J Geophys (1982) 51:129–140

Journal of Geophysics

Ground – Satellite Correlative Study of a Giant Pulsation Event

O. Hillebrand[1]*, J. Münch[2], and R.L. McPherron[3]

[1] Institut für Geophysik der Universität Göttingen, Herzberger Landstr. 180, 3400 Göttingen, Federal Republic of Germany
[2] Universität Siegen, Hochschulrechenzentrum, Hölderlinstr. 3, 5900 Siegen 21, Federal Republic of Germany
[3] Department of Geophysics and Space Physics, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, USA

Abstract. Simultaneous observations of a giant pulsation event during local morning by a ground based magnetometer station network and the geostationary ATS 6 satellite magnetometer and particle experiments are analyzed. The phase and polarization of the pg event show the characteristic behaviour of field line resonance, the wave number is 16 and the apparent phase velocity 10 km/s.

The waves at the satellite are compressional; possibly ATS 6 is close to the node of a transverse resonant oscillation. The wavelength in the east-west direction is approximately 2 R_E and in the radial direction less than one R_E. The observations of electrons in the energy range 32–46 keV and of protons in the energy range 25.5–234 keV show the same oscillations as the giant pulsations. At the beginning of the event the electron flux increases and the pitch angle distribution becomes isotropic. It then changes to anisotropic, with increases in the 90° flux and in the amplitude of the oscillations. The pulsations of the proton flux start later. Comparison of the observation with existing theories of pg excitation mechanisms does not give satisfactory agreement.

Key words: Giant pulsation – Pc 4 pulsations – Wave particle interaction – Polarization properties – Magnetic field line resonance

Introduction

History of Giant Pulsation Observations

Giant pulsations are one of the most remarkable types of geomagnetic field fluctuations because of their very regular waveform and comparatively long duration. Their pattern of geographical occurrence meant that early observations and statistical investigations were reported from the auroral zone: Birkeland (1901) was the first to describe the 'magnetic waves' ('ondes magnétiques') which he observed during an expedition to Northern Norway. Large-scale statistical investigations based on long term observations at the three Scandinavian observatories Abisko, Tromsø and Sodankylä were carried out by Rolf (1931), Harang (1932) and Sucksdorff (1939).

Properties of Giant Pulsations

Contrary to what the name might suggest, giant pulsations are not generally characterized by large amplitudes, but range from fractions of a nT, obviously limited by the instrument's resolution or by magnetic background noise, up to several tens of nT. Some authors, however, (e.g. Nagata et al., 1963) call large amplitude Pc 5 events giant pulsations. According to the statistical work of the Scandinavian authors mentioned above the giant pulsations (abbreviated pg), with oscillation periods 50–150 s, belong rather to the Pc 4 class than to the Pc 5 class of pulsations. They are early morning events with occurrence maxima around 03:00 LT (for the very regular 'type A') and around 09:00 LT (for the more irregular 'type B', after Sucksdorff, 1939). They occur predominantly around the equinoxes, usually during quiet magnetic conditions. Harang (1941) remarked that pg tend to occur on consecutive days. Their main characteristic is the very regular waveform in all three components comprising up to 100 consecutive cycles of oscillations. Eleman (1967) pointed out that giant pulsations have a high ratio of vertical to horizontal amplitudes. Giant pulsations arise in the auroral zone, exceptions have however been described: Veldkamp (1960) analyzed a pg which was observed by a large network of stations in mid-latitudes.

The development of high resolution sensors and recording equipment, the improvements in timing accuracy and, more importantly, the use of magnetometer arrays have recently added new details to the knowledge of giant pulsations. Annexstad and Wilson (1968) used data from two approximately magnetic-conjugate stations and came to the conclusion that giant pulsations are even-mode resonant oscillations. In contrast Green (1979) observed odd mode resonant oscillations at conjugate stations. The latter study gives mainly a detailed analysis of the dependence of the polarization parameters on the period of oscillation at two stations of different geomagnetic latitude in the same hemisphere. Hillebrand (1976), Rostoker et al. (1979) and Glaßmeier (1980) found that giant pulsations have resonant characteristics similar to other Pc 4 pulsations, in particular an opposite sense of rotation north and south of a demarkation line where the pulsations are linearly polarized and

* *Present address:* Abteilung für Medizinische Informatik, Universität Göttingen, Robert-Koch-Str. 40, 3400 Göttingen, Federal Republic of Germany

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where maximum amplitudes occur. The pg is usually confined to a narrow region in latitude and can shift its location in the course of an event.

Observations from space of so-called compressional waves have been suspected to be connected with giant pulsations on the ground. A typical example is that given by Barfield et al. (1971) which was compared to data from one ground station by Lanzerotti and Tartaglia (1972), where both observations were shown to be closely connected. Nevertheless, there was no clear evidence that the ground observations were of giant pulsations.

This study connects measurements of a 'compressional' magnetic wave event at the geosynchronous orbit with magnetometer array observations of a giant pulsation in a region close to the foot of the satellite's fieldline. Simultaneous oscillations in the fluxes of electrons and protons at the same frequency occurred in space.

Measurements and Data Presentation

During the IMS (International Magnetospheric Study) the Geophysical Institute of the University of Göttingen operated a pulsation magnetometer chain in Northern Scandinavia. The locations of the temporary stations in 1975 are listed in Table 1, and their geographic positions are marked in Fig. 1 together with the permanent observatories Tromsø (TR), Kiruna (KI) and Sodankylä (SO). All stations are equipped with Grenet type induction magnetometers (Grenet, 1949), recording the three components *H*, *D* and *Z* of the magnetic field fluctuations in the period range 2–600 s, approximately. The instrument's frequency characteristic has a maximum sensitivity around 0.05 Hz. Three of the stations (SKA, KUN and KEV) were equipped with digital recording systems, the other three stations (IVA, MAR and KUU) with FM magnetic tape recorders. The FM tapes can be processed by digitizing equipment and the data are usually converted to the same format as those tapes from the digital stations. The data from all six IMS ground stations are sampled at 1.0 s intervals. The paper chart records from KI and TR were digitized at 2 s intervals. During the time of the pulsation event described here the station MAR was not operating properly.

In the summer of 1975 the geostationary satellite ATS 6 was in a position at 35° E longitude. The satellite carried, among other experiments, a magnetometer and proton and electron detectors. The tri-axial UCLA fluxgate magnetometer has been described by McPherron et al. (1975). A description of the NOAA proton experiment with three different detector telescopes in fixed orientation relative to the spacecraft is given by Su et al. (1979). Details of the electron experiment of the University of Minnesota can be found in the paper by Walker et al. (1976). Figure 1 also maps the position of the foot of the magnetic fieldline through the ATS 6 satellite on the ground.

In 1975 more than two months of simultaneous magnetometer data from ATS 6 and the Göttingen chain of pulsation magnetometers were obtained. These data have been scanned for Pc 4 events in space, and out of 78 intervals which have been studied separately, there were 6 events which could be more or less distinctly identified as giant pulsations on the ground. The most prominent event of this set occurred on 26 June 1975 between 02:30 and 06:00 UT. Local time at the magnetometer chain is: LT = UT + 2.5 h. A four hour segment of the ATS 6 magnetometer record together with data from one of the ground stations (KEV) is plotted in Fig. 2. The upper panel presents the spacecraft magnetometer data in the dipole $VB_{\perp}B_{\parallel}$ coordinate system: $B_{\parallel}$ is antiparallel to the earth's magnetic dipole moment, $B_{\perp}$ is perpendicular to $B_{\parallel}$ and directed azimuthally eastward and V completes the right handed system. Note that $B_{\parallel}$ and $B_{\perp}$ are the same as the H and D of the VDH system (Arthur et al., 1978) and are not necessarily parallel and perpendicular to the local field direction. In the lower panel the KEV data are plotted in the common HDZ magnetic coordinate system. The instrument's frequency response has been removed and both data sets have

Table 1. Station codes, coordinates and *L*-values of the Göttingen IMS pulsation magnetometer stations in Scandinavia, and of the observatories Tromsø and Kiruna. The IMS stations have been operated intermittently between 1974 and 1979

Station	Code	Geogr. coordinates		Geomagn. coordinates		*L* value
		Lat.	Long.	Lat.	Long.	
Skarsvaag	SKA	71°07′	25°50′	67.2°	123.7°	6.8
Kunes	KUN	70°21′	26°31′	66.4°	123.3°	6.4
Kevo	KEV	69°45′	27°02′	65.8°	123.0°	6.1
Ivalo	IVA	68°36′	27°28′	64.7°	121.9°	5.5
Martti	MAR	67°28′	28°17′	63.6°	121.4°	5.1
Kuusamo	KUU	65°55′	29°03′	62.0°	120.5°	4.6
Tromsø	TR	69°41′	19°00′	67.1°	116.8°	6.3
Kiruna	KI	67°48′	20°24′	65.2°	115.6°	5.4

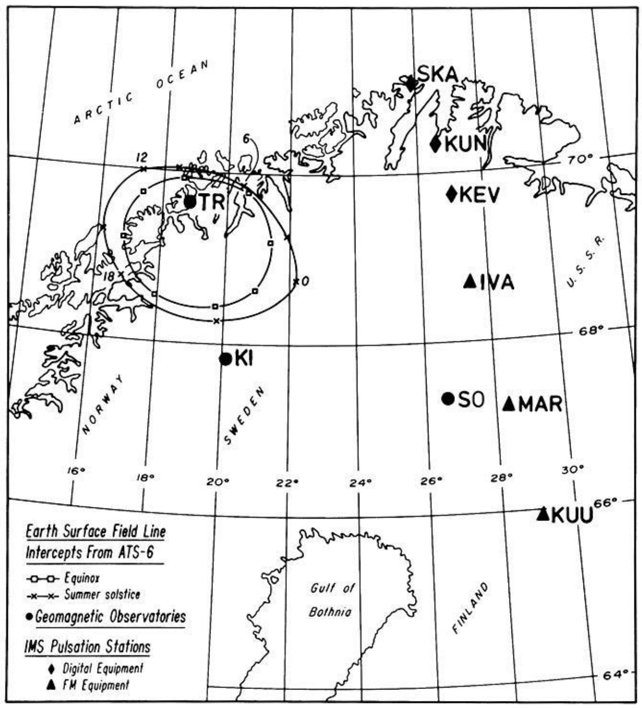

Fig. 1. Map of northern Scandinavia (geographic coordinates) showing the locations of the Göttingen IMS pulsation magnetometer stations (*triangles and diamonds*) and of the three observatories Tromsø (*TR*), Kiruna (*KI*) and Sodankylä (*SO*) (*circles*). Earth-surface intercepts from ATS 6 fieldlines for equinoxes and summer solstice are shown in the NW part of the map (courtesy of Olson and Pfitzer, personal communication)

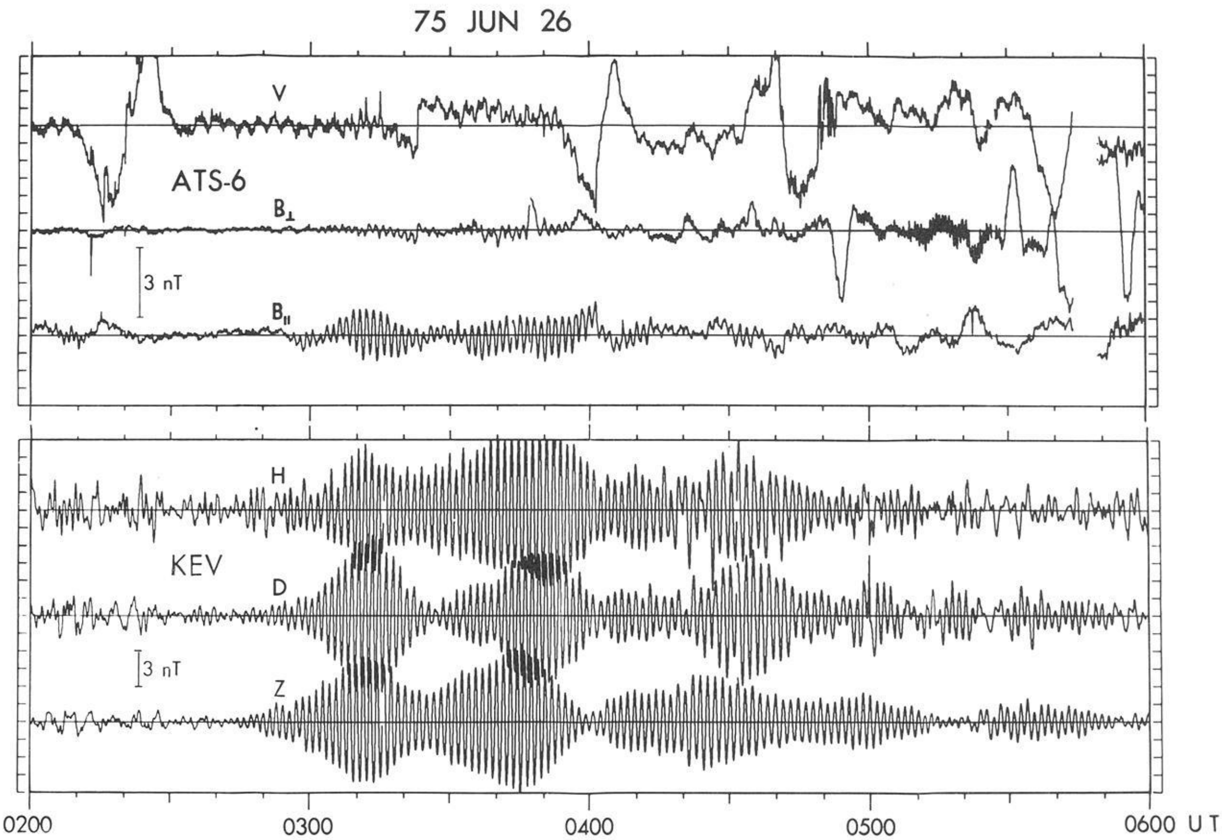

Fig. 2. Giant pulsations (pg) at KEV (*lower panel*) and as recorded by the ATS 6 magnetometer on 26 June 1975

been bandpass filtered in the range 10–1,000 s. Because of the different origins of the magnetograms, this figure presents 5 s averages of both data sets. The ground data show a signature typical of giant pulsations, regular magnetic oscillations with periods around 90 s and a duration of approximately 3.5 h. The signal is strongly modulated, and three distinct amplitudes maxima can be detected in all three components *H, D* and *Z*. The amplitudes of *Z* are large in comparison to those of ordinary Pc 4 pulsations, and peak to peak amplitudes of more than 10 nT can be found in all three components.

The magnetospheric data give a quite different pattern. Oscillations with the same period can be seen distinctly in the $B_{\parallel}$ component and barely in $B_{\perp}$, which means that the oscillations occur mainly in the field parallel direction. This type of pulsation with negligible transverse magnetic oscillations has been called a 'compressional wave' in the literature. The magnetic amplitudes of approximately 1.5 nT are smaller than on the ground. The signals at the spacecraft are slightly modulated, the first two maxima of the ground data also occurring in space, but the third maximum missing. This pattern resembles much more the ground data at Tromsø, which is closer to the foot of the ATS 6 fieldline, than is the Göttingen array. Except for one section of data in Fig. 3, a complete magnetic record from TR is not shown here but the amplitude pattern at TR can be seen in Fig. 7b. During the third interval there are oscillations of less than 2 nT at TR whereas there are amplitudes of roughly 5 nT during the first two maxima.

In order to get a more detailed picture of the giant pulsations on the ground, half an hour of pulsations from all seven available stations is shown in Fig. 3. With the exception of Tromsø (TR) and Kiruna (KI), which are situated some 300 km west of the magnetometer chain, the magnetograms are plotted in order of latitude along the meridian profile, each component separately. This is a plot of original magnetometer data without a correction for the instrumental frequency response. The data however can be compared since we use the same type of instruments at all stations. Clearly, the horizontal amplitudes have their maximum around KEV where large vertical amplitudes can also be found. North and south of this station the amplitudes decrease. An exception is SKA (North Cape station) where the large vertical amplitudes are caused by the induction anomaly at the sea shore. There is almost no phase difference in *D* between the stations along the meridional magnetometer chain. TR and KI which are separated in longitude have a phase lag of approximately 120° from those stations in the east. There are also phase differences in *H* between the stations on the north-south chain.

A forty-five minute section of the giant pulsations as observed by the two particle experiments on board ATS 6 is given in Fig. 4. The records of the magnetic *D* component from the ground station KEV and of the field parallel component $B_{\parallel}$ at the satellite are added for comparison in the lower two traces of this figure. The data segment just includes the first amplitude maximum of the giant pulsations. The *D* component from the ground station was selected here because of the high phase stability of *D* along the magnetometer chain.

Fluxes of electrons in the energy ranges 31–42 keV, 150–214 keV and 32–42 keV were recorded by the Minnesota experiment on board ATS 6 during the time considered here. References to the experiment description and records

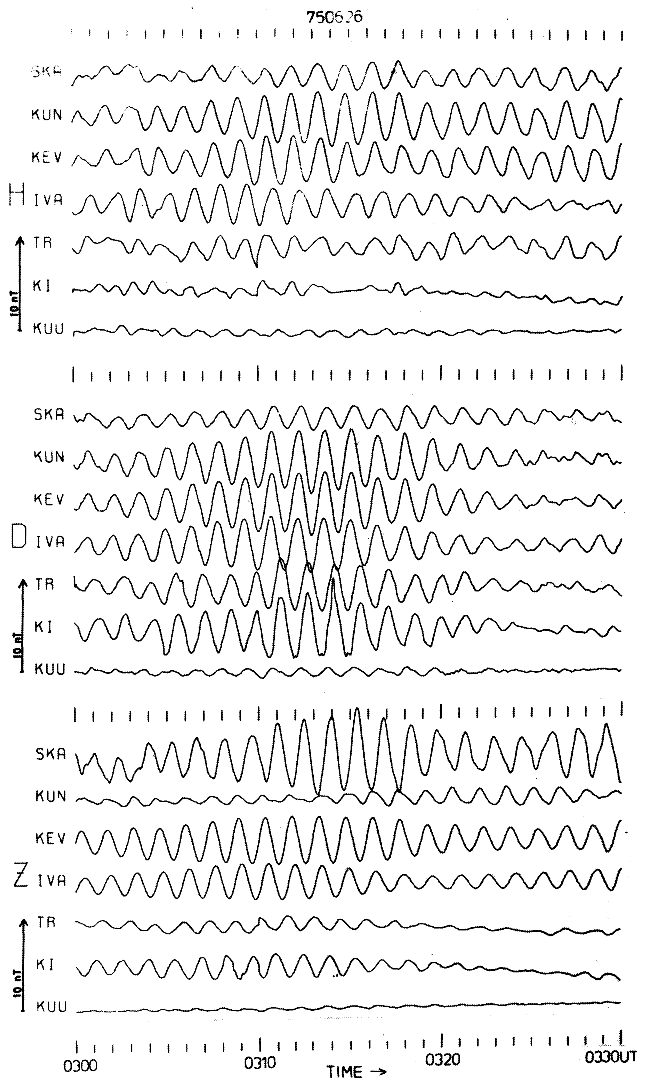

Fig. 3. Stacked pulsation magnetograms for 7 ground stations; 30 minute segment of the giant pulsation event on 26 June 1975

of pulsating proton fluxes are given by Su et al. (1979). One detector scans all the pitch angles in 90 s, the other has a fixed direction looking to the east at 90° pitch angle. The upper two curves show the pitch angle variations with time for both the fixed (dotted line around 90°) and the scanning detector (broken line oscillating between 0° and 180°). The following two curves display the electron flux measurements of the scanning detector and the third one the measurements of the fixed detector.

The electron fluxes measured by the scanning detector vary according to the variation of pitch angle; the maxima of the fluxes occur in both energy channels normally at 90° pitch angle. Until 02:55 the lower energy fluxes vary with a factor of 6 between 0° and 90° pitch angle. After 02:56 the electron flux at 0° pitch angle increases and the electron distribution becomes isotropic and remains so until 03:04. Thereafter the electron distribution anisotropy grows to a value larger than before 02:55, and the ratio between 0° and 90° flux is slightly enhanced. The flux in the energy range 150–214 keV shows no change during the time interval considered.

Time variations of the electron flux measured by the fixed detector start at 03:04 with a period of 90 s and continue until 03:21. This oscillation of particle flux is obviously related to the magnetic oscillations.

Data from the NOAA ion experiment are shown in the central part of Fig. 4. Three different telescopes for protons are directed towards three fixed directions in the spacecraft: conventionally a Cartesian coordinate system is defined with the positive z axis pointing toward the earth's center, with y directed southward parallel to the earth's rotation axis and x as the tangent vector to the spacecraft velocity, positive eastward. Telescope A points radially outward in the $-z$ direction, B is perpendicular to A having an angle of 13° with the y axis toward east, and C is mounted in the plane defined by A and B with an angle of 45° with the $-z$ direction toward north. Each of the detector telescopes is capable of measuring the differential energy number flux for protons with energies 25.5–234 keV in six intervals:

$25.5 \leqq \Delta E1 < 33.4$ keV
$33.4 \leqq \Delta E2 < 47.8$ keV
$47.8 \leqq \Delta E3 < 70.8$ keV
$70.8 \leqq \Delta E4 < 100.2$ keV
$100.2 \leqq \Delta E5 < 150.5$ keV
$150.5 \leqq \Delta E6 < 234$ keV.

The counting rates of the three energy channels labelled $\Delta E4$, $\Delta E5$ and $\Delta E6$ of detector C are plotted below the electron data in Fig. 4, the energy channels $\Delta E2$ and $\Delta E3$ together with $\Delta E5$ and $\Delta E6$ of all three detectors were used for further analysis. During more than half of the time interval, the proton fluxes vary in a random way. After 03:10 a superimposed periodical variation can be observed on channels 5 and 6. The solid lines through the proton data plots result from low-pass filtering the original proton counting rates. The selected filter has a cutoff slope between 54 and 66 s. These filtered time series clearly demonstrate the oscillations in the proton fluxes.

Data Analysis and Results

Power Spectra of the Wave Data

Some of the data sets for this special giant pulsation event have been analyzed by different methods, mainly because of the different origins of data. As far as possible, power spectra of the whole data set or of segments of data were calculated. Figure 5 is an example of the power spectra of magnetic data from the three ground stations SKA, KUN and KEV and from the ATS 6 satellite. Here the whole 4 h segment between 02:00 and 06:00 UT was analyzed. With a time increment of 5 s, and by averaging over 13 power estimates in the frequency domain, the resulting number of degrees of freedom is 26. Figure 5 gives the total power at each station, that is, the trace of the power matrix.

There is a distinct enhancement at the same frequency (0.011 Hz) in the spectra from the ground stations and the spacecraft data. The total energy of the magnetic oscillations in space is a factor of 100 less than on the ground. The enhancements of the ATS 6 magnetometer spectrum at frequencies of 0.026 Hz, 0.032 Hz and 0.036 Hz (dotted parts) are caused by artificial disturbances from other experiments on board ATS 6.

Dynamic Spectra of the Wave Data

A different technique of analysis which gives a good time resolution together with a sufficient frequency separation

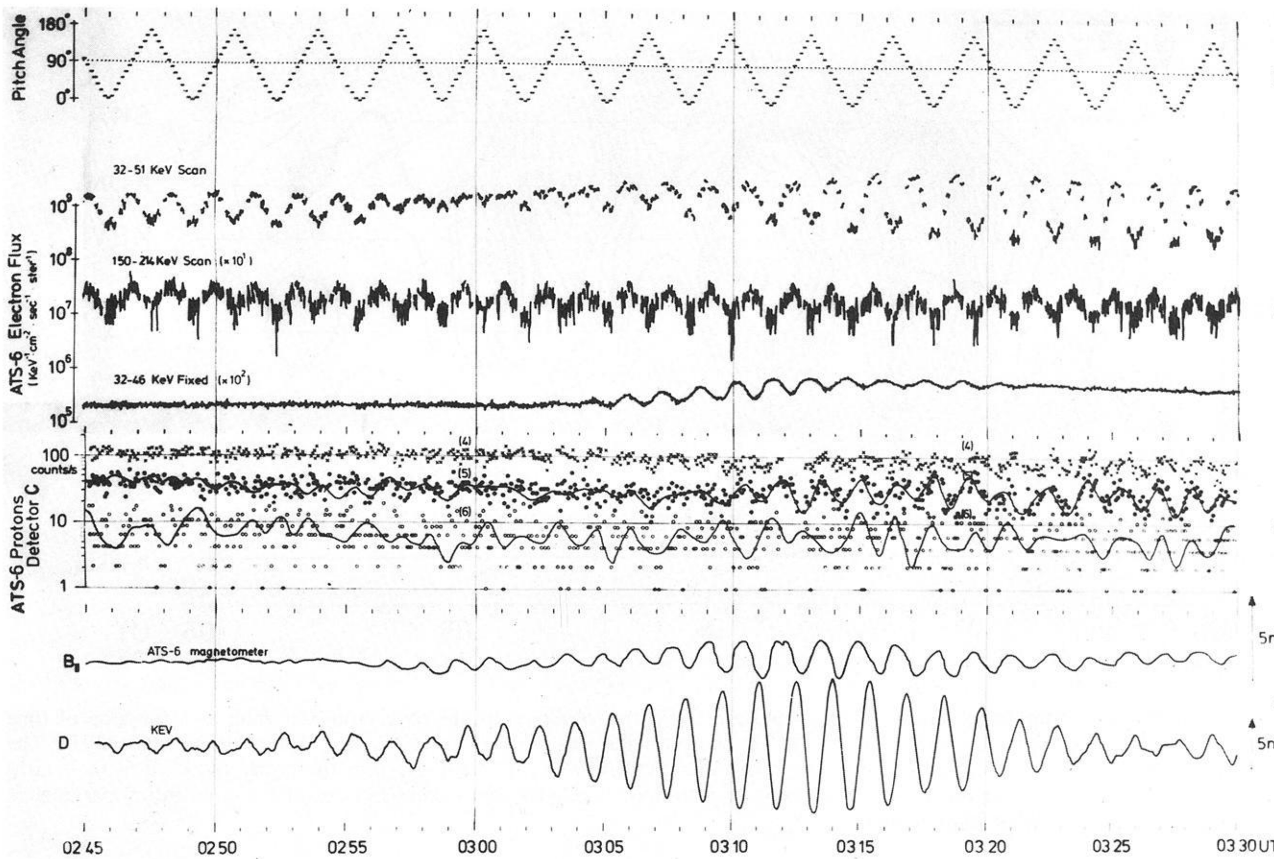

Fig. 4a–d. Particle observations at the ATS 6 satellite on 26 June 1975 (02:45–03:30 UT) during the event of giant pulsations on the ground. **a** Pitch angle directions for the electron experiment (fixed and scanning detectors); **b** Electron fluxes as observed by the 32–51 keV and 150–214 keV scanning detector and the 32–46 keV detector looking in the fixed direction; **c** Proton counting rates of the ATS 6 ion detector in 3 different energy channels; **d** $B_{\|}$ of the ATS 6 magnetometer and D of the KEV pulsation magnetometer are added for comparison

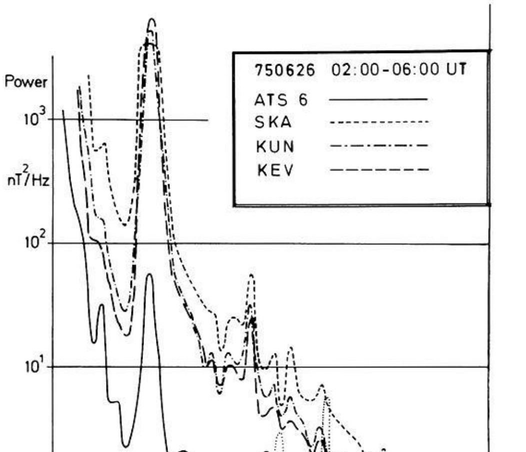

Fig. 5. Power spectra of the magnetic oscillations at three ground stations and at ATS 6 during the pg event

is the 'complex demodulation' of time series. This method has been applied to magnetic pulsations by Gokhberg et al. (1974) and by Beamish et al. (1979), for example. The distribution of the energy of the signal as a function of time and frequency is obtained by application of a set of filters to the transformed signal in the frequency domain. After a zero frequency shift and re-transformation of the filtered spectra, the instantaneous amplitudes and phases are obtained. This method was used here for analysis of the ground magnetic data. For each station the dynamic spectra of the horizontal components H and D were calculated separately in 4 segments of 1 h each. As a result the total horizontal amplitude

$$T(f_0, t_0)=\sqrt{H^2(f_0, t_0)+D^2(f_0, t_0)}$$

as a function of the central filter frequency f_0 and time t_0 were determined. The polarization properties, as a function of time, were derived from the amplitude and phase results. The instantaneous period of oscillation was defined simply as the center period of whichever filter band out of the 30 between 0.0095 Hz and 0.0133 Hz contains maximum amplitudes of the total horizontal component T, recorded at KEV. The instantaneous period of oscillation was found to be the same at all stations at the same time but the period varied slowly as a whole.

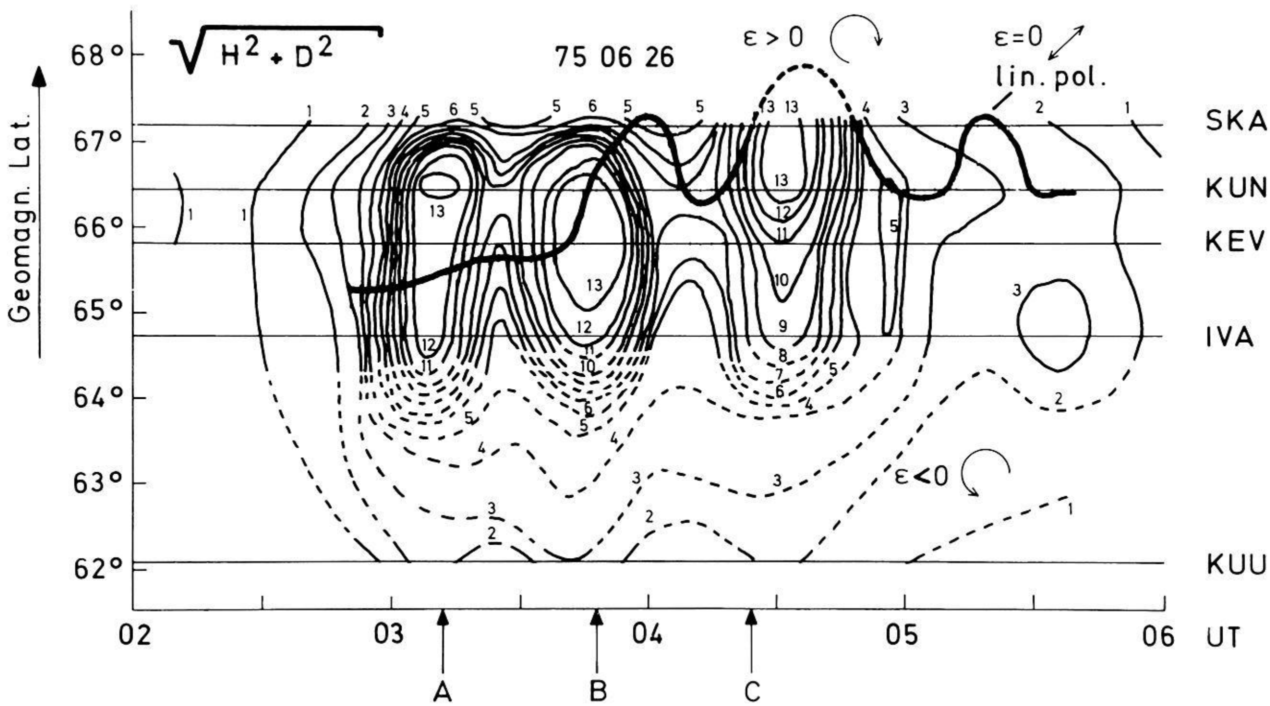

Fig. 6. Isolines of magnetic amplitudes during the giant pulsation event as observed by the magnetometer chain as a function of time and latitude derived from complex demodulation of the pg signals in the main energy band between 0.0095 Hz and 0.0133 Hz. The separation region between different senses of rotation of the horizontal disturbance vector ($\varepsilon > 0$ in the north and $\varepsilon < 0$ in the south) is marked by the solid line where the pulsations show linear polarization. The times where cross sections of the polarization parameters are given in Fig. 7 are marked below by *A*, *B* and *C*

Additionally, the ellipticity ε and the azimuth angle Φ were determined using the method of Rankin and Kurtz (1970). For each station, plots of amplitudes vs. time of 4 min averages were prepared. From these plots contour lines of equal amplitudes vs. time and geomagnetic latitude were derived. The result for the total horizontal amplitude *T* is shown in Fig. 6. The total time span comprises 4 h, 02:00–06:00 UT. The contour lines of peak to peak amplitudes are plotted in increments of 1 nT. The time and amplitude resolutions at the stations themselves (horizontal bars) are sufficiently good for determining the cross sections of the contour lines. The shape of the isolines between the stations, mainly in the gap between KUU and IVA, is estimated only.

Three distinct amplitude maxima, each one above 13 nT, can be distinguished, two of them at approximately the same latitude and the third north of the profile. The arrows at the bottom labelled *A*, *B* and *C* refer to those times where results of the coherence analysis are given in Fig. 7.

As a result of the polarization analysis the solid line depicts the latitude where the magnetic oscillations in the horizontal plane are linearly polarized. North of this line we find a clockwise sense of rotation of the polarization ellipse when looking down upon the horizontal plane ($\varepsilon > 0$), and in the south there is a counterclockwise sense of polarization ($\varepsilon < 0$). The separation region moves northward in the course of the pg event. At 04:30 UT all stations on the profile show a counterclockwise sense of rotation, and in the final quarter of the event a clockwise sense of rotation can be observed again at the northern stations. The separation region with linear polarization roughly follows the drift of the amplitude maximum.

A further result which is not shown in this figure is the simultaneous shift of the dominant period of oscillation. At the beginning the period is about 85 s, but during the two amplitude maxima *A* and *B* the period changes to 87 s and 88 s, respectively. After the second amplitude maximum the instantaneous period of oscillation rises slowly and grows to a maximum of 98 s during the third amplitude peak and after that reduces to some 89 s. Thus the northward motion of the region with maximum amplitudes and linear polarization is coupled with an increase of the instantaneous period of oscillation.

Polarization Analysis of the Wave Data

In order to get some more detailed information about the polarization parameters of the giant pulsations and their dependence on latitude, longitude and time, the data from all ground stations were subdivided into 25 overlapping segments each of 18 min duration. The polarization parameters in the three planes $H-D$, $D-Z$, $H-Z$ were determined using the method of Rankin and Kurtz (1970). Figure 7a and 7b give a few results for the meridional chain of magnetometers (7a) and the 'longitudinal profile' (7b), consisting of both Tromsø and Kiruna observatories together with the station KEV for reference. The latter 'profile' is set in quotes because of the considerable latitude difference between KI and TR.

Figure 7a gives the distribution of the different parameters along the profiles at the three distinct moments *A*, *B* and *C* (i.e. at 03:12, 03:48 and 04:24 UT) during the three amplitude enhancements. The times given here are the center times of those 18-min intervals of analysis which are closest to the real amplitude maxima at 03:10, 03:45

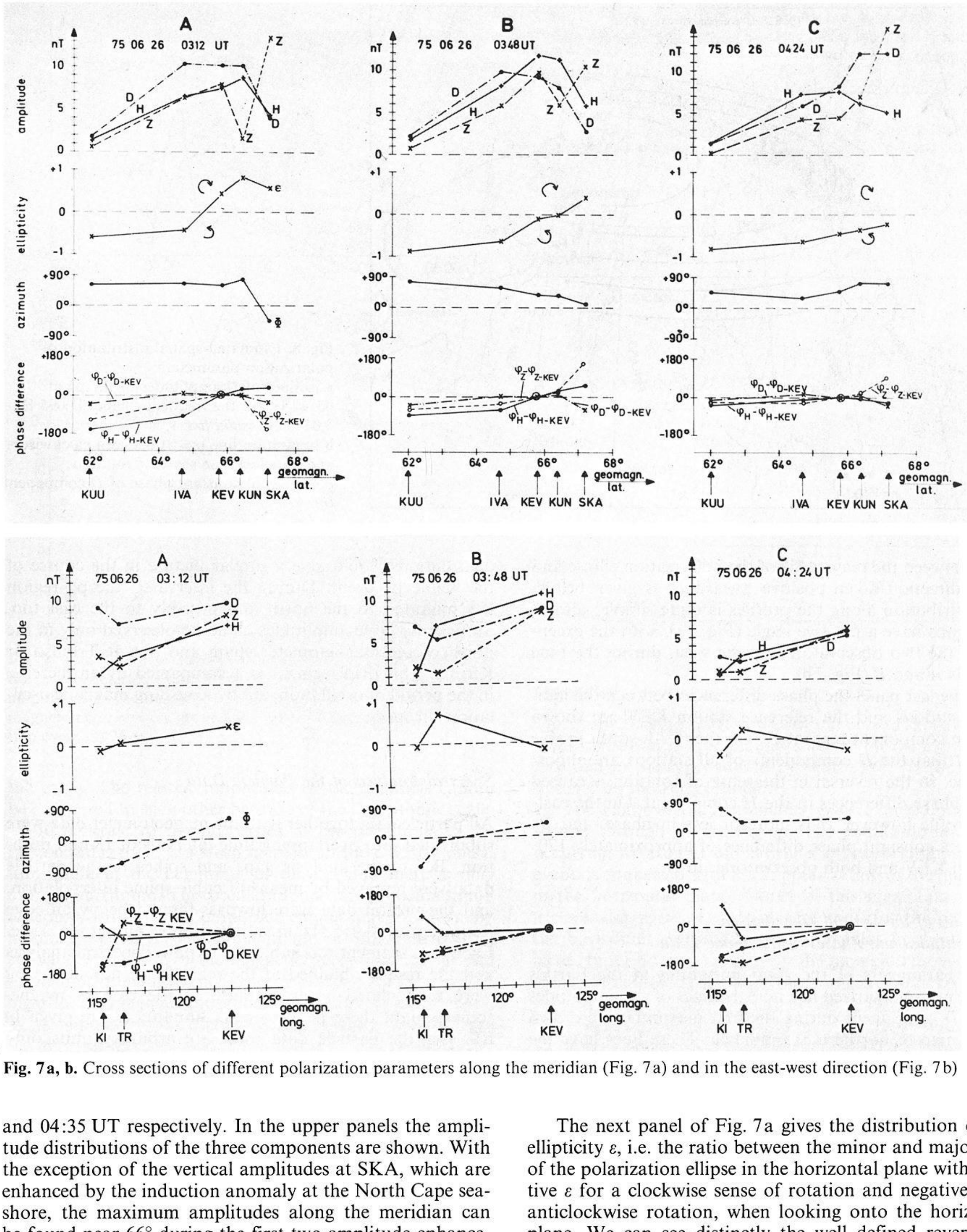

Fig. 7a, b. Cross sections of different polarization parameters along the meridian (Fig. 7a) and in the east-west direction (Fig. 7b)

and 04:35 UT respectively. In the upper panels the amplitude distributions of the three components are shown. With the exception of the vertical amplitudes at SKA, which are enhanced by the induction anomaly at the North Cape seashore, the maximum amplitudes along the meridian can be found near 66° during the first two amplitude enhancements. During the last enhancement, however, there is a similar maximum of *H* along the profile, but the *D* component is strongest in the north of the chain at 67.5°. Figure 7b shows that we have much smaller amplitudes in the west than in the east, and that they almost vanish during the third interval.

The next panel of Fig. 7a gives the distribution of the ellipticity ε, i.e. the ratio between the minor and major axis of the polarization ellipse in the horizontal plane with positive ε for a clockwise sense of rotation and negative ε for anticlockwise rotation, when looking onto the horizontal plane. We can see distinctly the well defined reversal in the sense of rotation in *A* and *B*, but during the interval *C* all stations on the meridian show an anticlockwise sense of rotation. On the other profile the dividing region between areas of different senses of rotation is situated between KI and TR, probably caused by their difference in latitude rather than longitude. The azimuthal angle Φ, that is the

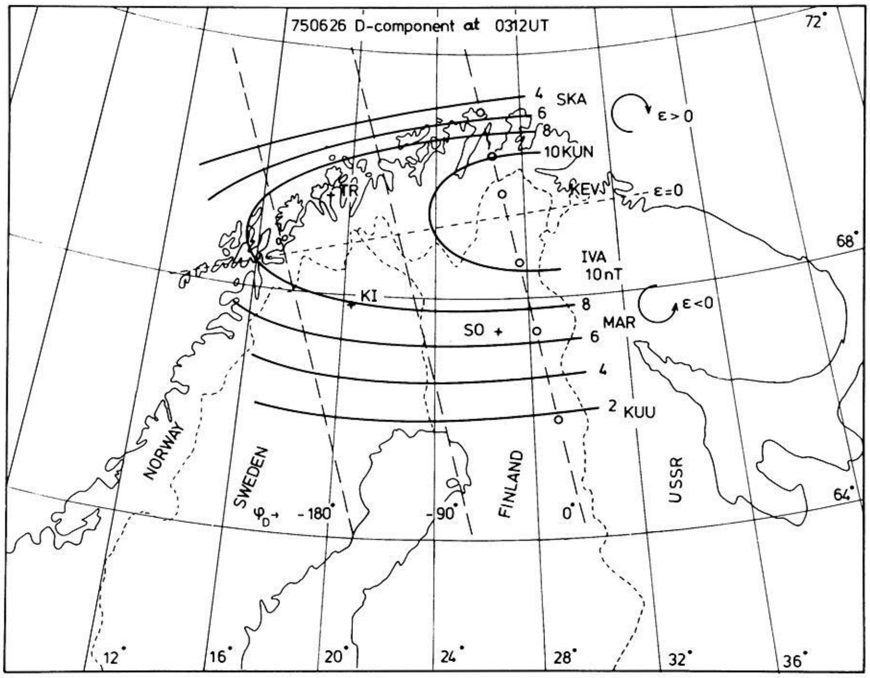

Fig. 8. Estimated spatial distribution of polarization parameters:
a isolines of D amplitudes of the pg at 03:12 UT in the frequency band 0.0095 Hz–0.0133 Hz (*solid lines*);
b separation line ($\varepsilon = 0$) between clockwise and anticlockwise sense of rotation;
c isolines of constant phase of D component (*broken lines*)

angle between the major axis of the polarization ellipse and the H direction taken positive toward D, is given below. The distribution along the profiles is quite simple: almost all stations have a positive angle (Fig. 7a), with the exception of the two observatories in the west, during the time intervals A and B (Fig. 7b).

In the last panel the phase differences between the individual stations and the reference station KEV are shown for each component separately. On the north-south profile we find that the D components of all stations are almost in phase, so the reversal in the sense of rotation is caused by the phase differences in the H component. On the east-west profile however H is more or less in phase, and we observe a constant phase difference of approximately 120° between KEV and both observatories in D.

Estimates of the Spatial Distribution of Amplitudes and Phases of the Wave Data

A few parameters of the giant pulsations at the Earth's surface are summarized in Fig. 8. Isolines of the amplitudes of the D component during the first maximum are drawn over a map of northern Scandinavia. These lines have the form of ellipses with roughly an east west orientation of the major axis. The major axis also forms the separation line between clockwise and anticlockwise rotation of the disturbance vector in the horizontal plane. The long dashed lines connecting equal phase values of the D component are oriented in the direction of the magnetic meridian. All stations along the meridional profile have negligible phase differences in D, whereas the stations in the west have a phase lag of 120°. From the phase differences we obtain an apparent phase velocity of 10 km/s, and the azimuthal wavenumber can be determined as $m = 16$. Although we have a good knowledge of the wave parameters along the chain of stations on the meridian, most of the properties outside the area covered with stations had to be extrapolated only roughly. A sequence of amplitude and phase distributions would give a similar picture in the course of the whole pg event. During the interval C the pg region has migrated to the north and possibly to the east too. Sufficiently large amplitudes could be observed only in the north of the magnetometer chain and not at Tromsø or Kiruna. This displacement is accompanied by an increase in the period of oscillation and by vanishing magnetic oscillations in space.

Spectral Analysis of the Particle Data

All particle data together with the magnetometer data were subdivided into overlapping time intervals of 18 min duration. Before the analysis gaps and spikes in the particle data were removed by means of cubic spline interpolation, and the proton data were lowpass-filtered below an edge frequency of 0.015 Hz in a logarithmic amplitude scale. Each time segment was subjected to power spectral analysis and the results obtained at the main frequency of the pg were recalculated as amplitudes. In the case of magnetometer data these peak to peak amplitudes are given in nT. For the particle data these are arbitrary units only which give a relative value of the particle fluctuations in the same frequency band as the giant pulsations.

The H, D and Z components from the ground station KEV depict the three maxima which are also visible in Figs. 2 and 6. The central panel with the results of the ATS 6 magnetometer data demonstrates that the main energy of the pg oscillations is concentrated in the field parallel component and that the third amplitude enhancement is missing in the satellite magnetometer data. The amplitudes of the counting rates of the proton detector C are shown for four energy bands $\Delta E2$, $\Delta E3$, $\Delta E5$ and $\Delta E6$. Oscillating proton counting rates occur in all energy channels. The lower energies are influenced during the main part of the event only, whereas the high energy channels have pulsating counting rates during the main phase and at the end of

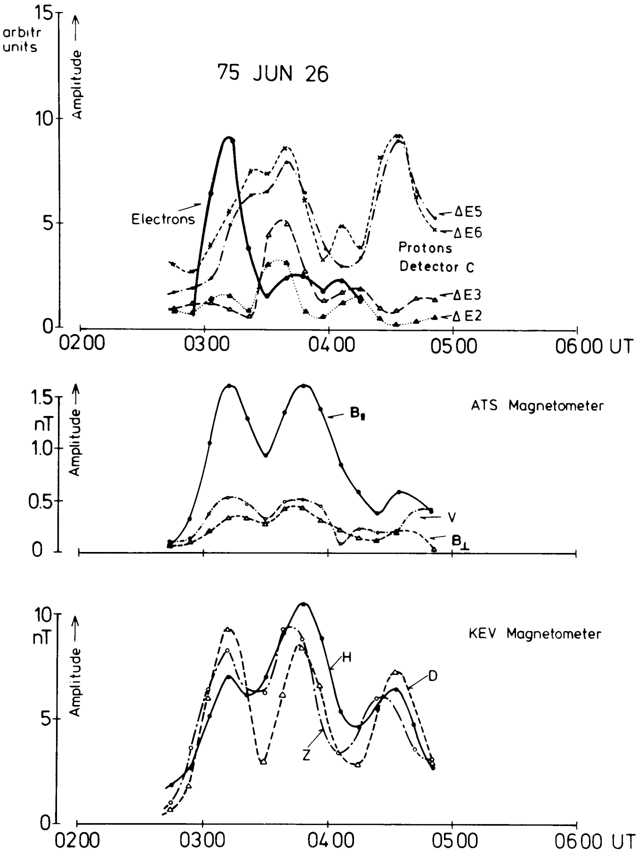

Fig. 9. Amplitudes of oscillation in different energy channels of the proton detector C and the fixed electron detector together with amplitudes of the magnetic oscillations as observed by the ATS 6 magnetometer and the ground station KEV during the giant pulsation event on 26 June 1975

the event. The relative amplitudes of the channels cannot be compared to each other because of the logarithmic scale.

In contrast to the properties of the pulsations in the proton data, there is a steep increase in the electron pulsations right at the beginning of the pg, and there is only a single maximum. This oscillation maximum occurs simultaneously with the first amplitude enhancement in the magnetometer data. The maxima in the proton data do not coincide with those of the magnetic pulsations. At the end of the time interval the high energy protons are still oscillating after the magnetic pulsations at the satellite have ceased.

A summary of the phase differences which resulted from the spectral analysis is given in Table 2. The phase differences between the single experiments and the $B_{\parallel}$ component of the ATS 6 magnetometer are specified for the three selected times A, B and C. All values denote those results where the coherence was above 0.5. The results for V and $B_{\perp}$ should not be overemphasized since their amplitudes are very small. The phase difference of approximately 100° between $B_{\parallel}$ and the electron fluctuations seems to be relatively stable. The proton fluctuations give a very contrasting picture: Their phase differences vary considerably from detector to detector and between different energy channels of the same detector, they are also different at the time intervals A, B and C. The phase differences of the pulsations at the ground station show a more or less constant value for the H component, but vary over a range of 90° for D.

Table 2. Phase differences relative to the $B_{\parallel}$ component of the ATS 6 magnetometer for ATS 6 magnetic field and electron and proton flux oscillations and ground station KEV magnetic field variations

			A 03:12 UT	*B* 03:48 UT	*C* 04:24 UT
ATS 6 Magnetometer		V	+19°	+ 24°	
		$B_{\perp}$	−99°	−143°	+110°
		$B_{\parallel}$	Ref.	Ref.	Ref.
ATS 6 Electrons		Fixed	+101°	+103°	
ATS 6 Protons	Detector *A*	*E2*	+148°	+34°	
		E3		+ 1°	+152°
		E5			− 18°
		E6	+147°	−145°	
	Detector *B*	*E2*			
		E3	−83°	+172°	
		E5	−52°		−122°
		E6	−50°	+52°	− 34°
	Detector *C*	*E2*	+101°		
		E3		−62°	+130°
		E5	− 4°	+ 5°	− 24°
		E6	+44°	+21°	+ 60°
KEV		H	−45°	−61°	−37°
		D	−95°	−41°	− 8°
		Z	− 5°	+ 1°	+20°

Discussion

This giant pulsation event was observed simultaneously by seven pulsation magnetometer stations on the Earth's surface and in the synchronous orbit in space by the magnetometer on the ATS 6 satellite.

The chain of magnetometers gives a meridional cross section through the pg region. The amplitude maximum, occurring at around 66° latitude at the beginning of the event, is connected with linear polarization of the pulsations in the horizontal plane. North of this maximum there is a clockwise sense of rotation and south of the maximum the horizontal disturbance vector rotates in the opposite sense. In the course of the event the pg region moves northward. Simultaneously with the motion from 66°–67.5°, roughly, there is an increase of the period of oscillation from 88–98 s. This relationship between the position of the pg center and the corresponding period of oscillation agrees well with observations by Green (1979). He also found a switch from anticlockwise to clockwise rotation of the horizontal polarization ellipse for a definite latitude and period. According to Green's observations this reversal occurs at Tromsø for a period of 104 s and at Kiruna for a period of 65 s. North of the position of the amplitude maximum he finds clockwise rotation and south of it anticlockwise. He obtained his result from a statistical analysis of a large number of single pg's. Our observation directly demonstrates this property of giant pulsations. We observe a period shift simultaneously with a drift of the center region. The phase and polarization of the pg event show the characteristic behaviour of field line resonance (Samson and Rostoker, 1972; Chen and Hasegawa, 1974; Southwood, 1974). A drift of the pg region has also been described by Glaßmeier (1980), who observed a westward motion of what he calls the A component pattern (A roughly corresponds to H), with the B component pattern (B corresponds to D), following later. Although he used a much larger network of stations we can exclude a westward motion of the pg region in our study: As Fig. 6 shows, the extent of the pg region is approximately 3° in latitude during time intervals A and B. During the last interval C the pg pattern has drifted northward. Additionally the magnetic oscillations at ATS 6 are diminishing.

We can exclude a westward motion of the pg region according to the following argument: During interval C the amplitudes at KUN and KEV remain relatively large while they decrease considerably at TR, which is situated at roughly the same magnetic latitude. A westward shift of the pg would have the opposite effect. The drift patterns of the H and D components are different from each other. As one can see in the half-hour section in Fig. 3 the maximum of H performs a rapid drift from IVA to SKA whithin 7 min whereas D remains almost stable. The amplitude pattern of the horizontal component as a whole can be found at 66° latitude during the first two maxima and at 67.5° latitude during the third maximum. Comparing our result and the result of Rostoker et al. (1979), who also found a poleward motion, to that of Glaßmeier (1980), we must conclude that the drift of the amplitude pattern may have different directions. Probably this reflects the individual behaviour of the source region.

In this study a connection is found between a compressional magnetic wave in space and giant pulsations observed on the ground. Space observations of this type of pulsations have been given by Barfield et al. (1971). Lanzerotti and Tartaglia (1972) found a clear correlation between compressional magnetic waves in space and Pc 4 pulsations observed at a ground station. There was no clear evidence of whether these were giant pulsations or not. A detailed study of one of these compressional waves in space, using data from three satellites, has been made by Hughes et al. (1979). They found large azimuthal wavenumbers around $m = 100$ and an azimuthal group velocity of about 30 km/s. We observe much smaller wave numbers, only $m = 16$. Hughes et al. concluded from additional particle observations that they observed a second harmonic fieldline resonance, probably caused by bounce resonance interaction of protons at the inner edge of the ring current. Cummings et al. (1978) studied Pc 4 of 150 s period at ATS 6, and found hydromagnetic waves along the magnetic field which propagate predominantly azimuthally from noon toward the dawn-meridian. During the pg event analyzed here the waves of the D-component of magnetic field propagate from dawn to noon. We find three time intervals (see Fig. 9) with amplitude maxima of the pg event at the ground, and two maxima and a smaller one at the satellite, which do correlate with each other. The smaller maximum occurs when the event on the ground has shifted northward.

As we stated above, we observe a fieldline resonance of a standing wave. Since it drifts out of the view of the satellite during the third time interval, we also conclude that the resonant region has drifted radially outward and has a very narrow extent. In radial direction, the extension would be less than one R_E. We estimate the wavelength of the pattern in the D-component as $\approx 2.3\ R_E$.

These estimates have been derived from the amplitude pattern of the pg at the earth's surface. The pg range in space is expected to be smaller or of the same order of magnitude. The steep gradient of both H and D component amplitudes in latitudinal direction can partly explain the large Z amplitudes of giant pulsations as shown by Southwood and Hughes (1978). Comparable gradients and Z amplitudes are observed together with high latitude Pi 2 pulsations. This does not explain however why maximum Z amplitudes are observed at latitudes where H and D have their maxima (see Fig. 7a).

ATS 6, in its position at 35° E longitude is relatively close to the magnetic equator ($\approx -5°$). Standing waves in space have a node of the transverse magnetic oscillations for odd modes and maximum amplitudes for even modes at the equator. From the observations we conclude that we are dealing with an odd mode standing wave: The transverse amplitudes (V and $B_\perp$) are very small. The relatively large field parallel ($B_\parallel$) component can be interpreted as the remainder of a large standing wave in a non homogeneous field. This can be derived from the wave equations given by Siebert (1965) assuming a dipole field. Furthermore we observe larger magnetic amplitudes on the ground than in space. Since the waves undergo ionospheric damping (Hughes and Southwood, 1976) larger amplitudes are expected in space. Therefore the maximum of the standing wave cannot be at the satellite. ATS 6 must be either on the resonant L shell or very close to it in the earthward direction since the radial extent of the pg as derived from the ground observations is of the order of 1 R_E. Taking the influence of the ionosphere into account, the radial extent of the resonant region in space is of the same order or smaller. A situation in which the resonance region is between the satellite and the ground is excluded, since the magnetic amplitudes at ATS 6 are diminishing during interval C. In summary, these arguments support the assumption of an odd mode standing wave in space. At magnetic latitudes away from the equator the magnetic amplitudes of the wave are expected to be much larger than on the ground.

A 90° rotation of the polarization direction by the influence of the ionosphere and non-conducting atmosphere is predicted by Hughes and Southwood (1976). Due to the extremely small transverse amplitudes, the determination of the polarization parameters in space gives only a nonsignificant result. A direct comparison to the properties on the ground (see Fig. 7a, b) is thus excluded. If the rotation is considered, the calculation of the phase propagation as stated above must be reinterpreted in terms of components.

Cummings et al. (1978) concluded from their data that they had observed an odd harmonic of the standing wave, and the fundamental mode is the most reasonable interpretation of the data. The question of the excitation mechanism of the magnetic standing wave has still to be answered. The simultaneous particle observations on board ATS 6 may give some hints. Inspection of the ground station magnetograms at high and low latitudes around the world reveals a magnetic field change only at Fort Churchill at 02:55 UT. The H-component increases by 70 nT. The magnetometer on board the geostationary SMS 1 satellite positioned at 75° W also records a 10 nT decrease of the radial component of the magnetic field which means that the field becomes more dipole-like around midnight. This reconfiguration of parts of the magnetosphere may also have implications on the morning side. The field change at local midnight occurs at the time of the increase of the electron flux at ATS 6. The electrons responsible for the increase can therefore not have drifted very far and the modulation of the electron flux must have taken place in the pg resonance region.

We observe at 02:55 UT an increase of the electron flux at the scanning detector in the energy range 32–51 keV together with a change of the pitch angle distribution from anisotropy to isotropy. The fixed electron detector does not see any flux increase. This implies that the more or less fieldline-parallel flux component increases. However, when the amplitude of the field line oscillations increases, the anisotropy again increases, and we observe a flux increase in the fixed detector, i.e. at 90° pitch angle.

The redistribution of the pitch angle of the electrons can also be seen in the recordings of the scanning detector. We observe periodic fluctuations of the electrons of the same period as of the magnetic field, with a phase difference of 100°. If the electrons behaved like charged particles in a magnetic bottle one would expect a 180° phase lag between the particle and magnetic oscillations, especially in view of the short bounce period of the electrons in the observed energy range and the short response time on changes of the magnetic field. Since we don't know the flux changes of the low energy plasma we cannot estimate the implications of the particles on field changes.

The 40 keV protons – channels $\Delta E2$ and $\Delta E3$ – reach their maximum at 03:30 UT. If the time difference between the amplitude maxima in channels $\Delta E2$, $\Delta E3$ and $\Delta E5$, $\Delta E6$ is due to drift, the protons first appeared at 10 h MLT. The second peak of the proton oscillation amplitude at 04:33 UT is most probably due to protons which have already drifted around the earth once.

Cladis (1971) gives a model where an injection of plasma produces a charge excess on field lines which can generate Alfvén waves. If a species of the injected particles continues to drift azimuthally in a sharp charge front, the field lines along the drift path will begin to oscillate as the charge front appears. The displaced field lines will therefore form a periodic pattern with the azimuthal periodicity equal to the product of the mean angular drift velocity of the particles and the period of oscillation, and the wave pattern moves in the azimuthal direction with a phase velocity equal to the mean azimuthal drift velocity of the particles. The extent of the wave pattern in that direction is roughly 18°. Therefore we can calculate the phase velocity v_D for the observed pg period of 90 s:

$$v_D = 12°/\text{min}.$$

This should correspond to the drift velocity of the particles responsible for the pulsation generation, according to Cladis (1971). Particles of 300 keV have drift velocities of this magnitude.

We observe an injection of electrons in the 40 keV range, but no appreciable increase in the flux of 150–214 keV electrons. Therefore electrons cannot be responsible for the generation of the wavepattern in the way proposed by Cladis' theory.

Thus protons could be the particles responsible for the giant pulsation excitation, but we don't find increases of high energy proton fluxes at 02:55 UT. The first increase of the flux occurs at 03:14 UT for 150 keV protons. The oscillations of proton fluxes also start later than 02:55 UT, and reach their maximum amplitude later than those of the 40 keV electrons and of the magnetic field, namely at 03:15 UT (see Fig. 9).

We observe major amplitudes of the modulation of the ion flux above an energy of 70 keV. The largest amplitudes occurred in the measurements of telescope C (pitch angle 125°).

Su et al. (1979) observed a similar event with the same experiment. They recorded the largest flux variations at small pitch angles ($\approx 36°$). They showed that the observed modulation of the ion flux cannot be explained by a simple model of the bounce resonant interaction. Su et al. assume that a B_0 parallel wave electric field together with an average particle distribution causes the flux modulation at small pitch angles.

During the event we observe, the wave phenomenon occurs earlier than the ion flux modulation, and we see the modulation preferentially at large pitch angles.

Southwood (1977) gives a theoretical explanation for compressional waves in the magnetosphere caused by the existence of a hot plasma component. He explains the existence of a magnetic compressional wave for low frequency disturbances in a hot inhomogeneous plasma. The disturbance is localized and surface-wave type structures in the magnetospheric ring current are possible. In this case the meridional transverse (V) and compressional components ($B_\parallel$) should be in phase or 180° out of phase. We observe waves which are localized at least in the radial direction. According to Table 2 we obtain a mean phase difference of 20° between both components during intervals A and B. The east-west component $B_\perp$ has a mean phase difference of $-120°$ relative to $B_\parallel$. Both transverse components are predicted to be in quadrature. This is obviously not the case. This result must be considered carefully because of the errors caused by the low signal to noise ratio of the transverse oscillations. On the other hand the theory requires a large ratio of hot ion pressure and magnetic pressure in the case of this pg, because the transverse oscillations are much smaller than the field parallel amplitudes.

Therefore the mechanism of generation of this giant pulsation event remains unexplained.

Acknowledgements. We would like to thank Dr. T.A. Fritz, NOAA Environmental Research Laboratories, Boulder, and Dr. J.R. Winckler and Dr. K.R. Erickson, School of Physics and Astronomy, University of Minnesota, Minneapolis, for making available the ATS 6 particle data. The assistance of the Scandinavian observatories Sodankylä, Tromsø and Kiruna during the ground based measurements is gratefully acknowledged. This study was supported by the Deutsche Forschungsgemeinschaft.

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Received February 1, 1982; Revised version May 14, 1982
Accepted July 9, 1982