Magnetic field line resonance – Surface wave – Complex demodulation

Introduction

One of the intervals selected for special study at the sixth workshop on IMS (International Magnetospheric Study) observations in northern Europe was an interval of quiet magnetospheric activity, 0–10 UT on 28 November (day 332) 1977. During this selected interval a large number of ground-based magnetometers were operational as part of the IMS. Data from the GEOS-1 satellite supported the magnetometer data for this interval. Five different pulsations were observed during the interval: a Pi2, a Pse, and Pc5, 4, and 3 events.

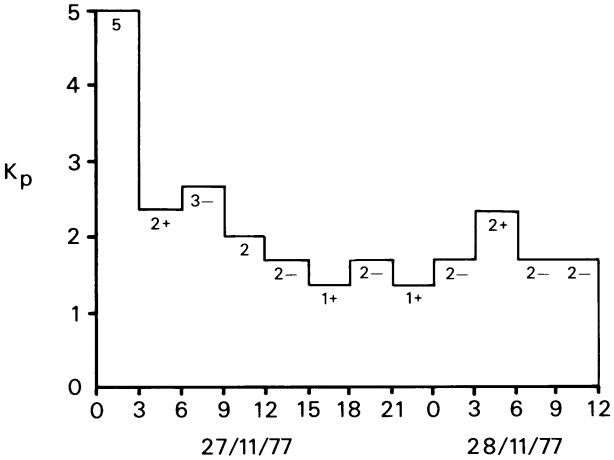

Fig. 1. The K_p values for the selected interval [0–10 UT 28 November (day 332) 1977] and for the preceding day

Figure 1 illustrates the level of magnetic activity prior to and during the selected interval, with the K_p values for 27 November and for the first half of 28 November. The values during the interval and for the previous 21 h were generally close to 2. Thus the pulsations observed during the selected interval have occurred in a 'steady state' magnetosphere, in which local time variations were more significant than universal time effects, providing an opportunity to test models of pulsation generation and damping under relatively stable conditions. In particular, we examine how flux tubes which have characteristic natural eigenperiods respond when driven by monochromatic signals. When the driving frequency matches a transverse mode eigenfrequency at a particular magnetic shell, a localised purely transverse wave will be generated. This is described as 'field line resonance' (Southwood, 1974; Chen and Hasegawa, 1974a). However, the ionosphere substantially modifies the magnetospheric wave signal in two ways: on the ground we obtain only an indirect measure of the magnetospheric wave fields, as the currents generated in the ionosphere rotate horizontal signal through 90° if the ionosphere is uniform; and the ionosphere screens short horizontal-scale variations from the ground (Hughes, 1974; Hughes and Southwood, 1976a). Damping is introduced to the magnetospheric wave as the currents in the ionosphere dissipate

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energy via Joule heating. This damping will alter the ground observations of the latitudinal profile of amplitude, phase and polarisation parameters of a field line resonance (Hughes and Southwood, 1976b; Orr and Hanson, 1981; Gough and Orr, 1984).

In analysing some of the pulsation events, the technique of complex demodulation has been used (Webb, 1979; Beamish et al., 1979) in addition to power spectral analysis. This technique provides a temporal series of estimates of the amplitude and phase of a waveform at a particular frequency. The results of this analysis, from a meridional chain of magnetometers, can be presented in the form of a contour map where contours of equal amplitude, phase or polarisation parameters are plotted in latitude and time (Hanson et al., 1979; Lester and Orr, 1981).

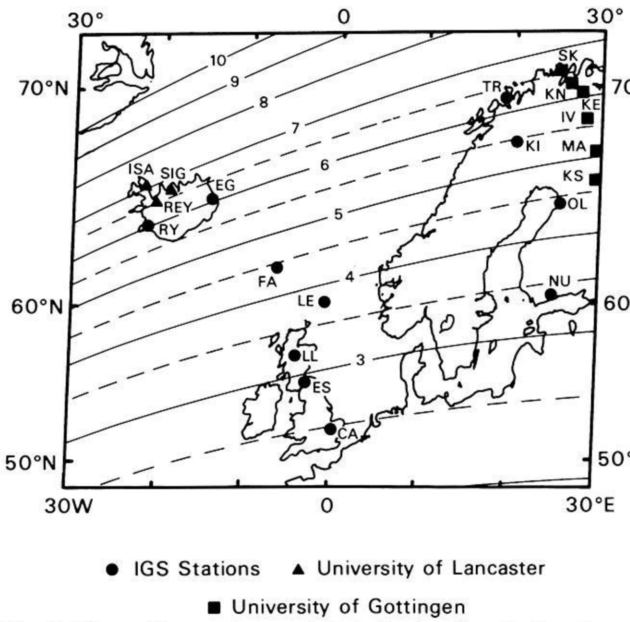

Fig. 2. Map with superimposed L-shells showing the locations of the magnetometers in northern Europe from which data are taken for the selected interval

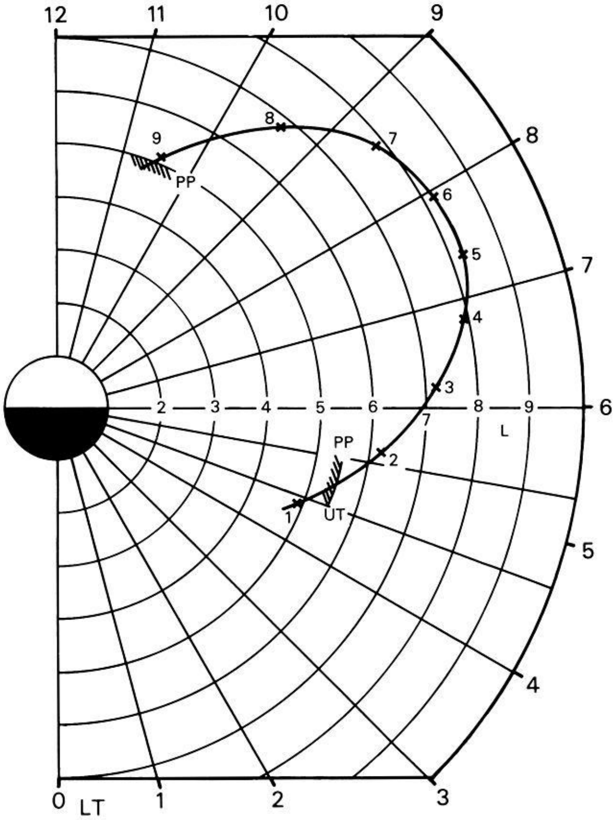

Fig. 3. The projection of the orbit of GEOS-1 on 28 November 1977 as a function of local time (with UT) and L-value. The crossings of the plasmapause as given by the electric field experiment are also shown

Magnetometer networks

Figure 2 shows the locations of all the ground-based stations in northern Europe from which data were taken for the selected interval. Data from several different magnetometer arrays have been employed. The Institute of Geological Sciences, Edinburgh, deployed a number of rubidium vapour magnetometers in the UK, Iceland, Scandinavia and Newfoundland as part of the IGS/University of York/Imperial College/British Antarctic Survey joint project for the IMS (Green, 1981 and references therein). The Institut für Geophysik of the University of Göttingen was operating a chain of six Grenet-type induction magnetometers in northern Scandinavia (Stuart, 1982) and the University of Lancaster was operating three fluxgate magnetometers on the northern coast of Iceland (Madahar and Hunter, 1982).

Essentially this gives a configuration, in Europe, of three chains, approximately along geomagnetic meridians, with a total longitudinal separation of about 30° or 2 h of local time. The western meridional chain of IGS stations through the UK to Iceland covers L-values of ~ 2.5–6.5; the central chain, the IGS Scandinavian chain, covers L-values ~ 3.3–6.5; and the eastern chain, the University of Göttingen stations in Finland and northern Norway, covers L-values ~ 4.6–6.8. The central and eastern chains are closer in longitude than either of them is to the western IGS chain.

Data were also available from stations in North America: the mid- and low-latitude stations of Bell Laboratories and the AFGL magnetometer networks and the high-latitude network of the University of Alberta. Mid-latitude data from Borok to the east of the three chains in Europe were also available.

GEOS-1

During the selected interval the European Space Agency satellite GEOS-1 was orbiting about its apogee of 7 R_e, which it reached at 5 UT. The inclination of the orbit was 26° above the equator. Figure 3 shows the projection of the GEOS-1 orbit onto the equatorial plane in L-value and local time coordinates. At 1 UT the satellite was at about 50° E geographic longitude, but by 9 UT it had moved westwards to about 20° E, approximately to the meridian of the University of Göttingen magnetometers.

Crossings of the plasmapause were detected by changes in the spacecraft potential. This is given by a probe-satellite voltage (Pedersen et al., 1978; S-300 experimenters, 1979) which, as the probe is at the plasma potential, gives the satellite potential. It is deduced that when the probe-satellite voltage has small negative values the plasma density is high and when the voltage becomes more negative the plasma is more tenuous. Using these measurements it is possible to observe that the satellite passed from the plasmasphere

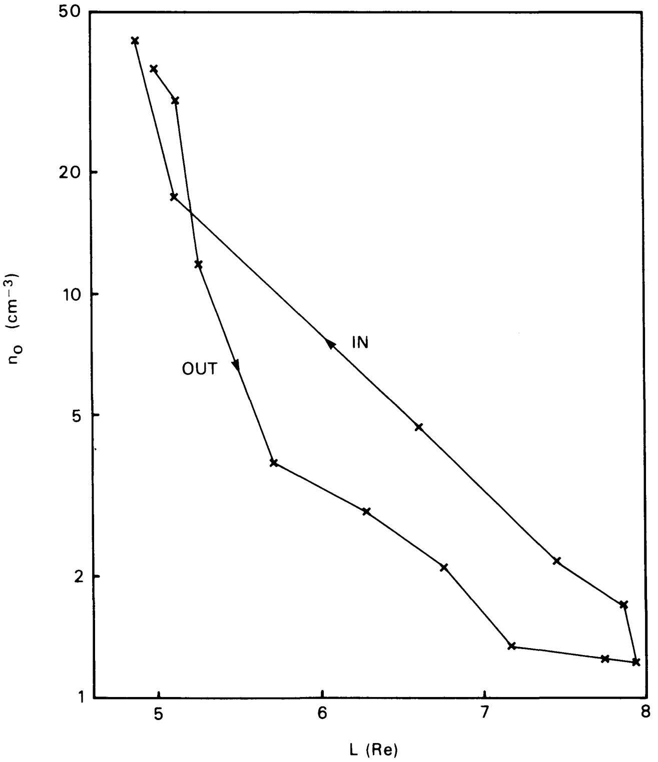

Fig. 4. The electron density vs L-value measured by the GEOS-1 relaxation sounder experiment during the orbit about apogee on 28 November 1977

to the plasmatrough at ~4:40 LT, the plasmapause being located at $L \sim 5.5$, and passed back from the plasmatrough to the plasmasphere at ~10:30 LT when the plasmapause was at $L \sim 5$ (A. Pedersen, personal communication).

The relaxation sounder experiment on GEOS-1 (Etcheto and Bloch, 1978; Higel, 1978) measures the local plasma frequency and thus gives the electron density in the vicinity of the spacecraft. The upper frequency limit of the experiment is 76 kHz, giving an upper limit of the plasma density measurement of ~70 cm^{-3}. Figure 4 shows the electron density measured during the part of the orbit about apogee shown in Fig. 3. The recorded density measurements have been scaled to the equatorial plane by assuming a dipole magnetic field and a $n_0 = n_r(r/r_0)^4$ variation in plasma density, where n_0 and n_r are the number densities at r_0 and r, respectively. We have chosen an r^{-4} variation in density along the geomagnetic field line as being appropriate to the collisionless plasma in the plasmatrough. Also $r = r_0\cos^2\lambda$ for a dipole field, where λ is the geomagnetic latitude and r_0 is the equatorial geocentric distance.

From Fig. 4 the L-value of the plasmapause, L_{pp}, can also be estimated from the relaxation sounder experiment. L_{pp} for both the inbound and outbound passes are in close agreement with those given by the spacecraft potential as measured by the electric field experiment. The difference in densities in the plasmatrough between the outbound and inbound parts of the orbit is possibly due to dayside filling of the flux tubes linking the plasmatrough plasma with ionspheric plasma, by photo-ionisation of the sunlit ionosphere. As the K_p values are generally close to 2 before and throughout the selected interval, the dayside filling is likely to be the dominant process which will alter the plasma density in the plasmatrough during the interval.

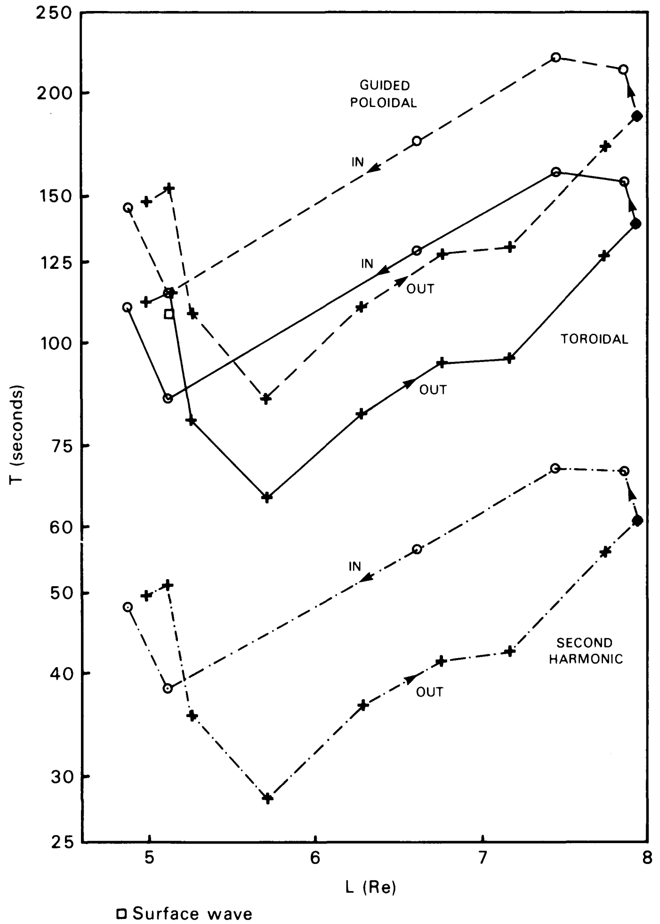

Fig. 5. The calculated eigenperiods as a function of L-value of the fundamental and second harmonic of the toroidal and guided poloidal eigenmodes calculated from the electron density measurements made by GEOS-1 (Fig. 4). Also shown, *by the box* at $L = 5.12$, $T = 108$ s, is the calculated period of a surface wave at the plasmapause

The Ion Composition Experiment on GEOS-1 was also operating during this interval and observed heavy ions (He$^+$ and O$^+$) inside the plasmasphere away from the position of the plasmapause on both the outbound and inbound passes. The experiment also observed plasma with a composition of 5%–10% of O$^+$ ions in the plasmatrough (H. Balsiger, personal communication).

The pulsation events

Five pulsation events occurred in the selected interval and each event will be discussed in this section. Figure 5 shows the calculated eigenperiods of the fundamental and second harmonic of the toroidal and guided poloidal eigenmodes, using the model of Orr and Matthew (1971). We have taken the number density distribution of the ions to be $n_r = n_0(r_0/r)^4$, where n_r and n_0 are the number densites at r and r_0, respectively. The model uses a dipole field $r = r_0\cos^2\lambda$, where λ is the geomagnetic latitude and r_0 the equatorial geocentric distance. We have used the electron density measurements made by GEOS-1 (Fig. 4) and have assumed charge neutrality and that all the ions are protons. Singer et al. (1981) have calculated the eigenperiods of transverse waves decoupled in a more general field geometry than a dipole

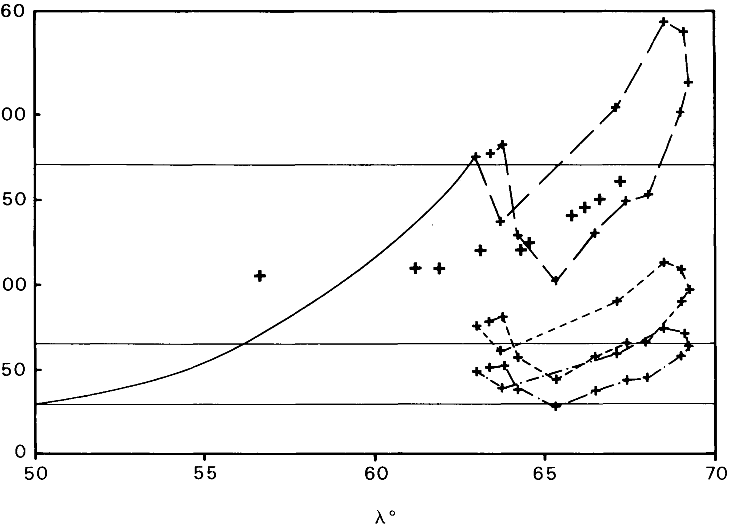

Fig. 6. The calculated eigenperiods as a function of geomagnetic latitude of the guided toroidal-mode fundamental (*long dashed line*), second (*short dashed line*) and third (*dashed-dot line*) harmonic. The eigenperiods have been calculated from the electron density measurements made by GEOS-1 (Fig. 4) assuming charge neutrality and, of the number density, 10% are O^+ ions and the remainder are protons. Also shown is the possible variation of the fundamental harmonic within the plasmasphere. The periods of the events E3 (65 s), E4 (170 s) and E5 (28 s) are shown as *horizontal lines* and the period of the Pse event at each station is marked by a *large cross*

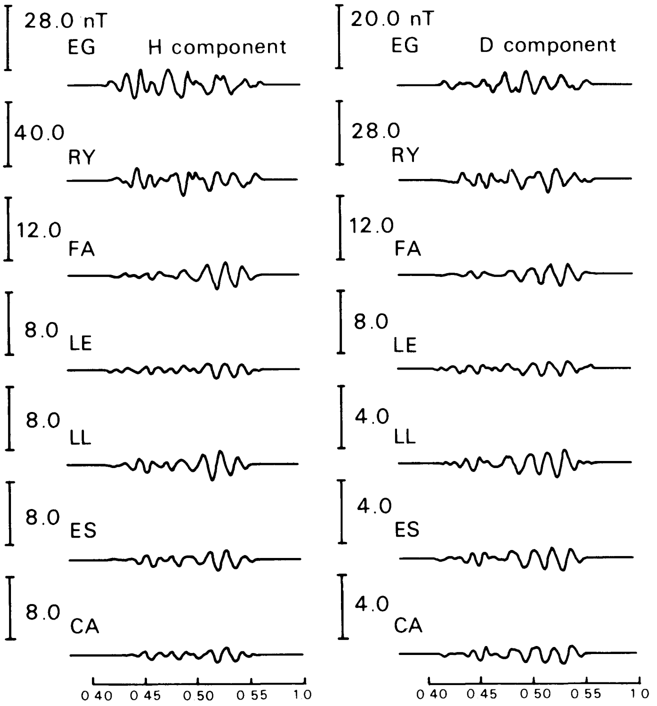

Fig. 7. The bandpassed (200–20 s) filtered waveforms of the Pi2 pulsation event E1 on the IGS UK chain which occurred on 28 November 1977 (Lester and Orr, 1983)

field. Their calculations highlight the differences for the periods calculated for high-latitude field lines and the variation with local time. They comment that inside of ~9 R_e deviations from the dipole field periods are less than 10% and there is little local time variation of period. For the second harmonic, the eigenperiods of the toroidal and guided poloidal modes are found to be within 1%–2% of each other (Orr and Matthew, 1971). Also shown in Fig. 5 (by the box at $L=5.12$, $T=108$ s) is the period of a surface wave which could be generated on the plasma density discontinuity at the plasmapause (Lanzerotti et al., 1973; Chen and Hasegawa, 1974b). The method of calculation and the relevance of this period will be discussed in the section which discusses the Pi2 event.

Figure 6 extends the results of Fig. 5 to show the calculated first, second and third harmonic toroidal-mode eigenperiods in the plasmatrough and at the plasmapause, when the effect of a 10% composition in number density of oxygen ions is included. The results from the fundamental harmonic have been extended to show how the toroidal-mode eigenperiods may have varied within the plasmasphere. We assume here that magnetic field and plasma density are such that the eigenperiods do not become longer at latitudes below that of the last electron density measurement of GEOS-1, and that the periods of the eigenmodes will decrease with decreasing latitude as the lengths of the geomagnetic field lines, associated with the guided standing waves, decrease (Orr and Hanson, 1981). Although the upper limit of the plasma density measurement by the relaxation sounder experiment on GEOS-1 is ~70 cm^{-3}, and thus it is not possible to obtain estimates of the plasma density when GEOS-1 is in the plasmasphere, the measurements made by the Suprathermal Plasma Analysers on GEOS-1 suggest that the plasma density in the high-latitude plasmasphere did not become greater than 100 cm^{-3} during this day. [See Fig. 6 of Wrenn et al. (1984) for the density as measured by the SPA during the inbound pass of the plasmapause at approximately 9:05 UT.] We thus conclude that as the plasma density does not increase significantly above the highest density measurements of the relaxation sounder and as the field lines become shorter in the plasmasphere, we have been able to calculate the longest eigenperiod within the plasmasphere. Also shown in Fig. 6 are the observed periods associated with the five pulsation events E1–E5 which will be discussed in the next subsections.

E1 : Pi2 event

Figure 7 shows the Pi2 pulsation event which occurred in Europe at 0:47 UT as seen on the IGS UK chain. The IGS data for this event have already been analysed as part of ground-satellite-correlated observations of Pi2 pulsations by Lester and Orr (1983). There appears to be two separate parts to this event. Power spectral analysis of the two parts reveals that in the first part the dominant period is ~70 s and in the second ~120 s, except at EG and RY which have a dominant component in the second part of 170 s.

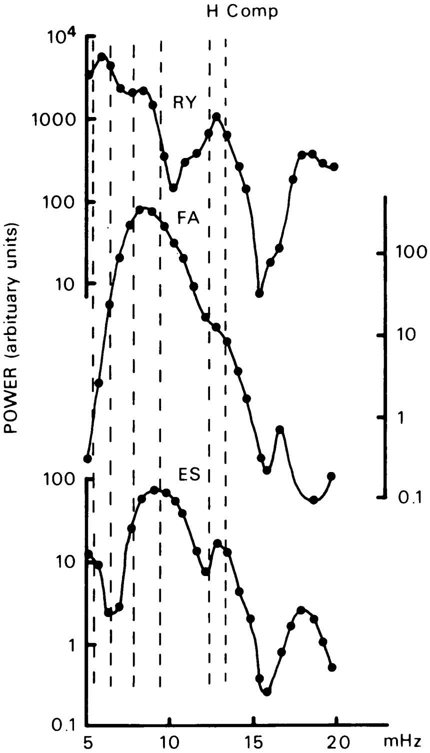

Fig. 8. H-component power spectra for three stations from the time interval 0:40–1:05 UT covering Pi2 event E1 on 28 November 1977 (Lester and Orr, 1983)

In analysing the 120-s component, Lester and Orr report a peak in H-component amplitude at RY and a secondary H-component amplitude peak at LL on the IGS UK array. In addition, there are phase and ellipticity reversals with latitude which are likely to be related to the position of the plasmapause as estimated from the GEOS-1 data. Furthermore, Fig. 8 shows the power at RY is predominantly in the longer 170-s period (frequency ~6 mHz), whereas at FA and ES the dominant spectral peak is at a shorter period, suggesting the power in the Pi2 at latitudes corresponding to these stations is being modified.

Chen and Hasegawa (1974b) suggest that a surface wave can travel over a plasma density discontinuity at some average of the Alfvén velocity along the line of magnetic force on the two sides of the boundary. The eigenmode of the wave would have an angular frequency

$$\omega_r = \left[\frac{k_{\|}^2 \,(B_{\mathrm{I}}{}^2 + B_{\mathrm{II}}{}^2)}{\mu_0 \,(\rho_{\mathrm{I}} + \rho_{\mathrm{II}})}\right]^{\frac{1}{2}},$$

where B and ρ are the magnetic field strength and plasma density and subscripts I and II refer to inside and outside the boundary.

At the boundary:

$$B_{\mathrm{I}} \sim B_{\mathrm{II}}$$
$$\rho_{\mathrm{I}} \gg \rho_{\mathrm{II}}.$$

Therefore,

$$\omega_r \approx \left[\frac{2k_{\|}^2 B_{\mathrm{I}}{}^2}{\mu_0 \,\rho_{\mathrm{I}}}\right]^{\frac{1}{2}} = \sqrt{2}\;\omega_{gm},$$

where ω_{gm} is the guided-mode (either poloidal or toroidal) angular frequency just inside the boundary.

Thus the period of a surface wave on the plasmapause will be given approximately by the longest period within the plasmasphere divided by $\sqrt{2}$. Using the plasma density measurements from GEOS-1 made at ~4 LT and the guided poloidal mode, this period is approximately 108 s (see Fig. 5), which is in close agreement with the observed dominant period at FA, the station closest to the plasmapause. If, as is discussed later, oxygen ions were present, then the surface wave period would be longer. From the spectrum at ES this period is still the major component in the plasmasphere even when the periods present at higher latitudes reappear in the spectrum.

A further interesting observation is a Pc5 pulsation of period ~300 s seen on the University of Alberta array, also starting at 0:45 UT. The position of the Alberta array at this time is ~17 LT. Samson and Rostoker (1981) reported observations of dayside Pc4/5 pulsations which changed their characteristics in response to the onset of a magnetospheric substorm near midnight. The common response of the dayside pulsations near local noon is an increase in the dominant frequency at stations inside the dayside auroral oval. This is possibly due to an increase in the ring current causing a change in the geomagnetic field line length. The Pc5 pulsation observed on day 332 does not appear to change its frequency, but does appear to start at the same time as the substorm onset in Europe. McPherron (1980) reported substorm-associated mixed-mode Pc4–5 pulsations seen at geosynchronous orbit, which had a maximum at dusk in diurnal occurrence.

E2: Pse event

Figure 9 illustrates what could be impulse-excited, transient, decaying waveforms observed by the Scandinavian chains at 4:47 UT (~7 LT). Siebert (1964) noticed such transient decaying pulsations at three stations in the geomagnetic latitude range 46°–52°, where the H component – and this component only – exhibited a very clear and systematic increase of period of oscillation with increasing latitude. He called these events 'pulsation single effect' (Pse) events. Similar latitude-dependent period pulsations have been observed in the geomagnetic latitude range 58°–78° (Rostoker and Samson, 1972) and by the STARE radar (Poulter and Nielsen, 1982; Poulter et al., 1984). Hasegawa et al. (1983) have shown that it is theoretically possible, in the presence of a broad-band source, for a local field line to oscillate at its Alfvén resonance frequency(ies) if the frequency band of the source covers the resonance frequency(ies), and thus to observe an L-dependence of period in magnetic pulsations during a given event. Using expanded time-scale magnetograms, the period of the waves in the H components of the University of Göttingen chain of magnetometers is seen to decrease systematically from 160 s at the highest latitude station to 110 s at the lowest latitude station. On the IGS Scandinavian array the corresponding decrease in period in the H components is from 145 to 105 s. The D-component periods on both chains are constant with latitude at ~130 s, suggesting that the H and D components are not strongly coupled.

The measured periods of the Pse waves from the University of Göttingen and IGS Scandinavian stations are shown in Fig. 6. The six stations in the latitude range 64°–67.2° (SK, KN, KE, IV, TR, KI) show very good agreement with the computed eigenperiods for the axisymmetric toroi-

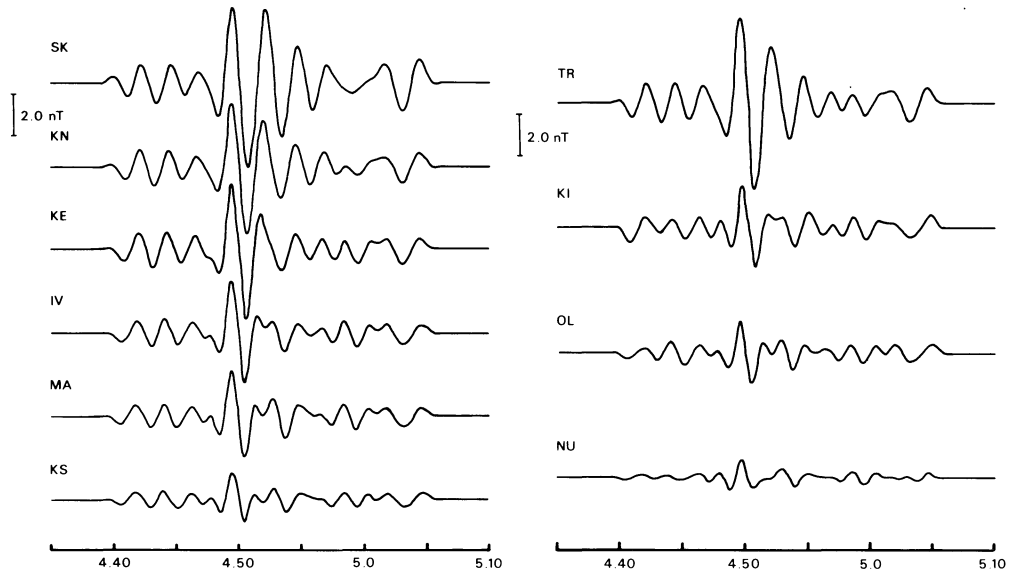

Fig. 9. The bandpassed (200–100 s) filtered waveforms of the Pse event E2 on the Scandinavian chains on 28 November 1977

dal first harmonic mode for the outbound pass of GEOS-1. The observed pulsation periods measured on the ground vary from 110 to 160 s, whereas the predicted periods, from the outbound GEOS-1 particle estimates and the modelling of standing Alfvén wave in the fundamental mode, range from 100 to 150 s.

The remaining four Scandinavian stations (MA, KS, OL, NU) in the latitude range 56.6°–63.1° have their geomagnetic field lines linking plasmaspheric plasma. The measured pulsation periods at these stations show only a small change in period with latitude (105 to 120 s) and do not correspond to the computed local eigenperiods. The periods approximately agree with the shortest first harmonic period supported in the plasmatrough (100 s).

Thus the six highest latitude Scandinavian stations have clear latitude-dependent *H*-component wave which, with the 90° rotation of the wave field by the ionosphere, suggests a toroidal magnetospheric wave mode. The Ion Composition Experiment on GEOS-1 observed that the plasma in the plasmatrough was made up of 5%–10% of oxygen ions. The toroidal mode eigenperiods shown in Fig. 6 include the effect of the 10% of O^+ ions. The mass density of the plasma is increased by 2.5 times that of a hydrogen plasma. Since the eigenperiod is proportional to the square root of the mass density, the eigenperiods are increased by a factor of 1.58. As can be seen from this figure, the presence of oxygen ions increases the toroidal eigenperiods calculated from the outbound pass of GEOS-1 so that they approximately agree with the observed periods. However, since the waves are not detected in the UK meridian it is clearly not the symmetric toroidal mode, with a globally in-phase signature, which has been computed in Figs. 5 and 6. This would suggest that the magnetospheric wave signature corresponds to a mixed-mode hydromagnetic wave or a non-axisymmetric toroidal mode. Comparing stations in the Göttingen and IGS Scandinavian arrays (TR with KN and KE, KI with IV and OL with KS) shows that the coherency between these longitudes is very high with a low value for the *m* number and a long azimuthal wavelength.

Poulter et al. (1984) have used auroral radar measurements to study latitude-dependent pulsations of the Pse type. They used such pulsations to determine equatorial ion mass densities in the plasmatrough. Comparing the mass densities with in situ electron density measurements they concluded that up to 50% O^+ ion populations can be present at all local times, but in general, the afternoon densities are about twice as large as those in the morning. Singer et al. (1979) reported plasma number and mass density measurements made in the morning sector of the plasmatrough by ISEE-1. The number densities were determined by both the sounder and propagation experiment and the plasma wave detector. The mass density was determined by the plasma composition experiment. Comparing the results showed that substantial quantities of O^+ resulted in a mass density five to nine times greater than that of a proton-electron plasma of the same number density, thus giving computed eigenperiods two to three times longer than they would have been if H^+ were the only ion present.

A pulsation event such as this Pse event allows the damping experienced by a standing-mode wave to be determined empiricially (Gough and Orr, 1984). The damping coefficient, *k*, which is the ratio of successive half-cycle amplitudes determined from successive peak to trough and trough to peak amplitudes, can be used to determine the damping factor γ/ω_n. This damping factor defines the rate of exponential decay of the 'transient' response of a simple harmonic oscillator. The damping factors γ/ω_n for the stations SK, KN, KE, IV and MA in the Göttingen array are 0.11, 0.11, 0.14, 0.13 and 0.17, respectively, and for the stations TR, KI and OL in the IGS Scandinavian array the values are 0.13, 0.14 and 0.15, respectively. These values are very similar to the values obtained by Gough and Orr (1984) for the daytime Pse event recorded by Siebert (1964) and used in an example of their model to illustrate the effects of damping on field line resonances observed on the ground.

E3 : Pc4 event

Figure 10 shows a Pc4 pulsation, with a well-defined wave packet from ~5:40 to 5:45 UT, seen on the IGS Scandinavian array. The period of the pulsation in the wave packet

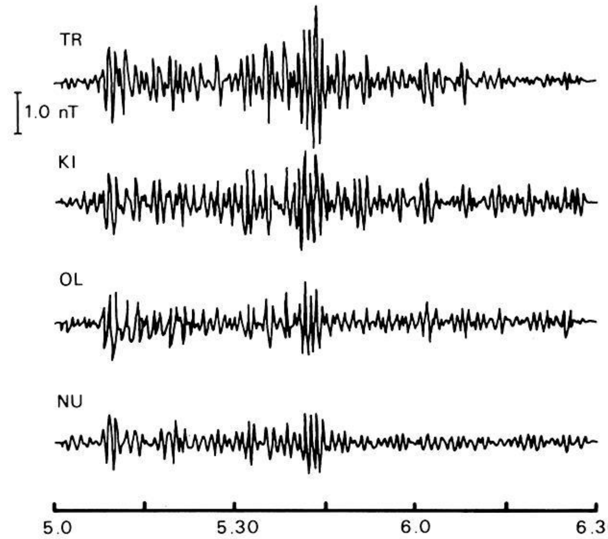

Fig. 10. The bandpassed (80–50 s) filtered waveforms showing the Pc4 wave packet, event E3, on the IGS Scandinavian array on 28 November 1977

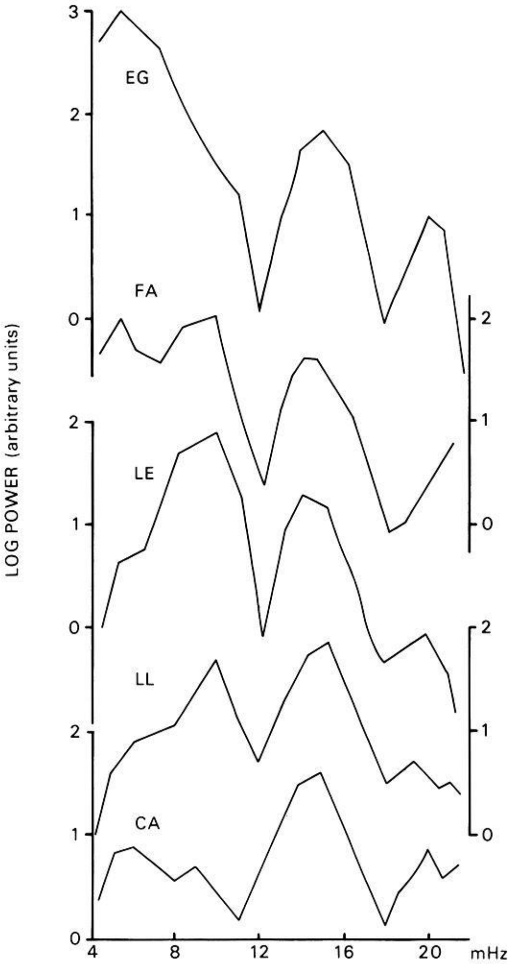

Fig. 11. *H*-component power spectra from 5:30 to 5:45 UT for the Pc4 wave packet, event E3, recorded on stations in the IGS UK chain

is ~65 s (frequency ~15 mHz). Figure 11 shows the power spectral analysis from stations in the IGS UK chain. There is an additional spectral component at ~180 s (6 mHz) appearing at Iceland and Faroes and another component at ~100 s (10 mHz) at FA, LE and LL. However, the 65-s component is present at nearly constant power over the complete chain, implying that is the ubiquitous driving component and that the other components are excited locally. For example, the near 100-s component seen at FA, LE and LL is similar to the shortest fundamental harmonic toroidal-mode period supported by the plasmatrough at the Scandinavian stations approximately 1 h earlier (event E2).

Figure 6 shows that a driving wave of 65-s period is likely to excite a second harmonic of the toroidal mode in the plasmatrough. It should also excite a fundamental harmonic toroidal-mode field line resonance within the plasmasphere. Figure 12 shows some of the results of complex demodulation carried out on data from the University of Göttingen and IGS UK arrays. Figure 12a shows the *H*-component amplitude for the event recorded on the University of Göttingen stations and reveals an attenuation of the wave amplitude at the lower latitude end of the array ($\lambda \sim 62°$). This could be due to the position of the plasmapause, which will alter the natural standing wave period, or it could mark the limit of the latitudinal extent of the second harmonic resonance. There is no discernible change in phase across this region suggesting that if it is a second harmonic resonance, there is no change in phase with latitude accompanying such a resonance or that it has been smoothed out by the ionosphere. Figure 12b and c show the *H*-component amplitude and phase for the pulsation event recorded on the IGS UK stations. The UK plasmatrough signature, Fig. 12b, has similar amplitude characterisitcs to those observed on the Göttingen array, namely a rather constant amplitude signal in the latitudinal range 62°–66° with attenuation to the south. In the plasmasphere, Fig. 12c reveals a 110° increase in phase with decreasing latitude from LE to CA associated with a small amplitude maximum between LL and ES (Fig. 12b). The complex demodulation also revealed a systematic change in the sense of the ellipticity of the signal between ES and CA, where the ellipticity values are 0.6 clockwise and 0.1 counterclockwise, respectively. This would suggest that there is a toroidal-mode resonance within the plasmasphere. The small amplitude peak and less than 180° change in phase could be due to heavy damping of the resonant wave by poor reflection from the dark ionosphere (Hughes and Southwood, 1976b; Gough and Orr, 1984).

E4: Pc5 activity

Figure 13 shows Pc5 activity, of period nearly 3 min, observed between 5:00 and 6:30 UT on Iceland at the northern end of the IGS array. Similar pulsations were also seen at the same time on the University of Göttingen Scandinavian array, where the amplitudes of the pulsations increased with latitude. Figure 6 would suggest that the resonant region for such a period would be to the north of the arrays and thus would not be directly identified by the available magnetometers. The Pc5 pulsation waveforms observed on the University of Göttingen Scandinavian array have a high coherence. The lack of a change in phase with latitude confirms that the resonance region is outside the latitudinal range of the available magnetometers.

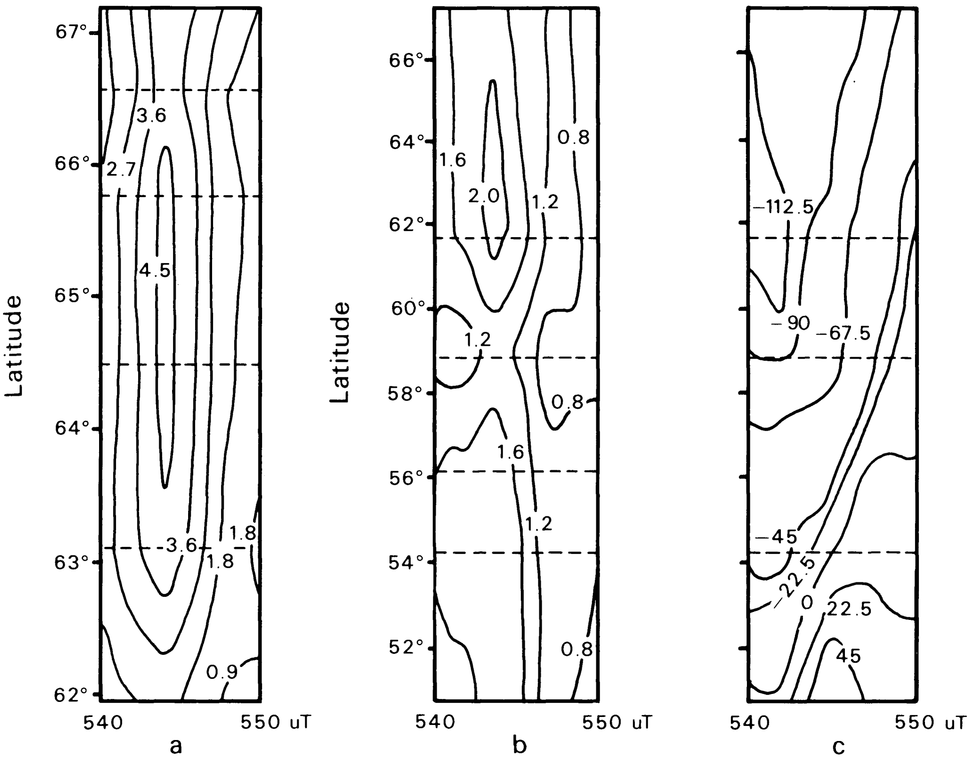

Fig. 12. Contour maps obtained from complex demodulation with band demodulation centred on 62 s and overall bandwith of 48–86 s of **a** the *H*-component amplitude recorded on the University of Göttingen Scandinavian chain, **b** the *H*-component amplitude and **c** the *H*-component phase recorded on the IGS UK chain of the Pc4 event E3 on 28 November 1977

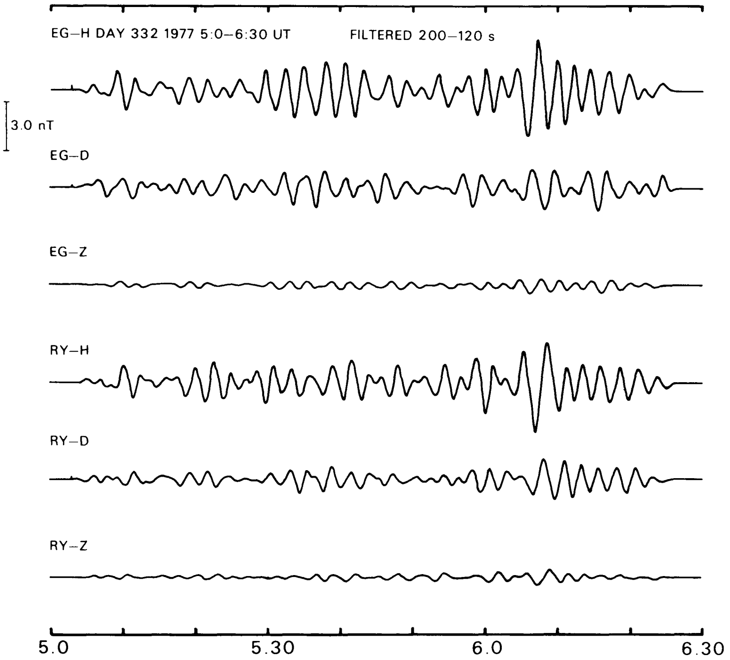

Fig. 13. Bandpassed (200–120 s) filtered waveforms showing Pc5 wave activity, event E4, recorded on the IGS Icelandic magnetometers

At this time GEOS-1 was passing through apogee at $L \sim 8$ and similar pulsations with a period of ~ 3 min were also seen in the electric field measurements. However, data are not available from the magnetometer on GEOS-1 at this time so it is not clear whether the satellite was detecting the resonance region.

E5: Pc3 activity

Between 6:20 and 7:20 UT four Pc3 wave packets were observed in northern Europe. Complex demodulation shows that these packets have peaks in the *H*-component amplitude between 63° and 65° geomagnetic latitude. Figure 14 shows the amplitude and phase characteristics of one of the Pc3 wave packets recorded on the University of Göttingen chain and shows that the phase increases by $\sim 90°$ with decreasing latitude across the peak in the amplitude.

Figure 6 shows that the period of this event, 28 s, is too short to be associated with the fundamental or second harmonic of a toroidal eigenmode wave in the plasmatrough. However, the amplitude peak and latitudinal

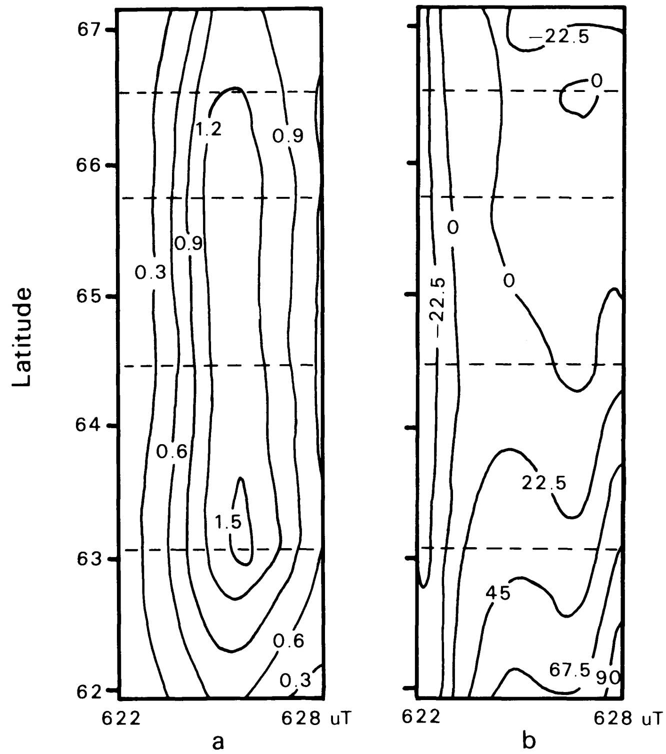

Fig. 14. Contour maps obtained from complex demodulation using a demodulation band centred on 27.5 s and overall bandwidth of 21.8–37.4 s of **a** the *H*-component amplitude and **b** the *H*-component phase of one of the Pc3 wave packets, event E5, recorded on the University of Göttingen Scandinavian chain on 28 November 1977

change of phase suggests that a resonance has taken place on field lines linking stations in the Göttingen array. The period agrees with the postulate that a third harmonic toroidal-mode resonance is being excited. Takahashi and McPherron (1982) report observations of Pc3 pulsations on ATS-6 which showed that Pc3 pulsations at geostationary altitudes correspond to the third or higher harmonics. Figure 6 also suggests there could be the possibility of a fundamental toroidal-mode resonance at the lowest latitude stations in the IGS UK array. However, although there is a slight enhancement in amplitude at ES and a further enhancement at CA, there do not appear to be any noticeable changes in phase with latitude.

Conclusions

We have presented results from the analysis of five different pulsation events which occurred during the interval between 0 and 10 UT on 28 November 1977, selected for special study at the sixth workshop on IMS observations in northern Europe. We have compared the periods and latitudinal characteristics of the pulsations recorded on three chains of magnetometers in northern Europe with theoretical eigenperiods calculated from simultaneous plasma density and composition measurements made in the plasmatrough and at the plasmapause by the relaxation sounder experiment and Ion Composition Experiment on GEOS-1. As the K_p values are generally close to 2 throughout and for 21 h before the selected interval, the plasma density profile as measured by GEOS-1 can be taken as representative of the plasma distribution in that region of the magnetosphere during the selected interval.

The Pse and Pc5 pulsation characteristics generally conform to those expected for the calculated fundamental harmonic toroidal-mode waves in the magnetosphere, particularly in the case of the Pse event if the effect of the presence of up to 10% of oxygen ions, as indicated by the Ion Composition Experiment on GEOS-1, is included. Singer et al. (1979) have also found such an ion composition in the plasmatrough with the ISEE-1 satellite. Young (1983) has observed energetic (>1 keV) O^+ ions in the magnetosphere during magnetically quiet days and suggests that energetic O^+ is detected under nearly all conditions with concentrations of a few percent to over 80% of the total density. Geiss et al. (1978) and Balsiger et al. (1980) have reported observations which suggest that significant O^+ populations remain for several days after a magnetic storm. Although the magnetic activity, as measured by the K_p and *Dst* indices, was low during the studied interval there was moderate activity on 26 November, 2 days before this interval. K_p rose to 5_+ and *Dst* decreased to approximatley -80γ. The trend over the next 2 days was for the magnitude of these two indices to decrease. Nonetheless, it is possible that some of the O^+ population observed in the magnetosphere during this interval could have been introduced by the previous active magnetic interval. With the extra oxygen ions it is necessary to invoke second and third harmonic field line resonances for the Pc4 and Pc3 events, respectively. It is interesting that the second harmonic field line resonance does not give a phase change with latitude on the ground, whereas the third harmonic field line resonance does. In this paper we have not discussed the possible energy sources of the toroidal-mode pulsations, but we note that at least two methods of pulsation generation were present. The Pse event requires an impulsive, broad-band driving mechanism such as a sudden impulse, whereas the continuous pulsations suggest a quasi-periodic energy source such as the waves generated at the magnetopause by the Kelvin-Helmholtz instability (Southwood, 1968; Pu and Kivelson, 1983). Although there is not a clear, indisputable toroidal-mode field line resonance event to confirm that a given eigenmode period exists at a given latitude, the latitudinal characteristics of the pulsations corroborate the calculated eigenperiods.

The second type of magnetospheric wave mode we observed during this interval is a surface wave on the plasmapause. The observed dominant period at stations close to the latitude of the plasmapause during the Pi2 event is in close agreement with the period calculated for the plasma density discontinuity using the model of Chen and Hasegawa (1974b).

Finally we conclude that the study of the pulsations which occurred in this magnetically undisturbed interval has allowed us to demonstrate models of driven field line oscillations and surface waves.

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References

Balsiger, H., Eberhardt, P., Geiss, J., Young, D.T.: Magnetic storm injection of 0.9- to 16-keV/e solar and terrestrial ions into the high-altitude magnetosphere. J. Geophys. Res. **85**, 1645–1662, 1980

Beamish, D., Hanson, H.W., Webb, D.C.: Complex demodulation applied to Pi2 geomagnetic pulsations. Geophys. J. R. Astron. Soc. **58**, 471–493, 1979

Chen, L., Hasegawa, A.: A theory of long-period magnetic pulsations 1. Steady state excitation of field line resonance. J. Geophys. Res. **79**, 1024–1032, 1974a

Chen, L., Hasegawa, A.: A theory of long-period magnetic pulsations 2. Impulse excitation of surface eigenmode. J. Geophys. Res. **79**, 1033–1037, 1974b

Etcheto, J., Bloch, J.J.: Plasma density measurements from the GEOS-1 relaxation sounder. Space Sci. Rev. **22**, 597–610, 1978

Geiss, J., Balsiger, H., Eberhardt, P., Walker, H.P., Weber, L., Young, D.T., Rosenbauer, H.: Dynamics of magnetospheric ion composition as observed by the GEOS mass spectrometer. Space Sci. Rev. **22**, 537–566, 1978

Gough, H., Orr, D.: The effect of damping on geomagnetic pulsation amplitude and phase at ground observatories. Planet. Space Sci. **32**, 619–628, 1984

Green, C.A.: Continuous magnetic pulsations on the IGS array of magnetometers. J. Atmos. Terr. Phys. **43**, 883–898, 1981

Hanson, H.W., Webb, D.C., Beamish, D.: A high resolution study of continuous pulsations in the European sector. Planet. Space Sci. **27**, 1371–1382, 1979

Hasegawa, A., Tsui, K.H., Assis, A.S.: A theory of long-period magnetic pulsations 3. Local field line oscillations. Geophys. Res. Lett. **10**, 765–767, 1983

Higel, B.: Small scale structure of magnetospheric electron density through on-line tracking of plasma resonances. Space Sci. Rev. **22**, 611–631, 1978

Hughes, W.J.: The effect of the atmosphere and ionosphere on long period magnetospheric micropulsations. Planet. Space Sci. **22**, 1157–1172, 1974

Hughes, W.J., Southwood, D.J.: The screening of micropulsation signals by the atmosphere and ionosphere. J. Geophys. Res. **81**, 3234–3240, 1976a

Hughes, W.J., Southwood, D.J.: An illustration of modification of geomagnetic pulsation structure by the ionosphere. J. Geophys. Res. **81**, 3241–3247, 1976b

Lanzerotti, L.J., Fukunishi, H., Hasegawa, A., Chen, L.: Excitation of the plasmapause at ultralow frequencies. Phys. Rev. Lett. **31**, 624–628, 1973

Lester, M., Orr, D.: The spatio-temporal characteristics of Pi2's. J. Atmos. Terr. Phys. **43**, 947–974, 1981

Lester, M., Orr, D.: Correlations between ground observations of Pi2 geomagnetic pulsations and satellite plasma density observations. Planet. Space Sci. **31**, 143–160, 1983

Madahar, B.K., Hunter, A.N.: The diurnal behaviour of the auroral current system. Ann. Geophys. **38**, 733–743, 1982

McPherron, R.L.: Substorm associated micropulsations at synchronous orbit. J. Geomagn. Geoelectr. **32**, Suppl. **II**, SII 57–73, 1980

Orr, D., Hanson, H.W.: Geomagnetic pulsation phase patterns over an extended latitudinal array. J. Atmos. Terr. Phys. **43**, 899–910, 1981

Orr, D., Matthew, J.A.D.: The variation of geomagnetic micropulsation periods with latitude and the plasmapause. Planet. Space Sci. **19**, 897–905, 1971

Pedersen, A., Grard, R., Knott, K., Jones, D., Gonfalone, A., Fahleson, U.: Measurements of quasi-static electric fields between 3 and 7 earth radii on GEOS-1. Space Sci. Rev. **22**, 333–346, 1978

Poulter, E.M., Nielsen, E.: The hyromagnetic oscillation of individual shells of the geomagnetic field. J. Geophys. Res. **87**, 10,432–10,438, 1982

Poulter, E.M., Allan, W., Keys, J.G., Nielsen, E.: Plasmatrough ion mass densities determined from ULF pulsation eigenperiods. Planet. Space Sci., 1984 (in press)

Pu, Z.-Y., Kivelson, M.G.: Kelvin-Helmholtz instability at the magnetopause: Solution for compressible plasmas. J. Geophys. Res. **88**, 841–852, 1983

Rostoker, G., Samson, J.C.: Pc micropulsations with discrete, latitude-dependent frequencies. J. Geophys. Res. **77**, 6249–6253, 1972

Samson, J.C., Rostoker, G.: Response of dayside Pc5 pulsations to substorm activity in the nighttime magnetosphere. J. Geophys. Res. **86**, 733–752, 1981

Siebert, M.: Geomagnetic pulsations with latitude dependent periods and their relation to the structure of the magnetosphere. Planet. Space Sci. **12**, 137–147, 1964

Singer, H.J., Russell, C.T., Kivelson, M.G., Fritz, T.A., Lennartsson, W.: Satellite observations of the spatial extent and structure of Pc3, 4, 5 pulsations near the magnetospheric equator. Geophys. Res. Lett. **6**, 889–892, 1979

Singer, H.J., Southwood, D.J., Walker, R.J., Kivelson, M.G.: Alfvén wave resonances in a realistic magnetospheric magnetic field geometry. J. Geophys. Res. **86**, 4589–4596, 1981

Southwood, D.J.: The hydromagnetic stability of the magnetopause boundary. Planet. Space Sci. **16**, 587–605, 1968

Southwood, D.J.: Some features of field line resonances in the magnetosphere. Planet. Space Sci. **22**, 483–491, 1974

Stuart, W.F.: Arrays of magnetometers operated in NW Europe. In: The IMS source book, C.T. Russell and D.J. Southwood, eds.: pp 141–152. American Geophysical Union, Washington, D.C., 1982

S-300 Experimenters: Measurements of electric and magnetic wave fields and of cold plasma parameters on board GEOS-1. Preliminary results. Planet. Space Sci. **27**, 317–339, 1979

Takahashi, K., McPherron, R.L.: Harmonic structure of Pc3–4 pulsations. J. Geophys. Res. **87**, 1504–1516, 1982

Webb, D.C.: The analysis of non-stationary data using complex demodulation. Ann. Telecomm. **35**, 131–137, 1979

Wrenn, G.L., Sojka, J.J., Johnson, J.F.E.: Thermal protons in the morning magnetosphere: Filling and heating near the equatorial plasmapause. Planet. Space Sci. **32**, 351–363, 1984

Young, D.T.: Heavy ion plasmas in the outer magnetosphere. J. Geophys. **52**, 167–175, 1983

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