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Pc5 pulsations and their possible source mechanisms: a case study

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Abstract. During the interval 0400–1600 UT on August 31, 1978 strong pc5 activity was observed in the morning and afternoon sector of the magnetosphere. Using data from a world-wide network of ground-magnetometer stations and from the geostationary satellites GEOS 2, GOES 2 and 3 as well as the satellite pair ISEE 1 and 2 a case study was performed with special respect to the question of possible source mechanisms responsible for the observed pulsations. Like earlier workers we came up with the result that the Kelvin-Helmholtz instability at the magnetopause or in the low latitude boundary layer is a likely candidate. In particular we found a change in the azimuthal phase propagation direction from westwards on the morning side and eastward on the afternoon side. Also the sense of polarization and the azimuth of the ground magnetic disturbance in the horizontal plane changed across the meridian of the stagnation point as predicted by a Kelvin-Helmholtz instability source mechanism. A more detailed analysis was carried out for an isolated, large amplitude pc5 event at 1040 UT. At the same time magnetic field observations from the ISEE satellite pair indicate a flux transfer event (FTE) like disturbance at the magnetopause. Also indications of magnetopause boundary oscillations were found, and we feel that this FTE-like event constitutes a possible source for the observed impulsive pc5 event recorded on the ground and on GEOS 2. Furthermore, as the observed pc5 pulsations exhibit a wave-packet structure, we studied whether these wave packets coincided with substorms or substorm intensifications observed simultaneously in the nighttime magnetosphere. However, only a partial one-to-one correlation was found.

Key words: Geomagnetic pulsations – Kelvin-Helmholtz instability – Flux transfer event – Night-time-daytime coupling of the magnetosphere

Introduction

At the present time geomagnetic pulsations are regarded as ULF hydromagnetic waves propagating in the earth's magnetosphere (see reviews: Lanzerotti and Southwood, 1979; Southwood and Hughes, 1983). Two different aspects, a passive one and an active one, are important in this context. The passive part concerns the propagation of hydromagnetic waves in, and the interaction with, the magnetospheric cavity. The theory of field line resonance, as developed by Tamao (1965), Southwood (1974) and Chen and Hasegawa (1974), is now widely accepted and well in accord with experimental data. The active aspect concerns the energy source of the ULF hydromagnetic waves. Plasma instabilities, such as the Kelvin-Helmholtz instability at the terrestrial magnetopause (e.g. Southwood, 1968; Pu and Kivelson, 1983) and in the low latitude boundary layer (e.g. Yumoto and Saito, 1980; Lee et al., 1981), or wave-particle interactions (e.g. Southwood, 1976) and internal plasma instabilities (e.g. Lanzerotti and Hasegawa, 1975) in the magnetosphere, have been suggested as possible source mechanisms. Also, sudden changes in the dayside magnetosphere as indicated by sudden commencements are associated with geomagnetic pulsations, and sudden changes of the night-time magnetosphere can be regarded as possible source mechanisms of transient Alfvèn impulses or pi2 pulsations (see, for example, Nishida, 1979, or the review by Baumjohann and Glaßmeier, 1984). Substorm onsets identified by pi2 pulsations may in turn be related to pulsations in the pc5 period range observed on the dayside (Samson and Rostoker, 1981).

The aim of the present paper is to study in detail a longer period of prominent and regular pc5 pulsation activity with special emphasis on the question of possible source mechanisms. As a suitable interval the August 31, 1978, 0400–1600 UT interval has been chosen, when large amplitude pc5 pulsations were observed both on the ground and by geostationary satellites. Our study is based mainly on ground magnetic observations in the European sector (the UT interval given above corresponds to 0630–1830 magnetic local time) and the GEOS 2 satellite, with the footpoint of the GEOS 2 field line lying in northern Scandinavia. Where necessary, we also used ground magnetic observations from the American sector and the USSR, as well as the geostationary satellites GOES 2 and 3 and the satellite pair ISEE 1 and 2.

The approximate locations of magnetometer stations and the positions of the geostationary satellites GEOS 2,

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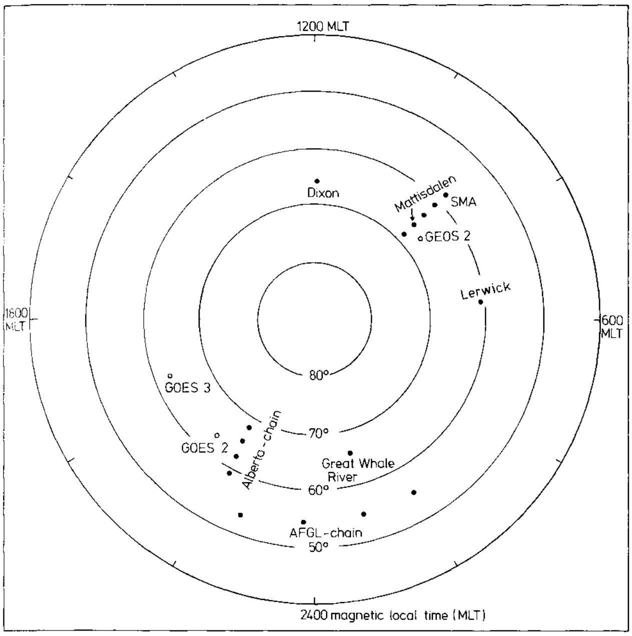

Fig. 1. Magnetic local time distribution of ground magnetic stations and geostationary satellites, from which data were available for 0600 UT. Not all stations of the different magnetometer networks are shown but the networks are indicated schematically

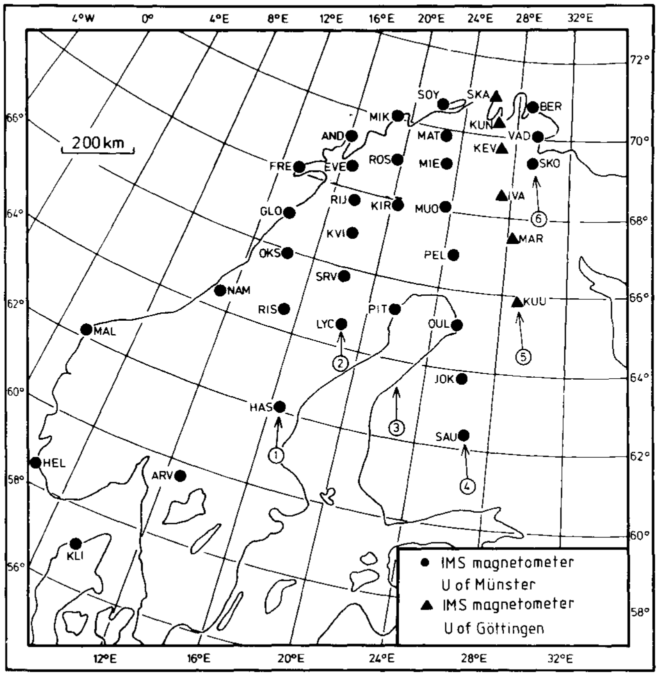

Fig. 2. Station map of the Scandinavian IMS (International Magnetospheric Study) magnetometer array and the Göttingen IMS meridian chain of pulsation magnetometers in geographic coordinates

Table 1. List of ground magnetometer stations used in this study

Code	Name	Geographic		Geomagnetic	
		Lat.	Long.	Lat.	Long.
GWR	Great Whale River	55.3	282.2	64.3	344.8
CHUR	Fort Churchill	58.8	265.9	67.5	323.0
FCMC	Fort McMurray	56.4	248.9	64.2	303.5
FTCH	Fort Chipewyn	56.5	248.9	66.3	303.1
LEDU	Leduc	53.1	246.7	60.6	302.9
SMIT	Fort Smith	60.0	248.0	67.3	299.6
DIK	Dixon Island	73.5	80.6	64.3	144.6
MAT	Mattisdalen	69.8	23.0	66.6	107.8
LE	Lerwick	60.1	358.9	59.8	80.0
SUB	Sudbury	42.2	288.7	55.8	1.9
MCL	Mt. Clemens	42.6	277.1	55.8	344.8
CDS	Camp Douglas	44.0	269.7	56.3	334.2
RPC	Rapid City	44.2	256.9	54.1	317.3
NEW	Newport	48.3	242.9	55.2	299.6

GOES 2 and GOES 3 are displayed in Fig. 1, in local time and geomagnetic latitude for 0600 UT. The GEOS 2 position shown is the approximate position of the footpoint of the GEOS 2 field line while GOES 2 and 3 positions were determined as the ground positions having the same geographic longitude as the satellite and, for the geomagnetic latitude, using the invariant latitude corresponding to the L-value 6.6 of the geostationary orbit in a dipole magnetic field. Thus these latter positions only roughly indicate the footpoints of the GOES 2 and 3 magnetic field lines. Figure 2 displays the locations of the stations of the Scandinavian Magnetometer Array (SMA; see Küppers et al., 1979) and the Göttingen chain of pulsation magnetometers. In Table 1 geographic and corrected geomagnetic coordinates of those magnetic stations noted elsewhere in the following are given. For more detailed descriptions of the magnetometer chains and satellites, from which data are used in this study, the reader is referred to the IMS Source Book (Russell and Southwood, 1982).

Figure 3 shows bandpass-filtered (3 dB points of the bandpass used are 120 s and 600 s) data featuring the ground magnetic field variations in northern Scandinavia and the magnetic and electric fields recorded on GEOS 2. Data from the ground magnetometer station MAT (see Fig. 2) have been chosen as an example in Fig. 3, as they are representative of the magnetic observations in Scandinavia, and MAT is close to the footpoint of the GEOS 2 magnetic field line. The range of the bandpass has been chosen as we shall concentrate on studying pc5 pulsations. The electric field variations shown were measured with the electron gun experiment (Melzner et al., 1978) onboard GEOS 2. For the GEOS 2 electric and magnetic field observations a meanfield-aligned coordinate system $(\mathbf{e}_r, \mathbf{e}_\varphi, \mathbf{e}_\parallel)$ is introduced where $\mathbf{e}_\parallel$ denotes the unit vector in the direction of the mean magnetic field observed by the satellite. $\mathbf{e}_\varphi$ is the unit vector perpendicular to $\mathbf{e}_\pi$ and to the earth's axis of rotation which points eastward, and the unit vector $\mathbf{e}_r$ completes the $(\mathbf{e}_r, \mathbf{e}_\varphi, \mathbf{e}_\parallel)$ triad. (E_r, E_φ) and $(b_r, b_\varphi, b_\parallel)$ denote the electric and magnetic disturbance field vectors, respectively, in this system. The mean magnetic field has been determined as a moving average of the measured magnetic field over half-hour intervals.

Both at the ground and at GEOS 2, our observations (Fig. 3) show prominent pc5 pulsation activity lasting for several hours. The activity is not really continuous but exhibits a clear wave-packet structure which is most clearly visible on the ground. The obvious difference in the main periods of the oscillations in the E_r trace ($T \sim 200$ s) and the b_φ trace ($T \sim 400$ s) during the interval 0500–0800 UT

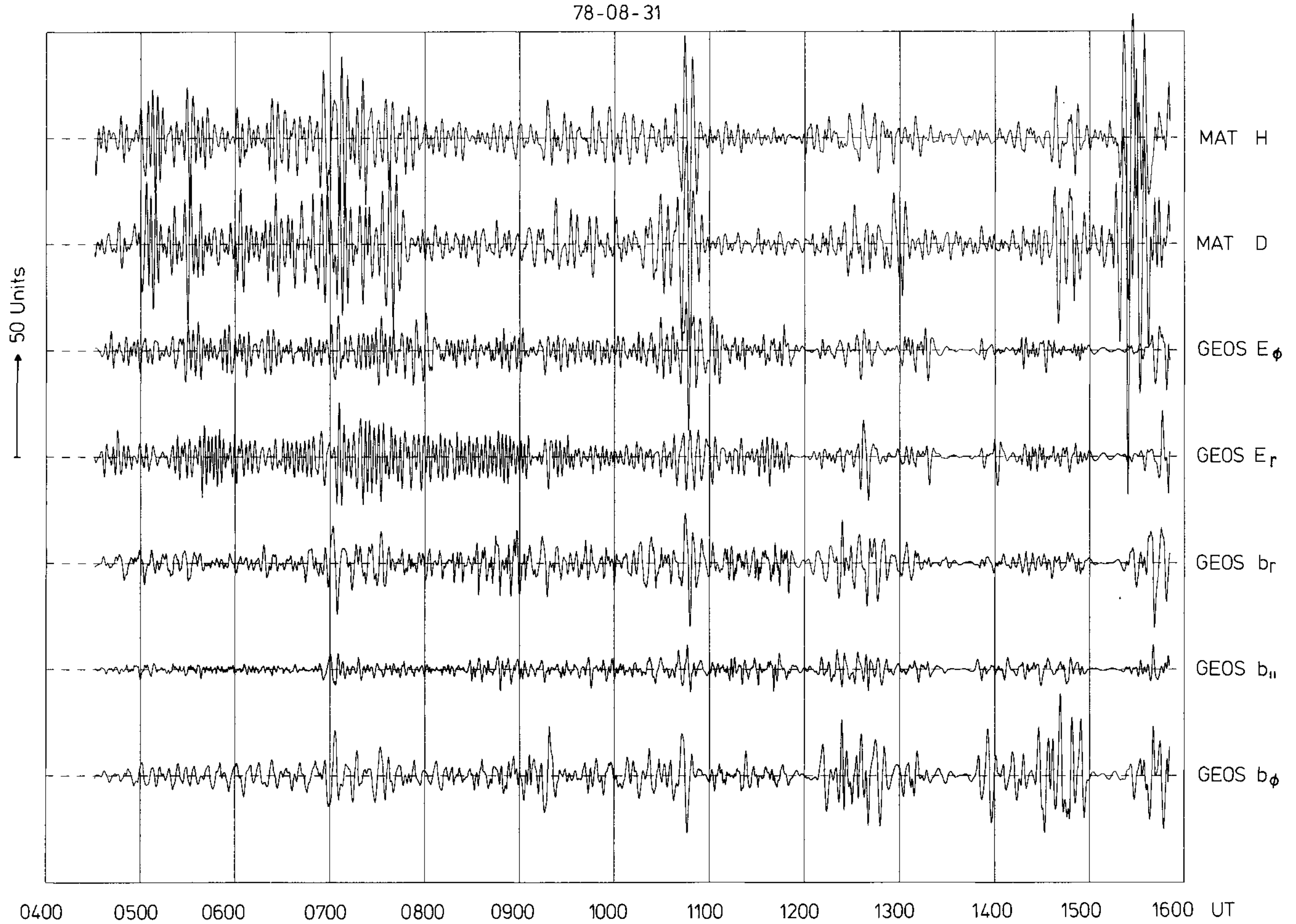

Fig. 3. Bandpass-filtered records of the magnetic observations made at MAT (cf. Fig. 2) and of the electric and magnetic field measured on GEOS 2; data are given in units of nT (for the ground magnetic field) and 10^{-1} nT and 10^{-1} mV/m (for the satellite magnetic and electric field). The bandpass used is between $120\ \mathrm{s} < T < 600\ \mathrm{s}$

may indicate that a fundamental and a second harmonic magnetic field line oscillation was observed by GEOS 2 (e.g. Takahashi and Mc Pherron, 1982). During the interval under discussion general magnetospheric activity was characterized by K_p values in the range from 4 to 5; D_{st} was about -65 nT throughout the whole interval. The interplanetary magnetic field was substantially southward after 0500 UT, until around 1600 UT on August 31, 1978.

In the following analysis of this data set we shall concentrate on three major points related to the question of possible source mechanisms responsible for the observed pc5 pulsations:

1) The Kelvin-Helmholtz instability in the magnetopause boundary region is a likely candidate as a source mechanism for pc5 pulsations. This mechanism allows, for example, predictions on local time variations of the azimuthal phase propagation direction of pc5 signals. While Green (1976) found no obvious diurnal pattern in the phase propagation, Olson and Rostoker (1978) came up with the result of westward propagation in the morning hours and eastward propagation in the afternoon hours, which is quite in accord with a Kelvin-Helmholtz instability source mechanism. Thus, further observational work is necessary, and we shall check whether our observations are compatible with a Kelvin-Helmholtz instability source mechanism.

2) As can be seen from Fig. 3, at around 1040 UT an isolated, large-amplitude pc5 pulsation event is recorded both on the ground and in space. At about the same time the satellite pair ISEE 1 and 2 crossed the magnetopause on an inbound orbit. Thus an in-situ view of the structure of the magnetopause boundary layer region during a pulsation event recorded at the ground and in the geostationary orbit is possible. Therefore, this event deserves special attention and the relevance of flux transfer events (e.g. Russell and Elphic, 1979; Saunders, 1983) at the magnetopause as a source of impulsive pulsations, as suggested by Russell and Elphic (1979), is regarded.

3) Just as non-steady field line reconnection at the dayside magnetopause may be related to pc5 generation (e.g. Reid and Holzer, 1975) so, in a similar way, substorm-associated changes in the night-time magnetosphere may be related to pc5 activity. Observational evidence for a correlation of substorms or substorm intensifications in the nighttime magnetosphere and corresponding pc 4–5 pulsations in the daytime magnetosphere was found by Samson and Rostoker (1981). Having simultaneous ground magnetic and satellite observations available from the night-time sector (in our case the American sector) and the daytime sector (the European sector) of the magnetosphere, we can contribute further to this question.

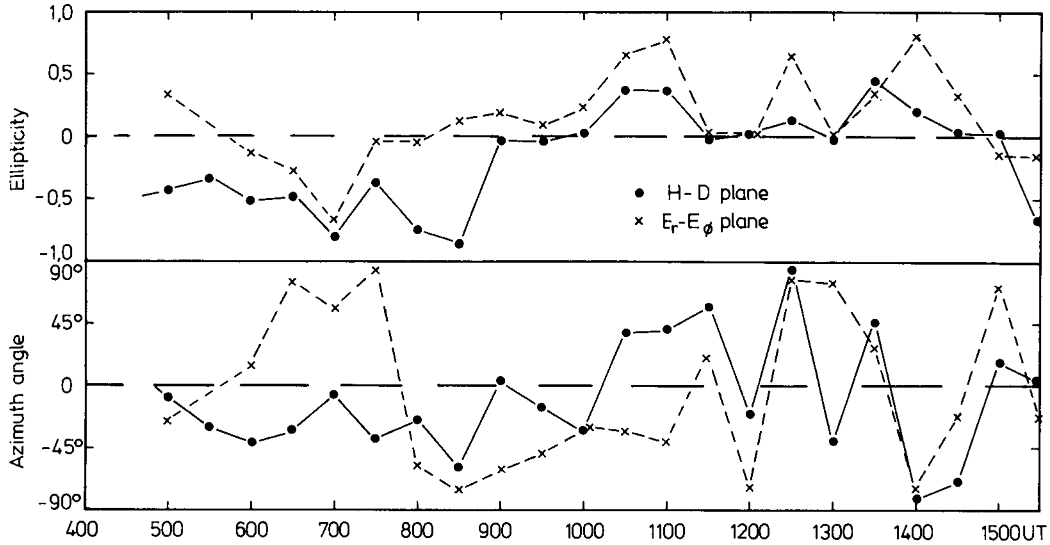

Fig. 4. Results of a polarization analysis of the ground magnetic horizontal disturbance vector at MAT and the electric field variation in the plane perpendicular to the ambient magnetic field at GEOS 2. Azimuth is counted positive from D to H or from E_φ to E_r, respectively; sense of rotation is clockwise (counterclockwise) if the ellipticity is positive (negative) and when looking in the direction of the ambient magnetic field

Local time behaviour of pc5 on August 31, 1978, and the Kelvin-Helmholtz instability

The Kelvin-Helmholtz instability in the magnetopause boundary-layer region has been suggested as a possible source mechanism for ULF pulsations (see Southwood and Hughes, 1983, and references therein). From it, together with the field line resonance theory, predictions can be made on the local time behaviour of the pc5 activity at one particular station and on the Universal Time dependence of the pulsation behaviour at stations separated in local time. For example, one would expect to observe counterclockwise (clockwise) rotation of the horizontal magnetic or electric field disturbance vector south of the resonance region in the morning (afternoon) sector. Furthermore, longitudinal phase propagation should be in the direction of the solar wind or the plasma bulk velocity in the low latitude boundary layer, i.e. to the west on the morning side and to the east on the afternoon side. Thus changes of characteristic parameters, such as the sense of polarization or EW phase velocities, are expected to occur when crossing the local time sector of the stagnation point of the solar wind flow around the dayside magnetopause.

When doing a corresponding data analysis, it may be of importance to note that there exist different results concerning the exact location of the stagnation point. Hundhausen et al. (1969) and Formisano (1979) report an 8° (i.e. 0.5 h) westward deflection of the stagnation point from the earth-sun line, thus confirming early theoretical predictions by Walters (1964) and Axford (1963). On the other hand, Zhuang et al. (1981) found only an insignificant deflection from the earth-sun line from their model calculations.

Around the stagnation point, generation of hydromagnetic waves by the Kelvin-Helmholtz instability will probably be suppressed in a broader region. As Sen (1965) concluded, the magnetopause may be expected to be stable with respect to the Kelvin-Helmholtz instability for about 1.5 h before and after the stagnation point local time. In about the same region, the so-called depletion layer has been found just outside the magnetopause (see, for example, Haerendel and Paschmann, 1982). Such a layer of very low plasma density results in conditions at the magnetopause which are stable against the Kelvin-Helmholtz instability. Altogether, it may be expected that pc5 amplitudes are suppressed in a 3–4 h sector around the local time of the stagnation point, i.e. from about 10 MLT to about 13 MLT.

Considering this latter point, we can see from Fig. 3 that the pc5 activity in northern Scandinavia (station MAT) is relatively small from about 0800 UT to about 1030 UT and from 1100 UT to about 1430 UT. The first interval coincides rather well with the above-mentioned interval of presumed wave-generation suppression, because magnetic local noon occurs at about 0930 UT at MAT. On the other hand, the GEOS 2 electric and magnetic field data do not show a similar decrease of activity during this interval.

More convincing results were obtained by comparing the sense of polarization of the horizontal magnetic disturbance vector in northern Scandinavia and of the electric field disturbance vector at the GEOS 2 location as a function of local time with the predictions mentioned above. For that comparison we calculated cross-spectral densities for the H or E_r and D or E_φ components, respectively, from which the polarization parameters of the waves are calculated (e.g. Rankin and Kurtz, 1970). The cross-spectral analysis has been performed for 1-h segments, with the segments overlapping for 0.5 h. The main results of this polarization analysis are shown in Fig. 4 where the ellipticity is shown of that frequency component having maximum power in the analysed interval. The time assigned to each measurement is the centre time of the analysed interval. Positive (negative) ellipticity corresponds to a clockwise (counterclockwise) sense of polarization when looking in the direction of the earth's magnetic field. The frequencies of the spectral components whose polarization parameters are shown vary in the range 3–5 mHz and show a slight tendency to decrease towards noon. Obviously, the sense of polarization of the horizontal ground magnetic distur-

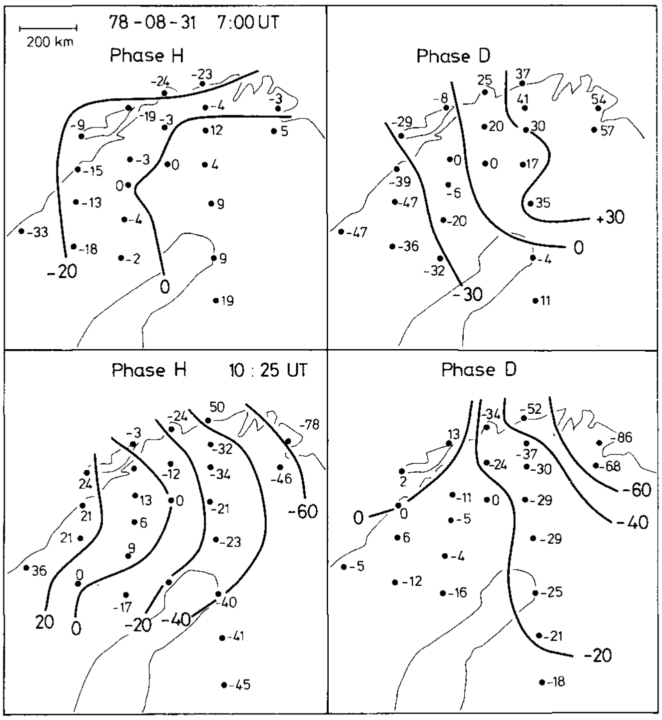

Fig. 5. Spatial distribution of Fourier phases relative to the station Kiruna for the horizontal components of the ground magnetic disturbance computed for the time intervals 0700–0740 UT and 1025–1105 UT; the frequency of analysis is 3.25 mHz and 2.73 mHz, respectively

bance vector changes sign around MLT noon (about 0900 UT), from counterclockwise before 0900 UT to clockwise after 1000 UT. The electric field onboard GEOS 2 indicates a similar change of the sense of polarization, though a little less clearly and possibly 1 h earlier. These results are consistent with the field line resonance theory and solar wind-controlled energy source if the ground magnetometer station is south of the resonant field line and the satellite earthwards of it.

We added the azimuth angle (counted positive counterclockwise from the D or E_φ direction in Fig. 4) because calculations by Chen and Hasegawa (1974) gave the result that this angle should also change sign when crossing the meridian of the stagnation point. However, in our case such behaviour is only barely observed and only for the ground magnetic field vector. Until around 1000 UT the azimuth of the ground magnetic disturbance is predominantly in the first quadrant of the H-D plane, as anticipated by the above-mentioned theory, whereas after 1000 UT it behaves in a rather chaotic manner. There is a change in the azimuth observable in the satellite electric field data at around 0800 UT from being predominantly in the second quadrant of the $E_r - E_\varphi$ plane before that time and in the first quadrant after that time. This also agrees with the calculations of Chen and Hasegawa (1974) if one assumes that the wave polarization ellipse undergoes a significant rotation when passing the ionosphere (e.g. Hughes, 1974; Glaßmeier, 1984).

The Institute of Geological Sciences (IGS) magnetometer stations in the United Kingdom meet the stagnation point meridian almost two hours later than MAT. For one of these stations, namely Lerwick, we performed a similar analysis as for MAT and found a clear sense-of-polarization-switch at around 1100 UT, i.e. about 1130 MLT. Before that time predominantly counterclockwise sense of polarization of the horizontal disturbance vector is observed while for the hour 1100–1200 UT the sense of polarization in the pc5 frequency range is predominantly clockwise. This result at first sight additionally supports the idea of the Kelvin-Helmholtz instability as a source mechanism. However, one should note that the pulsation event at 1040 UT (which will be discussed below) exhibits special features and that it is during this event when the polarization changes sign at Lerwick.

As mentioned above, the EW phase propagation direction may be considered as another critical parameter when discussing the Kelvin-Helmholtz instability as a possible source mechanism for pc5 pulsations. To determine this phase propagation over the Scandinavian Magnetometer Array around MLT noon, a spectral analysis was done for several selected time intervals before MLT noon and the interval 1025–1105 UT after MLT noon when pc5 amplitudes were large enough to allow a reliable determination of phase differences between different stations. For every station of the array that spectral component of the H and D records which has maximum power in the pc5 frequency range was determined. Then, phase differences for both components, H and D, with reference to the H and D traces recorded at Kiruna have been determined for that spectral component which most often has been found as the component with maximum power in the particular interval.

As a typical example of the situation before MLT noon, isocontours of the phase differences for the interval 0700–0740 UT are displayed in Fig. 5 (top panel) for the frequency component 3.25 mHz. The phase contours shown are consistent with a westward-travelling wave, both for the H and the D components. The eastward deflection of the contour lines of the H component near the station line AND – MAT – VAD (cf. Fig. 2) can be attributed to the proximity of a field line resonance region north of this line, as prominent changes of the phase are expected across the resonance region (see, for example, Southwood, 1974). Estimation of the apparent azimuthal wave number m along the EW profile FRE – EVE – ROS – MIE – SKO (cf. Fig. 2) from both the H and D components gives a mean value $m = 6.3 \pm 1.4$ (positive m corresponding to westward, negative m to eastward, phase propagation) or a phase velocity $V_{ph} = 9.4 \pm 1.7$ km/s, a value consistent with earlier results by Olson and Rostoker (1978).

For the time interval 1025–1105 UT on the afternoon side of the stagnation point, the analysis shows eastward-propagating phase fronts (bottom panel of Fig. 5) for the frequency 2.73 mHz. The apparent azimuthal wave number, m, determined from the same EW station line as before, gives $m = -6.0 \pm 1.5$ and $V_{ph} = -7.7 \pm 1.6$ km/s, i.e. an m-value similar to that observed before magnetic noon. Both results on the direction of phase propagation are obviously in accord with the predictions to be made from a theory which invokes the Kelvin-Helmholtz instability as the source of pc5 pulsations.

The 1040 UT pc5 event

The agreement discussed above between observations and predictions from the Kelvin-Helmholtz instability source mechanism for pc5 pulsations is partly based on the well

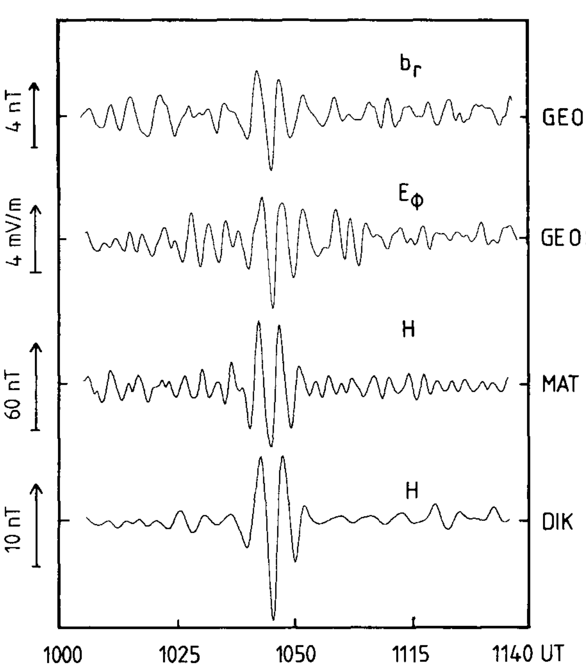

Fig. 6. Bandpass-filtered ($120\,\mathrm{s} < T < 600\,\mathrm{s}$) records of the b_r and E_φ components from GEOS 2 and the H components from the ground magnetometer stations DIK and MAT for the August 31, 1978, 1040 UT event

isolated, large amplitude wave packet occurring around 1040 UT. However, this event seems to deserve special attention because it coincides with a presumable flux transfer event (e.g. Russell and Elphic, 1979) at the magnetopause detected by the satellite pair ISEE 1 and 2.

In Scandinavia the event starts at about 1037 UT (i.e. about 1310 MLT) and lasts for about 20 min, as shown in Fig. 6 for the H trace from MAT. Also shown is the H trace from the station DIK east of Scandinavia. The apparent simultaneous appearance of this event at the two stations, separated by about 2.5 h in magnetic local time, must be taken with care as the DIK H trace has been digitized from a normal run magnetogram, and we estimate the time accuracy for this digitized trace to be about ± 2 min. However, the similarity of the wave forms of the H traces at MAT and DIK suggests that both stations are recording the same pulsation event.

We have added in Fig. 6, as an example, the E_φ and b_r traces of the electric and magnetic disturbance field observed on GEOS 2. The signals have a wave form similar to those at the ground, and the periods of the magnetic and electric field variations are similar ($T \sim 360$ s). This is different as compared to the interval 0500–0800 UT where **E** and **b** have different main periods (see above) and suggests that no higher harmonic standing field line oscillations have been invoked.

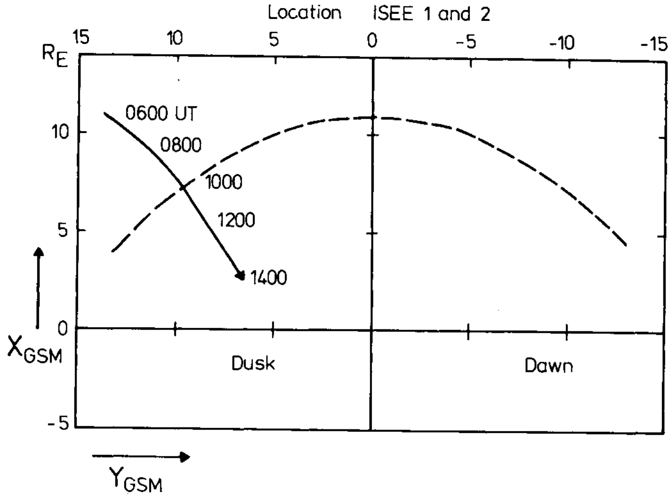

Fig. 7. ISEE 1 and 2 location during the August 31, 1978, 0400–1400 UT interval

When the 1040 UT event occurred, the two closely spaced satellites ISEE 1 and 2 were located near the magnetopause in the afternoon sector at about 1500 MLT (see Fig. 7). Figure 8 shows the magnetic field observed by the satellites in the so-called boundary normal coordinate system (see Russell and Elphic, 1979), where B_N denotes the component normal to the estimated magnetopause (positive, if outwards directed), the B_L component points, if positive, roughly northwards such that the GSM Z axis lies in the $B_N - B_L$ plane, and the B_M component points roughly westward (if positive), completing the (B_N, B_L, B_M) triad. Before 1017 UT the satellites were in the magnetosheath when a boundary crossing occurred, as can be seen from the change of negative to positive B_L values at this time. Between 1025 UT and 1046 UT ISEE 1 and 2 were definitely inside the magnetosphere, observing several minor field perturbations. One of them, which occurred from 1040 UT to 1042 UT at the position of the satellites, shows signatures which may, very probably, be interpreted as being due to a flux transfer event (FTE). Flux transfer events were first clearly recognized by Russell and Elphic (1979) (see also the review by Saunders, 1983) and are interpreted as signatures of patchy and impulsive reconnection at the front side magnetopause. In the boundary normal coordinate system an FTE is characterized by a bipolar (positive excursion followed by a negative one) perturbation in B_N together with a deflection in the tangential components (Saunders, 1983). The magnetic field signatures observed at 1040 UT by ISEE 1 and 2 are not as clear as those usually observed with a flux transfer event. This is probably because the observations are made close to a magnetopause crossing, indicated by the negative B_L component at 1046 UT. Therefore, a clear identification is not certain and the observed variations are classified as FTE-like. However, this FTE-like event may give rise to magnetopause boundary oscillations that could also be the source of the magnetic pulsation event observed at about 1040 UT. That this event starts at 1037 UT at MAT, i.e. a few minutes earlier than the FTE-like event, does not preclude an identification of the FTE as a source of the pulsation since the localized flux tube in an FTE is pulled along the magnetopause due to the tension of the reconnected field lines. Thus 1040 UT may be the time when the FTE passes the satellite pair.

The two re-entries of the satellite pair back into the magnetosheath at about 1046 UT and 1048 UT indicate such boundary oscillations. As ISEE 1 and 2 are on an inbound orbit, it should be possible to observe the magnetic field perturbations caused by the FTE-like event within the outer magnetosphere. But between 1100–1150 UT no ISEE 1 and 2 data are available and it is only after 1150 UT that the satellite pair records an irregular, but continuous train of magnetic field oscillations in the pc5 band (data not shown).

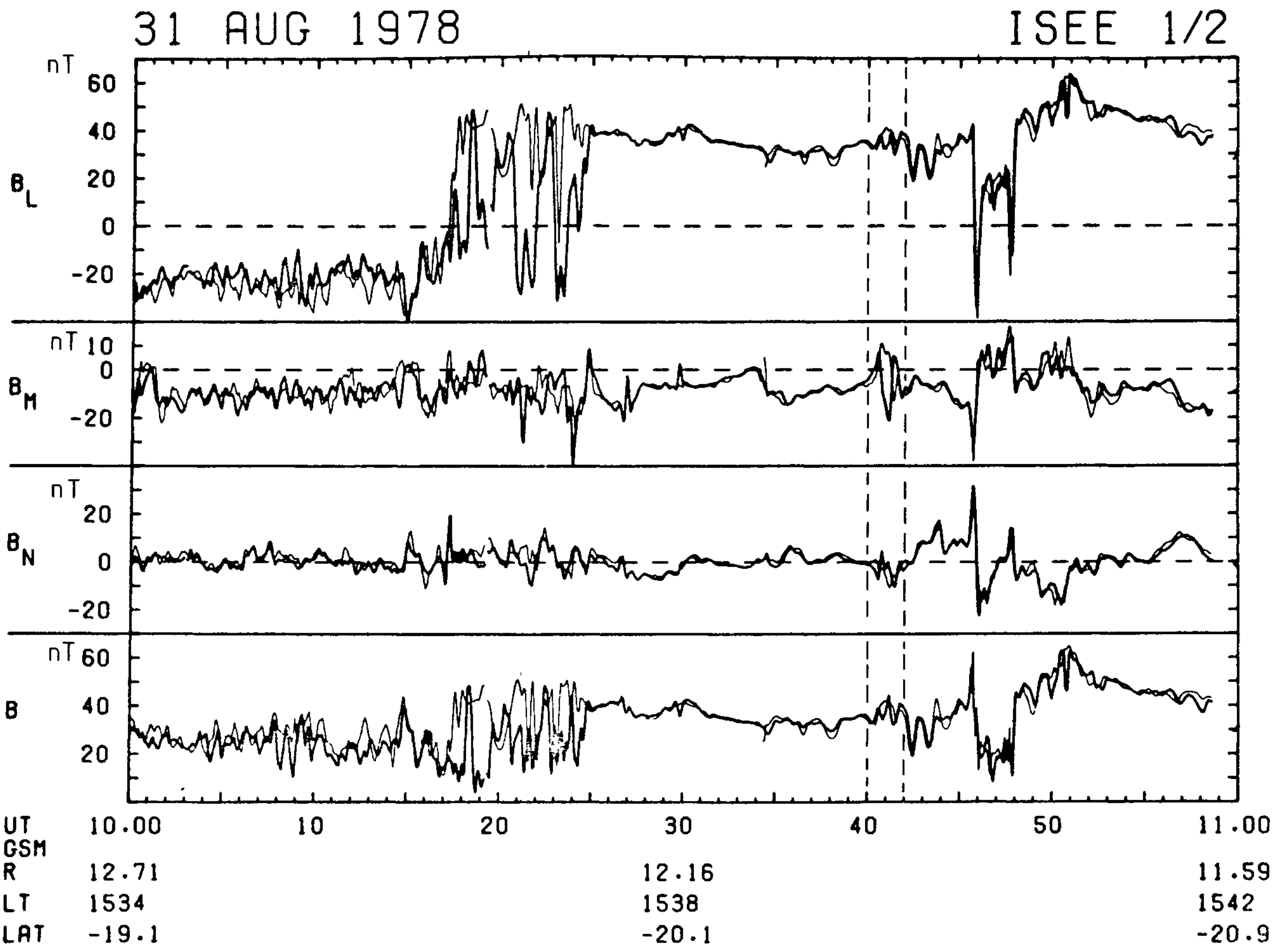

Fig. 8. ISEE 1 (*thin line*) and 2 (*thick line*) magnetic observations in the boundary normal coordinate system (see text). *B* is the total magnetic field amplitude. The observations are given in units of nT Satellite positions are given (*at the bottom*) in terms of geocentric radial distance (*R*) in earth radii, and GSM local time (*LT*) and latitude (*LAT*)

If the FTE-like event at 1040 UT is somehow related to the pulsation event observed simultaneously on the ground, the velocity of the FTE along the magnetopause may be seen as a group velocity of the magnetic field disturbance over Scandinavia, for example. For this region, a detailed analysis of the amplitude distribution of the horizontal magnetic disturbance has been carried out using the method of the analytical signal (see, for example, Glaßmeier, 1980). As a result Fig. 9 displays instantaneous amplitude curves, i.e. the envelopes of the observed *H* and *D* traces together with the *H* and *D* traces themselves along an EW profile of ground stations (cf. Fig. 2). From the dashed lines in Fig. 9, connecting corresponding maxima or minima along the EW station line, we deduce a westward velocity of about 4 km/s. No corresponding poleward or equatorward movement is found. If the westward movement is considered to be a direct image of processes in the magnetospheric boundary region, a velocity of the order of 100 km/s may be deduced for that region (the distance of the magnetopause from the earth's surface is assumed to be 10 R_E). In fact, this is the magnitude of typical plasma velocities in the low latitude boundary layer. Along a NS station line no corresponding poleward or equatorward movement is detectable in the ground magnetic data.

A further interesting observation during the 1040 UT event concerns the Poynting vector **S** describing the energy flux transported by the wave field at the GEOS 2 location. It has been estimated from bandpass-filtered data (3 dB points of the bandpass used are 120 s and 600 s) and we obtained, for averaged values over the interval 1035–1100 UT, the interesting result

$$\begin{aligned} S_r &= 25\times10^{-8}\ \mathrm{W\,m^{-2}},\\ S_\varphi &= -7\times10^{-8}\ \mathrm{W\,m^{-2}},\\ S_\parallel &= -98\times10^{-8}\ \mathrm{W\,m^{-2}}. \end{aligned}$$

The field-aligned Poynting flux is probably due to Joule dissipation in the ionospheres both of the northern and southern hemispheres. The point along a field line where this field-aligned Poynting flux changes from a northward to a southward one is called the null point (Allan, 1982). If we interpret the magnetic and electric field variations at 1040 UT as being due to a standing hydromagnetic wave in the magnetospheric cavity, the comparably large field-aligned Poynting flux indicates that GEOS 2 is located southward of such a null point. The westward-directed azimuthal Poynting flux, i.e. the negative S_φ component, is in agreement with a westward group velocity as deduced from the ground observations in Scandinavia. However, the large radially outwards-directed energy flux is particularly surprising, as one would expect an inward Poynting flux for a wave generated at the magnetopause. No conclusive explanation for this observation can be given. But it

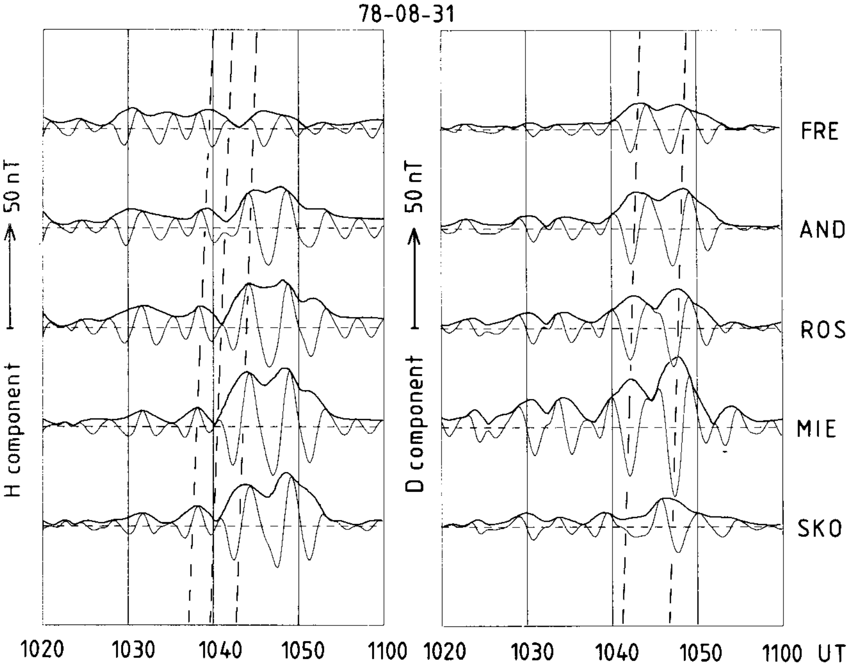

Fig. 9. Instantaneous amplitude curves (*thick line*) and corresponding H and D traces along an EW station line in northern Scandinavia. *Dashed lines* connect corresponding maxima and minima of the instantaneous amplitude

should be noted that later on, after 1200 UT, magnetic field disturbances, again travelling radially outwards, are clearly observed by the ISEE 1 and 2 satellites in the magnetosphere.

Relation between dayside pc5 activity and nightside substorms

The response of dayside pc5 pulsations to substorm activity in the nightside magnetosphere has been studied by Samson and Rostoker (1981), who found that each substorm onset during the time intervals they looked at was associated with an increase in the dominant frequency of pulsations occurring on the dayside near local noon. In a subsequent study, Rostoker et al. (1984) examined the response of pc5 activity across the morning sector to substorm expansive phase onsets near midnight. They found that the behaviour of pc5 activity at substorm onset differed from event to event, depending on whether the observing stations were near dawn or closer to noon. In particular, pulsation activity in the pc5 frequency range appeared to intensify at stations near dawn, whereas the frequency shift out of the pc5 spectral band and into the pc4 band reported earlier by Samson and Rostoker (1981) tended to be observed closer to noon.

In our case, we used data from North America in addition to the data from the Scandinavian sector discussed above to examine further such a relationship. Figure 10 shows corresponding ground magnetic H observations from the array of magnetometers in central and northern Canada where magnetic midnight occurs between 0800 and 1100 UT. These data exhibit a series of substorms or substorm intensifications while the pc5 pulsations observed on the dayside in, or over, Scandinavia (Fig. 3) show a clear packet structure, especially in the ground magnetic data. Thus it is tempting to try at first to correlate substorm onsets or intensifications with pulsation trains. To facilitate such a detailed comparison, Fig. 11 gives the H records from FTCH (cf. Fig. 10) and pure state filtered data (Samson, 1983) from LEDU together with bandpass-filtered ($120\ \mathrm{s} > T > 600\ \mathrm{s}$) data from the H component at MAT and the E_r component at GEOS 2. In addition, Fig. 12 exhibits filtered (in the pi2 period range) data of the NS component of the geomagnetic disturbance field recorded along the Air Force Geophysics Laboratory (AFGL) mid-latitude, east-west magnetometer chain (cf. Fig. 1).

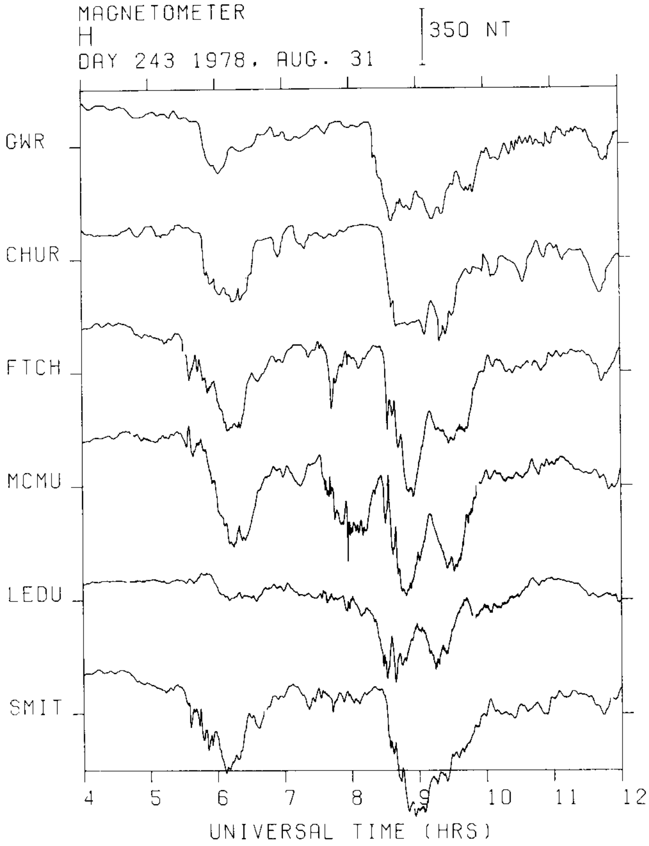

Fig. 10. Magnetic records of the H component at stations of the Canadian magnetometer array

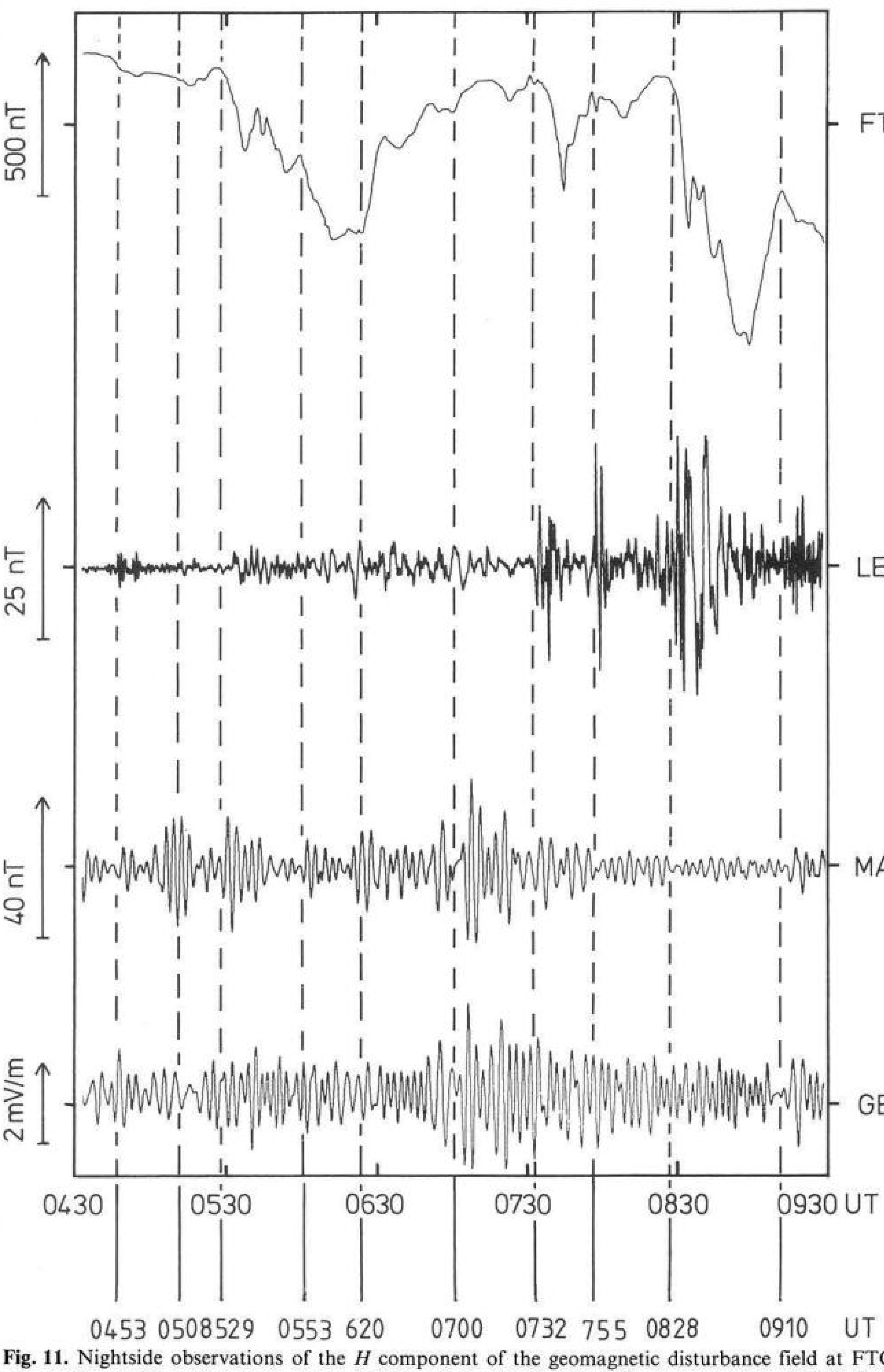

Fig. 11. Nightside observations of the *H* component of the geomagnetic disturbance field at FTCH and LEDU, together with dayside observations of the *H* component at MAT and the E_r electric field component on GEOS 2 (both records bandpass filtered in the range 120–600 s). *Dashed lines* indicate times of major events listed in Table 2

To demonstrate the variety of daytime pc5–night-time substorm correlation observable in Figs. 11 and 12 some examples are discussed in detail below. A complete overview is given in Table 2 where the times given denote the beginning or time of maximum amplitude of pc5 wave packets, pi2 activity or any other prominent change in the magnetic field observed on the nightside. To perform this overview we used magnetic field observations of the two geostationary satellites GOES 2 and 3 (located in the night-time part of the magnetosphere) in addition to the ground data.

At about 0450 UT a pc5 wave packet is observed in the dawn sector while two pi2 pulsations are observed on the nightside, as can be seen from the LEDU record (Fig. 11) and the records of the AFGL mid-latitude chain (Fig. 12) at 0445 UT and 0453 UT, respectively. The corresponding high-latitude observations (Fig. 10) indicate a

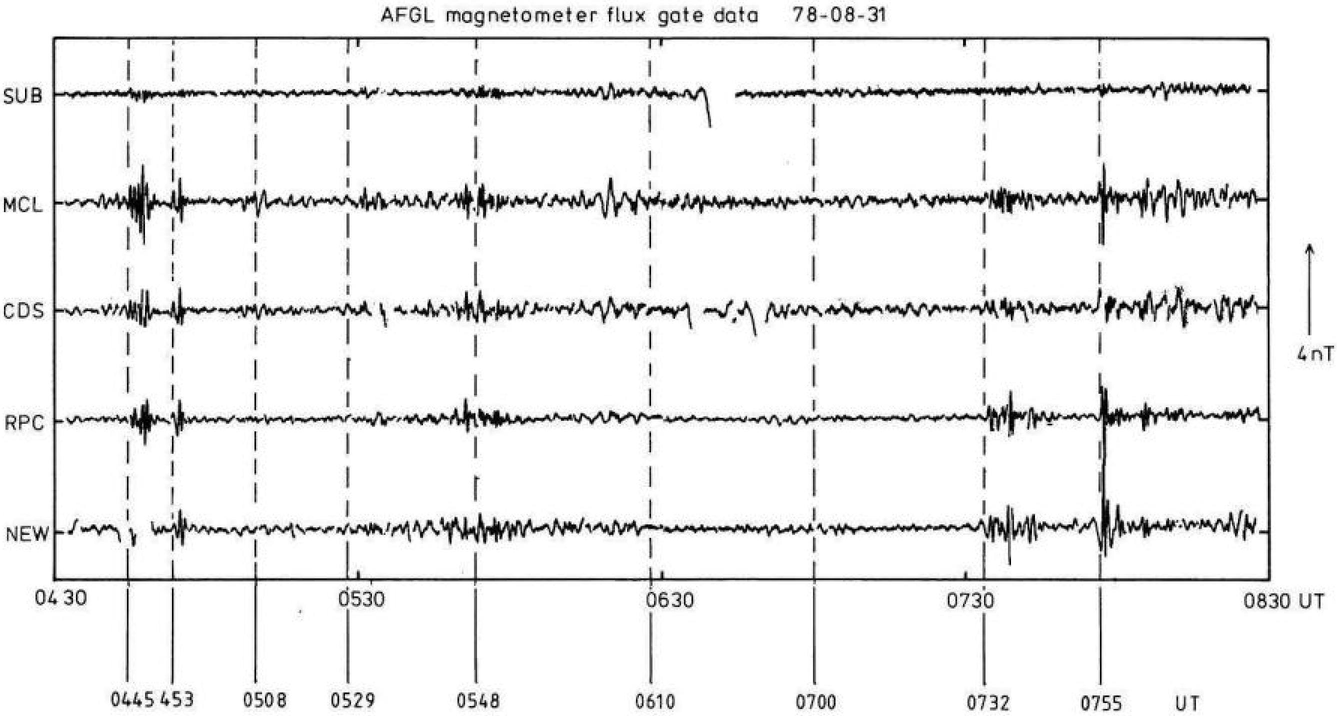

Fig. 12. Bandpass-filtered (50 s $< T <$ 150 s) data of the NS component of the geomagnetic disturbance field at the stations of the AFGL mid-latitude chain

Table 2. Times of occurrence of major pc5 wave packets, pi2 events, substorm onsets, *D*-spikes or other rapid changes of the magnetic field in the nightside magnetosphere during the interval 0400–0930 UT on August 31, 1978

Time (UT)	pc5	Substorm	Remarks
0445	Yes	Yes	Onset; pi2; dipolarization (GOES 2)
0453		Yes	Pi2 at AFGL chain
0500	Yes	Yes	*D* – spike (GOES 2)
0528	Yes	Yes	Onset; no clear pi2; neg. bay (GOES 3)
0548		Yes	
0553	Yes	Yes	Several intensifications; pi2;
0556		Yes	increase in *H* at GOES 3
0605	No	Yes	Recovery phase
0620	Yes	Yes	Rapid change of magnetic field (Canadian chain)
0635	Yes	Yes	Rapid change of magnetic field (Canadian chain)
0655	Yes	?	Increase of *H* at AFGL chain
0700	Yes	No	No pi2 activity
0720	Yes	?	No clear sudden change in nightside sector, but short long period effect visible at LEDU
0732	Yes	Yes	Onset; pi2; negative spike at GOES 3
0755	Yes	Yes	Pi2 activity
0828	?	Yes	Onset; pi2; sudden change at GOES 3
0850	No	Yes	Sudden recovery at Canadian array but substorm does not end
0910	No	Yes	Clear intensification at Canadian chain

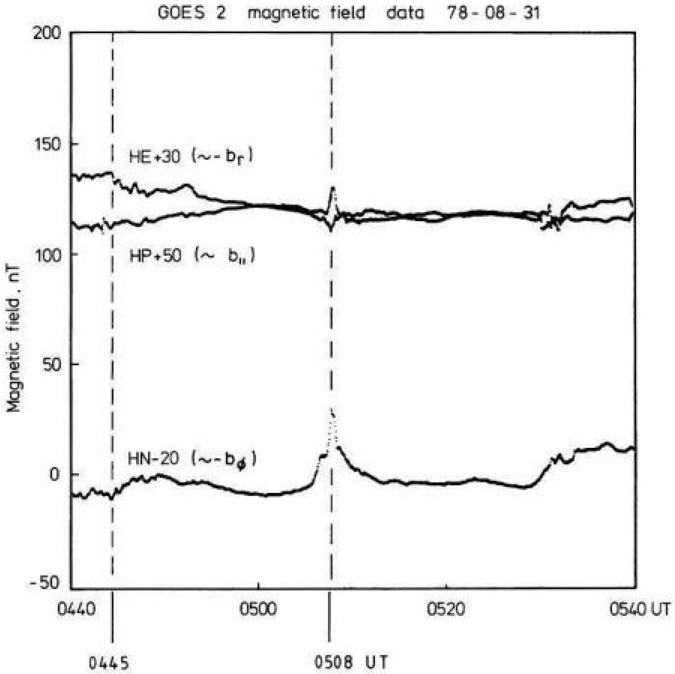

Fig. 13. GOES 2 magnetic observations for the time interval 0440–0540 UT on August 31, 1978; *HE* corresponds to $-b_r$, *HN* to $-b_\varphi$, and *HP* to $b_\parallel$. The numbers at the component code give values which have to be subtracted from the scale value, i.e. *HP* + 50 with a value 120 nT is actually 70 nT

substorm onset, probably east of the Canadian array. At 0445 UT, GOES 2 (Fig. 13) shows a decrease in the *HE* (approximately $-b_r$) component while *HN* (approximately $-b_\varphi$) gradually increases. It should be noted that though there are two pi2 events, only one pc5 wave packet appears.

This is similar to the series of intensifications around 0550 UT (see Table 2) where the time difference between the three successive pi2 events is of the order of the period of the observed pc5 wave packet.

At 0508 UT another pc5 wave packet is associated with a spike in the *HN* (approximately $-b_\varphi$) component observed on GOES 2 (Fig. 13) and accompanied by weak pi2 activity in the North American sector introducing an episode of substorm expansive phase activity which peaks soon after 0600 UT.

An example of apparent absence of a pi2 – pc5 correlation is the pc5 event starting at around 0700 UT with a maximum amplitude at 0708 UT. The event is not accompanied by any pi2 on the nightside, and only a minor change of the *H* component at FTCH (cf. Fig. 11) is observed as it often occurs during the analysed time interval but without relation to the pc5 activity on the dayside.

No substorm–pc5 correlation is found for the interval 0830–0930 UT when strong pi2 activity is observed in the North American sector, but no accompanying pc5 pulsations are recorded in the European sector. Even for the most pronounced substorm onset at 0830 UT no corresponding pc5 was observed.

While there is evidence, at least in some cases, for a relationship between substorm activity or rapid changes of the magnetic field observed on the nightside and pc5 activity observed by ground magnetometers, no such correlation can be found in our data between night-time disturbances and pc5 activity measured onboard GEOS 2 (see Fig. 11). The GEOS 2 electric field shows rather continuous activity, being less structured than the ground magnetic observations.

Summary and conclusions

On August 31, 1978, 0400–1600 UT, pronounced pc5 pulsation activity was observed by ground magnetometer stations and the geostationary satellite GEOS 2 in the European sector (in this case the dayside sector of the magnetosphere). Our main interest in studying this time interval was devoted to the more general question of the energy source of the pulsations observed. Like earlier workers, we came up with the result that the Kelvin-Helmholtz instability at the magnetopause or in the low latitude boundary layer is a likely candidate as a source mechanism for the morning-time pulsation activity. In particular, on comparing observations on the forenoon and afternoon side of the magnetopause, we found changes in the direction of apparent horizontal phase propagation and in the sense of polarization which are predicted by the Kelvin-Helmholtz instability source mechanism. Pulsation activity on August 31, 1978 also ceased at about 1000 MLT, i.e. when approaching the local time sector of the depletion layer (e.g. Haerendel and Paschmann, 1982) or the stability region existing around the stagnation point (Sen, 1965). This is additional evidence for a Kelvin-Helmholtz instability source mechanism. However, it must be noted that a resurgence of the pulsation activity, as suggested by the theory after having passed the meridian of the stagnation point, was not convincingly observed.

Our results concerning the Kelvin-Helmholtz instability are partly based on a rather isolated pc5 wave packet at around 1040 UT (about 1310 MLT in Scandinavia). Analysis of this isolated pc5 event deserved special attention, as simultaneous observations on the ground, within the magnetosphere, and in the magnetosphere's outer boundary region are available. Magnetic field observations by the satellite pair ISEE 1 and 2 indicate the occurrence of an FTE-like event at around 1040 UT. FTEs have earlier been suggested by Russell and Elphic (1979) as a possible source mechanism for long-period hydromagnetic waves. The reconnected flux tubes in an FTE, pulled along the magnetopause, press in on the boundary like a ball moved on the surface of a balloon and thus constitute a large (up to about 1 R_E amplitude; see Daly and Keppler, 1983) ripple driven along the magnetopause.

Two re-entries of the satellite pair back into the magnetosheath at 1046 and 1048 UT possibly indicate such oscillations of the magnetosphere boundary region. Boundary oscillations have also been observed by Fritz and Fahnenstiel (1982) using particle observations. From the ground magnetic observations in northern Scandinavia we deduced an approximate westward group velocity for the 1040 UT pc5 event of about 4 km/s. This corresponds to typical plasma flow velocities at the magnetopause. Daly and Keppler (1983) reported poleward movements of FTEs along the magnetoapuse with a velocity of 100 km/s. No corresponding movement was found in the ground magnetic data.

The Poynting vector determined from electric and magnetic field observations on GEOS 2 shows a westward-directed component which agrees with the observed westward movement found in the ground magnetic data. The large radially outwards-directed component of the Poynting vector derived for the 1040 UT event is surprising, as it suggests a source somewhere earthward of the satellite and remains unexplained. However, further experimental work is required to confirm our conjecture that flux transfer events at the magnetopause may be associated with pc5 pulsation. An obvious question that arises is whether pc5 activity in general correlates with a southward component of the interplanetary magnetic field.

Summarizing our analysis of the substorm–pc5 relationship, we conclude from the detailed information given in Table 2 that certain pc5 wave packets in the morningside are clearly coincident with substorm activity on the nightside. However, the correlation is not strictly one-to-one as, for example, the pc5 event at about 0700 UT is not accompanied by any pi2 in the night-time magnetosphere. Also, after 0830 UT any substorm–pc5 correlation ends and pi2 activity observed in the North American sector is not related to pc5 pulsations. Further theoretical work is required to understand in more detail the propagation of hydromagnetic waves generated in the night-time magnetosphere into the dayside magnetosphere, which may help in the understanding of the partial correspondence of substorm activity and pc5 activity.

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