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Magnetometer Array Observations of a Giant Pulsation Event

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Abstract. On 19 November 1976 a rather well developed giant pulsation event occurred at about 0600 MLT over northern Scandinavia. Results of observations obtained with a dense network of magnetometer stations are reported. The method of analysis is based on the concept of the analytical signal. The disturbance region was strongly localised. The amplitudes of the horizontal components show a pronounced difference: the amplitude maximum of the N-S component is clearly moving to the west while that of the E-W component is nearly fixed relative to the array. The frequency of the event decreased with time. Both the frequency decrease and the drift of the amplitude maximum are interpreted in terms of bounce - resonance instability. The spatial polarisation pattern found is in agreement with the fieldline-resonance theory in that the sense of rotation of the horizontal disturbance vector is as predicted by the theory. At the region of maximum amplitudes the pulsation is linearly polarised in E-W direction, as observed by other workers. This does not agree with the fieldline-resonance model. Apparent azimuthal wave numbers of the horizontal components show that the event analysed is a westward-travelling wave. The wave numbers are as large as predicted by Olson and Rostoker's (1978) empirically derived relation between the E-W wave number and the frequency of pc 4-5 pulsations.

Key words: Giant pulsation - pc 4 and 5 Pulsations - Bounce resonance instability - Fieldline-resonance model - Apparent EW wave numbers - Analytical signal.

Introduction

Among the various types of geomagnetic micropulsations, giant pulsations (pg) are striking because of their sinusoidal form and their large amplitudes. According to the definition given by Annexstad and Wilson (1968), (1) they occur simultaneously at conjugate points; (2) their average period is about 100 s; (3) their spatial distribution is confined to a narrow range of latitudes in the auroral zone; (4) they occur predominantly in the early morning hours (Harang 1936); and (5) they are well modulated and have amplitudes of several tens of nT (Jacobs 1970). Another well-known feature of pgs is the change of their period with time. This may be positive or negative and typically is of the order 10 s/h (Eleman 1967; Annexstad and Wilson 1968; Hillebrand 1974; Green 1979).

As a possible cause of pgs, Obayashi and Jacobs (1958) suggested fieldline-guided hydromagnetic waves. This idea was supported by Annexstad and Wilson's (1968) study of the conjugate behaviour of pgs, and by Ol's (1963) observation of a clear relationship between the latitude of a pg region and the main period of the event.

Hillebrand (1976), Green (1979), and Rostoker et al. (1979) recently showed that giant pulsations exhibit some features that are otherwise known from pc 4–5 micropulsation studies (e.g. Samson et al. 1971; Green 1978). A region exists where the disturbance amplitude reaches a clear relative maximum. North of this demarcation or resonance region the horizontal disturbance vector shows a clockwise rotation (if viewed in the direction of the geomagnetic fieldline); south of the resonance region the opposite sense of rotation is found. Starting from these observations and from the fieldline-resonance theory as described by Southwood (1974) and Chen and Hasegawa (1974), Green (1979) suggested that pgs are westward travelling waves.

To prove this, and the applicability of the fieldline resonance model to giant pulsations, and also to derive a more detailed picture of the spatial amplitude, phase and polarisation behaviour, observations by a dense magnetometer array seem to be necessary.

Since summer 1976 the University of Münster has been operating such an array of up to 36 magnetometers of an improved Gough-Reitzel type (Gough and Reitzel 1967; Küppers and Post in press 1980) in northern Scandinavia (Küppers et al. 1979). In this paper we will give results of the observation of a pg event by means of the Scandinavian Magnetometer Array and of a detailed data analysis.

Instrumentation

The sites of the magnetometers used in this study are shown in Fig. 1. The instruments are located along five N-S profiles nearly parallel to geomagnetic meridians (profile 1: FRE-HAS, profile 2: AND-LYC, profile 3: MIK-PIT, profile 4: SOY-SAU, profile 6: BER-SKO). The spacing between magnetometers along these profiles and between the profiles themselves varies 100–150 km. All magnetometers observe the magnetic field variations with 10 s temporal resolution. A detailed description of this magnetometer array has been given by Küppers et al. (1979).

The coordinate system indicated in Fig. 1 was introduced by Küppers et al. (1979) and has been named the Kiruna System. It is a cartesian system obtained by a stereographic projection of the globe onto a tangential plane centered at Kiruna, Sweden (67.8° N, 20.4° E). The y_{KI} axis of the system, whose origin is

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situated at Kiruna (KIR, see Fig. 1), has been chosen as the tangent to the projection of the line $\phi_c = \phi_c$ (KIR) = 64.8° with ϕ_c denoting the revised corrected geomagnetic latitude as given by Gustafsson (1970). The x_{KI} axis points approximately 12° west of geographic north of KIR.

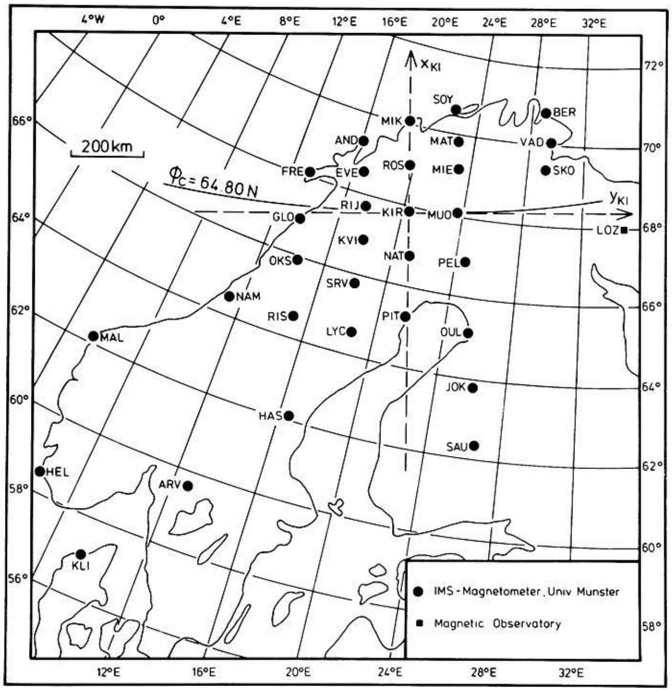


Fig. 1. Station map in geographic coordinates. Also indicated are the axes of the Kiruna system (see text) and the line of constant revised corrected geographic latitude $\phi_c = 64.80$ N (after Gustafsson 1970)

For pulsation studies the amplitude and phase response of the magnetometers are of some importance. Typical response curves may be found in Küppers and Post (1980). Here, we restrict ourselves to pointing out that, for periods around 100 s, no amplitude correction is necessary whereas phase distortion is of the order of 10°. The uncertainty in phase determination caused by a time resolution of 10 s is more severe and, for a period of 100 s, may amount to ±20°. The amplitude resolution is about 2 nT (Küppers et al. 1979).

Description of Data and Method of Analysis

On 19 November 1976 a rather well developed giant pulsation event was observed between 0330 UT and 0450 UT (about 0550–0710 MLT) by the 20 northernmost instruments of the Scandinavian Magnetometer Array at a time of moderate magnetospheric activity ($K_p = 3+$). As an example, the magnetic variations of the A component (magnetic deflection parallel to the x_{KI} axis), the B component (magnetic deflection parallel to the y_{KI} axis) and the Z component are given for the northernmost stations of profile 4 relative to the averaged quiet day level on 18 November 1976, 0800–1200 UT (Fig. 2). The magnetograms show the known quasi-monochromatic nature of pgs as reported by others (Rolf 1931; Annexstad and Wilson 1968; Hillebrand 1976; Green 1979). The pulsation event occurred during the recovery phase of a small magnetic deflection seen in the A and Z components, while the low frequency part of the B component remained nearly constant. To isolate the pulsation train with a main period of about 100 s, all records were band-pass filtered with a filter of trapezoidal shape (Schmucker 1978) and cut-off frequencies at 4 and 16 mHz.

Some of the band-pass-filtered A and B data are given in Fig. 3 for a north-south profile (SOR-PEL) and east-west line (FRE-VAD). The strong localisation of the disturbance is remarkable. Between MIE and MUO the amplitude diminishes to

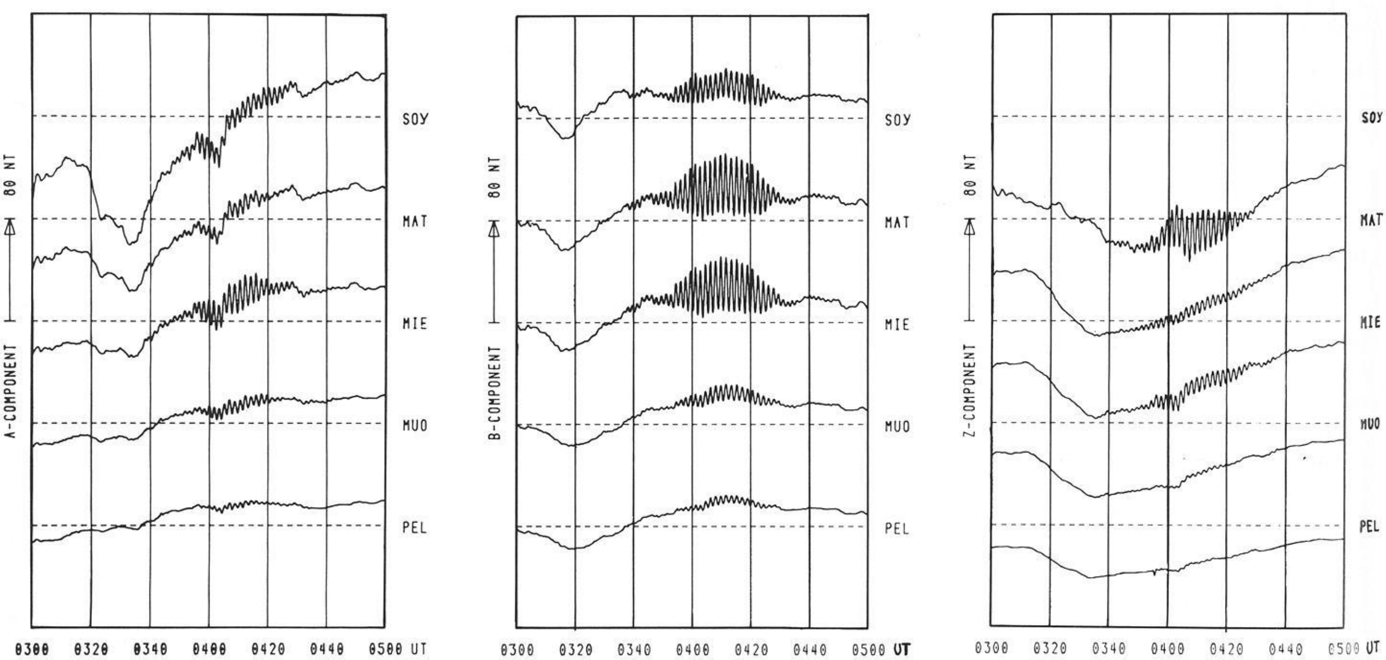


Fig. 2. Magnetograms of the unfiltered A, B, and Z components for profile 4 on 19 November 1976, 0300–0500 UT. The A and B components are defined parallel to the x_{KI} and y_{KI} axis, respectively (see Fig. 1)

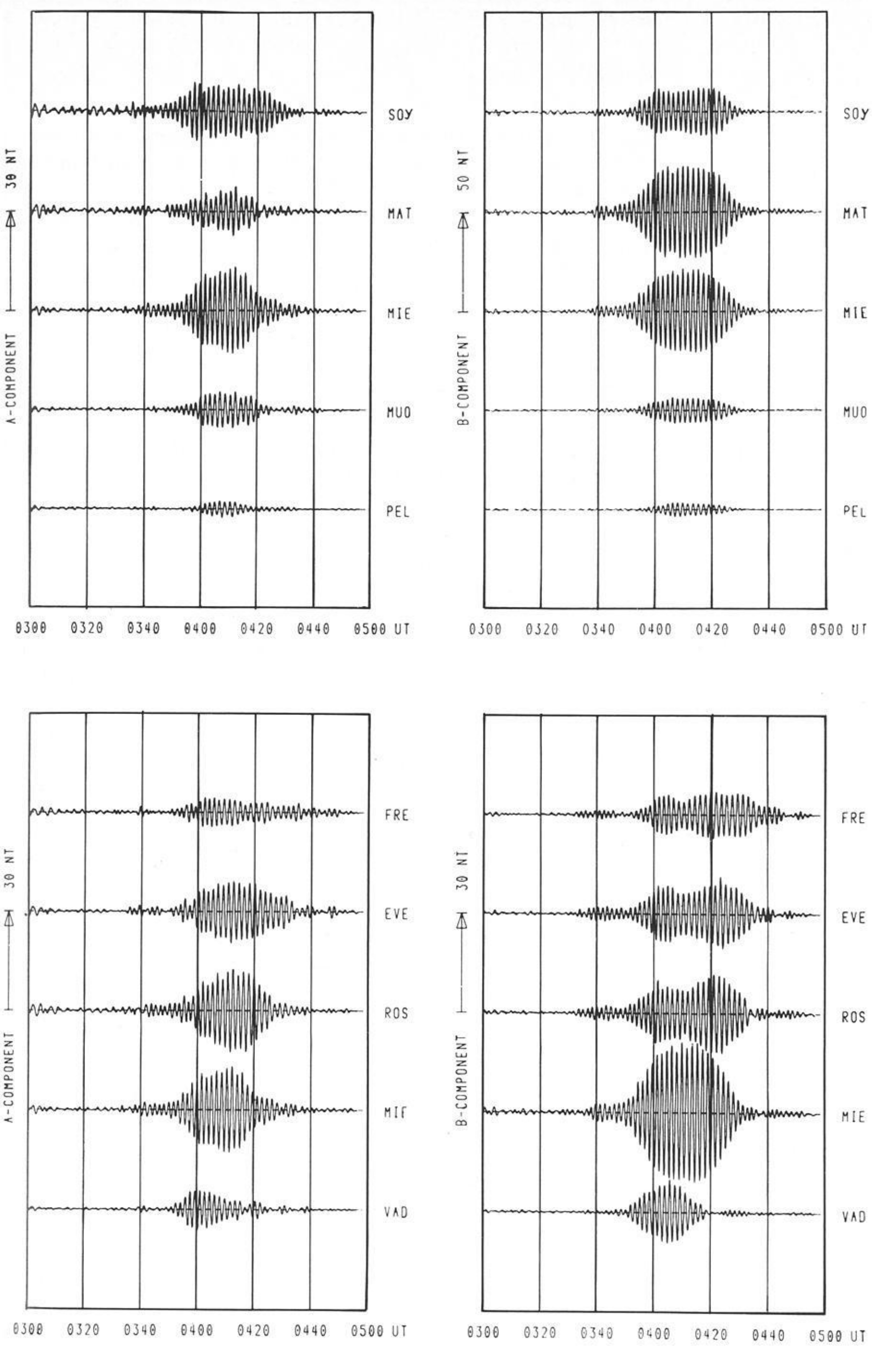


Fig. 3. Magnetograms of band-pass filtered A and B components for profile 4 (*upper part*) and for an E-W profile from FRE to VAD (*lower part*) (see Fig. 1). Note also the different scale in the upper right part of this figure

about one-half over a north-south distance of about 100 km. On the profile (FRE-VAD) the stations west of MIE show a clear double-peak structure in B, whereas all other stations show a simple wave-packet. In the following no regard is paid to the Z component because, in the pulsation frequency band, there are marked induction effects in this component over Scandinavia, especially near the northern coast (Jones and Olafsdottir 1979; Küppers et al. 1979).

During further analysis of the data we considered the nearly sinusoidal character of pgs and regarded them as amplitude- and phase-modulated quasi-monochromatic wave trains. We considered the techniques of statistical frequency analysis to be inapplicable to our data because of the obvious non-stationary character of the event. To derive amplitude and phase information from the data we used the complex or analytical signal method as first described by Gabor (1946).

For a given amplitude and phase modulated monochromatic signal $x(t)=A(t)\cos(\omega t+\varphi(t))$ a complex or analytical signal $z(t)$ may be defined by

$$z(t)=x(t)+i\,y(t) \tag{1}$$

where $y(t)$ is the Hilbert transform of $x(t)$

$$y(t)=-\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}\,d\tau. \tag{2}$$

For the instantaneous amplitude $A(t)$, the instantaneous phase

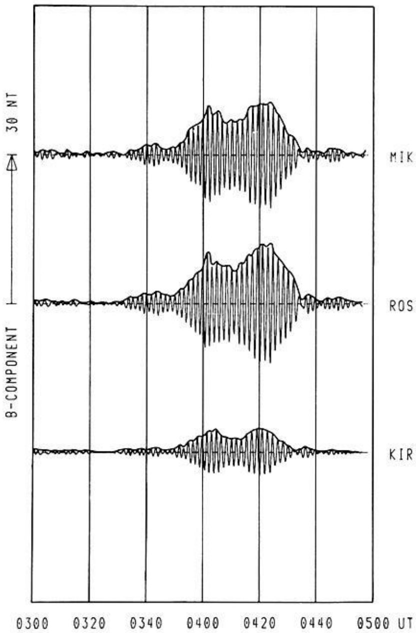


Fig. 4. Magnetograms of the band-pass filtered B components of some selected stations together with the curves of the instantaneous amplitude computed by the analytical signal method

$\varphi(t)$, and the instantaneous frequency $f(t)$, the following relations hold:

$$A(t)=\sqrt{x^2(t)+y^2(t)}$$

$$\varphi(t)=\arctan(y(t)/x(t))$$

$$f(t)=\frac{d}{dt}\,\varphi(t). \tag{3}$$

The idea of the analytical signal is based on certain advantages shown by operations with exponentials $\exp(i\xi)$ as compared to operations with $\sin\xi$ or $\cos\xi$ functions (Gabor 1946). The appearance of the Hilbert transform may be understood by remembering that the sin function is the Hilbert-transform of the cos function. To provide for the computation of the Hilbert transform of our records all band-pass filtered data (see the examples shown in Fig. 3) were set to zero before 0300 UT and after 0500 UT. More detailed descriptions of this demodulation technique are given by Fischer (1969), Farnbach (1975), and Kodera et al. (1977).

As an example of what the above-described method may yield, in Fig. 4 the band-pass filtered B records of the stations MIK, ROS and KIR are shown together with the amplitude curves as computed by the analytical signal method. The amplitude curves are just the envelopes of the records, and even very minute changes in the envelopes are resolved.

Assuming the amplitude error, δA, to be as large as the magnetic resolution of 2 nT (Küppers et al. 1979), we may estimate the phase error, $\delta\varphi$, and the frequency uncertainty, δf, from Eq. (3) to be $\delta\varphi \approx 11°$ and $\delta f \approx 2$ mHz for an amplitude A = 10 nT.

With the amplitude and phase values of two components, A and B for example, it is also possible to compute instantaneous polarisation parameters in the way given by Born and Wolff (1975, p. 28).

Observations

Amplitude Behaviour

The geographical distribution of the instantaneous amplitudes of the horizontal components (Fig. 5a, b) shows, at all times, an ellipsoidal shape, i.e., strongly localised, but with slightly different half-widths, in both main directions. In the N-S direction the half-width of the A and B distributions may be estimated to be about 300 km, as already found by Hillebrand (1974, 1976). In the E-W direction it amounts to about 500 km for the A component and 300 km for the B component. For most of the time there is a pronounced amplitude maximum in the B component situated on profile 4. Pulsation magnetograms from the Soviet Union station Lovozero (LOZ, see Fig. 1) still show the pg event but with an amplitude smaller than 2 nT.

The most striking feature in Fig. 5 is the completely different behaviours which the disturbance maxima of the A and B components show in time. The A maximum is indicated by the dashed circles in Fig. 5a. It clearly moves to the west along the line MIE-FRE (65.7° geomagnetic latitude). Only very late within the event (0430 UT, Fig. 5b) do we see a movement of the B maximum to the west. For the A component a small movement of the maximum to the south may also be noticed (Fig. 5a), but this observation is of doubtful significance.

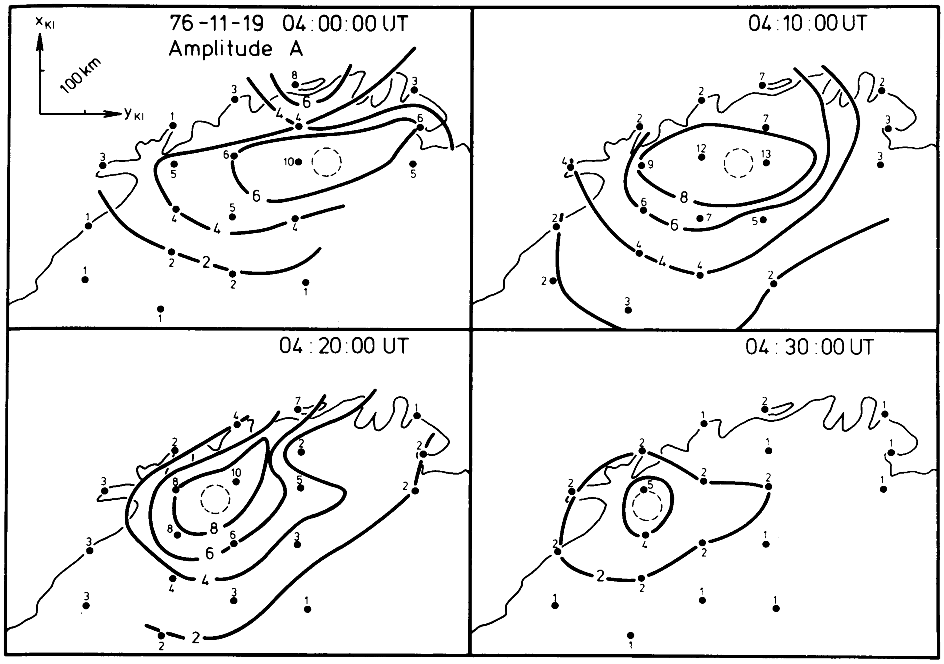
The E-W drift velocity of the A maximum is $v=-(0.18 \pm 0.02)$ km/s, where the negative sign indicates a drift to the west. If we transform this value to an apparent angular velocity around the earth's axis by virtue of $\omega_A = v/R_E \cdot \cos\Phi$, with R_E the earth's radius and Φ the geomagnetic latitude, we get $\omega_A = -(6.8 \pm 0.7)\cdot 10^{-5}$ rad/s which is, in magnitude, remarkably close to the earth's angular velocity of rotation of $7\cdot 10^{-5}$ rad/s. Altogether this means that the A maximum is nearly fixed with respect to the magnetosphere throughout the event.

Phase Behaviour

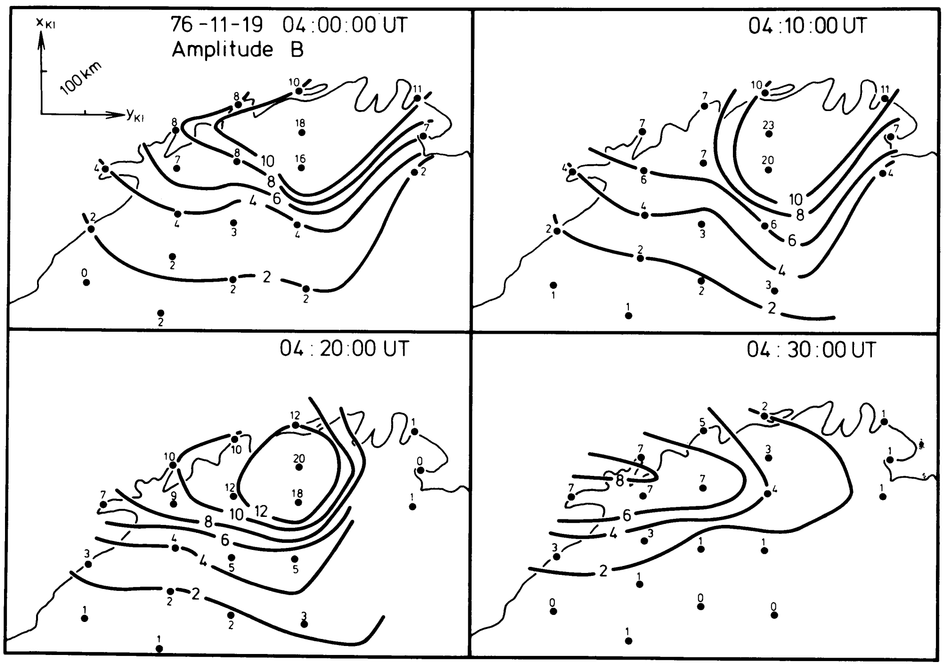
Again isolines are used to demonstrate the phase behaviour of the event analysed (Fig. 6a, b). For the A component the isolines are very roughly straight, N-S directed lines up to the latitude of KIR. Further to the north large-phase differences between the coastal stations and the neighbouring inland stations are observable. For example, at 0410 UT this difference reaches 177° between the stations SOY and MAT over a distance of only about 100 km.

For the B component no such sudden phase changes are visible. The isolines are strongly aligned along the N-S direction. As for the A component, the eastern stations lead in phase which means phase propagation to the west. This was suggested earlier by Green (1979) from pg observations at Kiruna and Tromsö using the predictions of the fieldline resonance theory (Southwood 1974), and was found observationally by Rostoker et al. (1979).

For three E-W profiles (AND, MAT, VAD along about 66.6° geomagnetic latitude, FRE, EVE, ROS, MIE, SKO along about 66.0°, and GLO, RIJ, KIR, MUO along about 64.8°) we computed apparent azimuthal wave numbers, m, for the B component at three different times (see Table 1). For the A component azimuthal wave numbers have only been computed on the last two profiles because the northernmost E-W profile (AND, MAT, VAD) is already in the region where large N-S spatial phase-gradients are found. The given wave numbers are



a



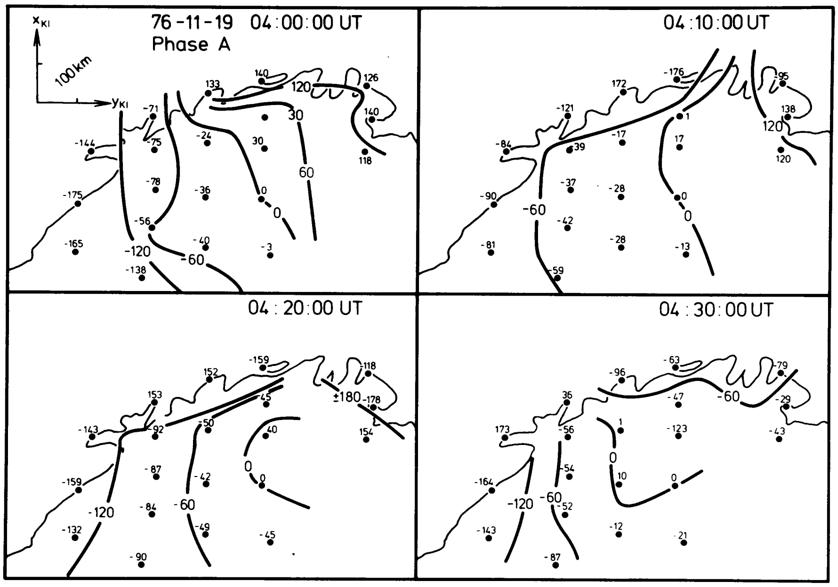
b

Fig. 5. a Maps of the instantaneous amplitude (in nT) of the A component at four different times. Linear interpolation has been used to construct the isolines. The *dashed circles* indicate the region of the A disturbance maximum
b As Fig. 5a, but for the B component

mean values as computed from the phase differences between successive station pairs. An apparent wave length, λ, is defined by $\lambda = \frac{2 \cdot \pi \cdot R_E \cdot \cos \Phi}{m}$ (Green 1976). As may be seen from Table 1 there is no systematic difference between the wave numbers for the various times and geomagnetic latitudes of the profiles considered. Within the uncertainty of each m value there is no significant difference between the wave number of the A and B components.

Polarisation

As examples, the polarisation ellipses in the A-B plane of the event analysed, at two times, are given in Fig. 7. In every case, two perpendicular straight lines may be recognised dividing the pg region into four quadrants, S_1–S_4 (Fig. 8). One line, in the E-W direction, separates two regions in which the senses of rotation of the horizontal disturbance vectors are different. Along this line, nearly linear polarisation in the direction of the



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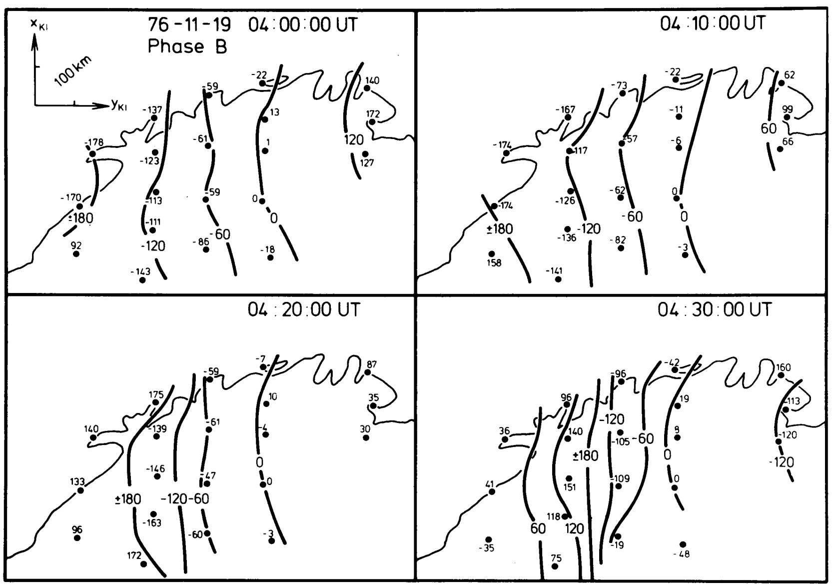

b

Fig. 6. a Maps of the instantaneous phase (in degrees) of the A component, φ_A, relative to the station MUO: $\varphi_A = \varphi_{ST} - \varphi_{MUO}$, where φ_{MUO} is the phase of the reference-station and φ_{ST} is the phase of a station as computed by the analytical signal method
b As Fig. 6a, but for the B component

Table 1. Apparent azimuthal wave-numbers, m, at different times, measured along the three EW-profiles (AND, MAT, VAD), (FRE, EVE, ROS, MIE, SKO) and (GLO, RIT, KIR, MUO). λ denotes the corresponding apparent azimuthal wave-length

Time (UT)	A component				B component					
	FRE		GLO		AND		FRE		GLO	
	m	λ (km)	m	λ (km)	m	λ (km)	m	λ (km)	m	λ (km)
4:00	24.0 ±5.8	678 ±130	20.5 ±6.5	831 ±180	29.9 ±2.9	534 ±50	23.5 ±4.1	693 ±100	21.7 ±4.7	785 ±120
4:10	17.9 ±11.9	909 ±350	10.2 ±5.6	1,670 ±600	25.5 ±4.8	626 ±100	19.5 ±3.8	834 ±100	22.7 ±8.0	751 ±200
4:20	24.1 ±9.9	675 ±200	19.4 ±1.8	878 ±80	36.2	441	27.5 ±4.4	591 ±80	29.1 ±13.8	585 ±180

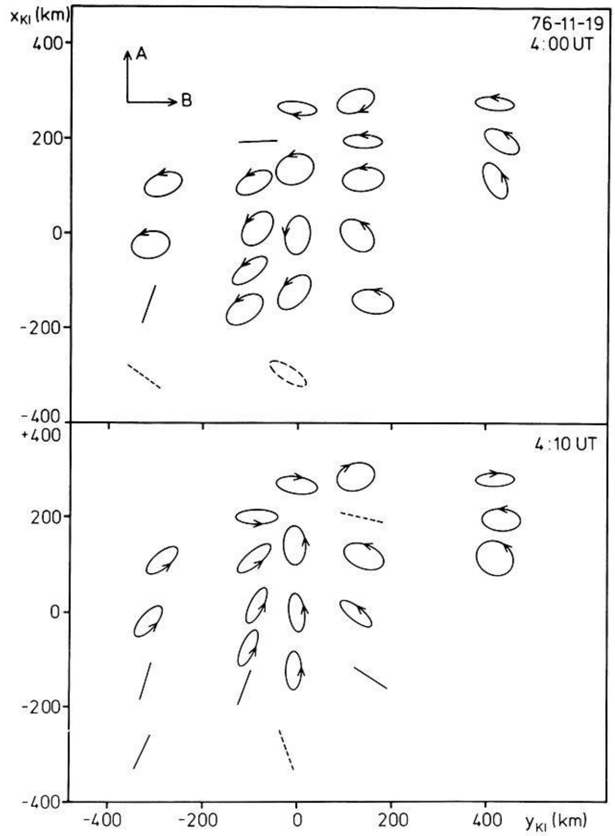

Fig. 7. This figure shows the polarisation state of the pg event analysed, for two different times. The ellipticity, the azimuth angle, the main axis, and the sense of rotation are averaged over two periods (4:00:00 – 4:03:20, 4:10:00 – 4:13:20). At all stations the horizontal disturbance vector is normalised to the main axis so that the polarisation ellipses shown all are of the same length. The direction of the main axis is given correctly, whereas different ellipticities have only been indicated. The sense of rotation is given by the *arrows*. *Dashed ellipses* are ambiguous

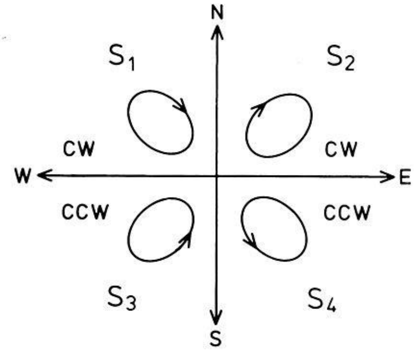

Fig. 8. Schematic representation of the observed polarisation state of the pg analysed. S_1 to S_4 denote the different sectors. The line $\overline{WE}$ represents the demarcation line and $\overline{NS}$ is the meridional separator line (for a definition of these lines see text)

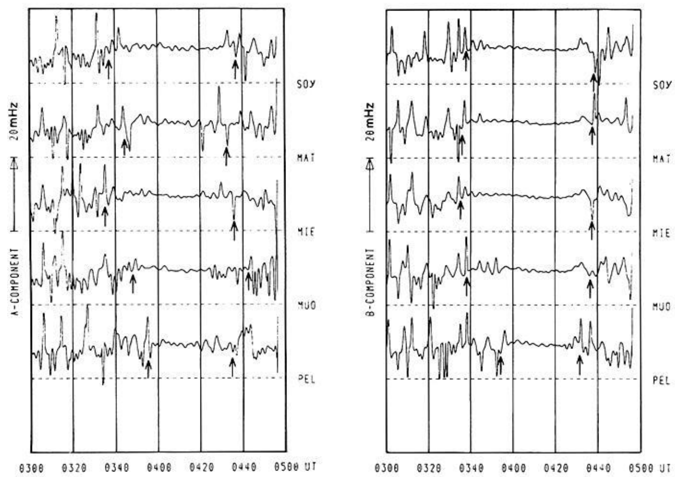

Fig. 9. Curves of the instantaneous frequency of the A (*left*) and B (*right*) component for the northernmost stations of profile 4. The *arrows* indicate the beginning and end of the pulsation event judged from the band-pass filtered magnetograms (see Fig. 3)

B component is found and therefore this may be called the demarcation line, according to the definition of Samson et al. (1971). The second line, in the N-S direction, which we would like to call the meridional separator line, divides two regions in which the inclination of the main axis of the ellipses with respect to the northern direction is positive or negative, respectively. In agreement with the prediction of the fieldline-resonance model for a westward travelling wave (as in our case) in the northern sectors S_1 and S_2 the rotation is clockwise (when viewed in the direction of the geomagnetic field), and counterclockwise in the southern sectors S_3 and S_4. The change of the sense of rotation of the horizontal disturbance vector at the station BER between 0400 UT and 0410 UT may be explained by a drift of the pg region, and therefore also of the demarcation line, to the south. Such a drift is also indicated in Fig. 5a, as mentioned above. The observation of an equatorward drift of the pg region is in contrast to the observation of Rostoker et al. (1979) who reported a poleward motion.

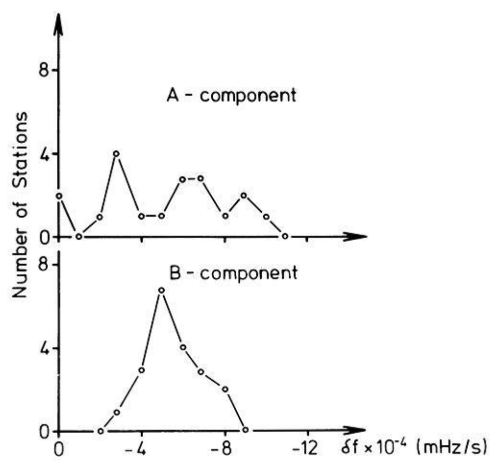

Fig. 10. Distribution of the rate of the frequency change with time as computed by a least-squares fit to the curves of the instantaneous frequencies between the two times marked by arrows in Fig. 9, at the 20 northernmost stations of the array for the A and B components

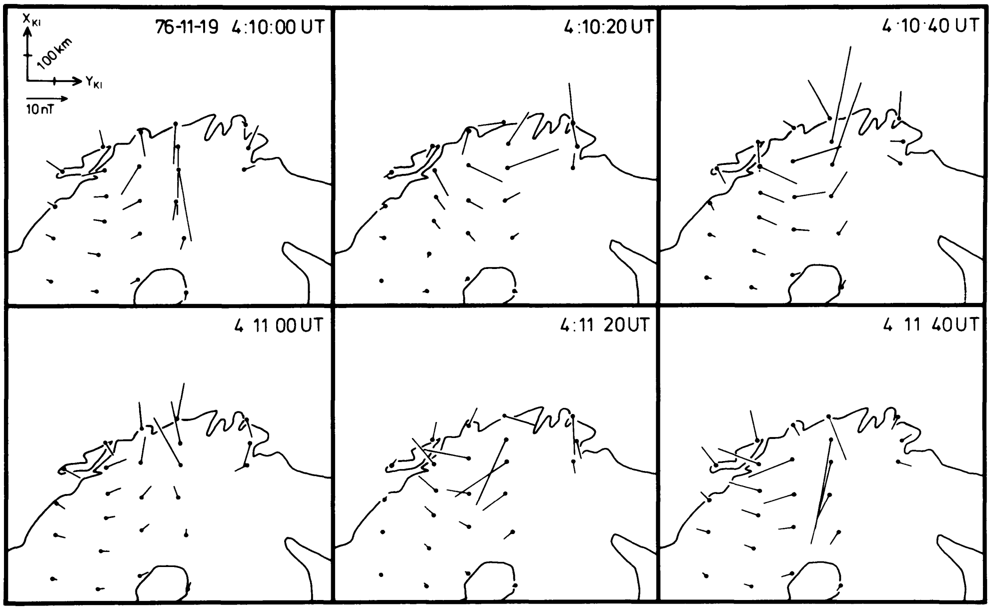

Fig. 11. Equivalent current vectors (in nT) at selected instants of time within the northern part of Scandinavia. The current vectors have their origin at the stations where the corresponding magnetic disturbances have been recorded

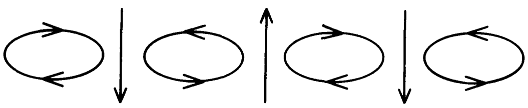

Fig. 12. Schematic representation of an equivalent current system whose periodicity in space may produce the observed temporal variations if the system drifts (after Obertz and Raspopov 1968)

Instantaneous Frequency

Curves of the computed instantaneous frequency show, on the average during the event, a decrease (Fig. 9). Between the start and end points of the event, which are indicated by arrows in Fig. 9, a linear least-squares fit to the frequency curves was made. The distribution of the calculated frequency gradients for A and B is given in Fig. 10. Again, as for the amplitude, the two horizontal components show different behaviour. For the B component we see a narrowly peaked distribution around the value $-5\ 10^{-4}$ mHz/s whereas the A component shows a wide distribution between $-2\ 10^{-4}$ and $-10\ 10^{-4}$ mHz/s. The mean frequency gradient from both components is $-5.5 \cdot 10^{-4}$ mHz/s corresponding to an increase of the period of about 20 s/h, a value already found by others (e.g., Annexstad and Wilson 1968; Green 1979). No dependence of the frequency gradient on the location of the magnetometer station has been observed.

System of Equivalent Current Vectors

Equivalent overhead current systems have been used before to represent magnetic micropulsations (e.g., Jacobs and Sinno 1960; Wilson 1966; Obertz and Raspopov 1968). For the event analysed, at 0410 UT the equivalent current vectors, i.e., horizontal magnetic disturbance vectors rotated 90 degrees clockwise if viewed from above, seem to show two current vortices (Fig. 11). The one to the west is well developed while that to the east is only suggested. The following diagrams in Fig. 11 demonstrate the time behaviour of the equivalent currents during one period (100 s). It appears that a system of current vortices with the currents flowing against each other (see Fig. 12) is moving to the west. The extent of a single current vortex is about 10° in longitude (see Fig. 11), and the mean velocity of the whole system is estimated from Fig. 11 to be (8.3 ± 2.7) km/s.

Discussion and Interpretation

The question of a drift of the pg region has already been discussed by Eleman (1967). He states – in contrast to the corresponding result of the present paper – that the pulsation region remains rather fixed relative to the earth. We suppose that the magnetometer network which he used was not as dense as is necessary for an exact determination of the location of the disturbance maximum. Furthermore we like to point out Eleman's (1967) observation that the events which he analysed were apparent not only in Scandinavia but also at Leirvogur, Iceland, at about 1800 km distance west of KIR, and occurred there up to 1 h later. This may correspond to a westward drift of the disturbance center of the order of 0.5 km/s, which is comparable to our present observation.

Interpreting the measured drift velocity as the azimuthal group velocity of a pg signal, a possible explanation for its value may be found in terms of a drift instability like the bounce resonance mechanism (Southwood et al. 1969; Southwood 1976). The resonance condition for such an instability is

$$\omega - l\omega_D = N\omega_B \qquad (4)$$

where ω, ω_D, and ω_B are the wave frequency, the drift frequency and the bounce frequency, respectively, of a particle trapped in the earth's magnetic field, l is the magnetospheric azimuthal wave number of the disturbance, and N is an integer.

Our results about the phase behaviour of the pg event considered imply phase velocity towards the west and therefore $l<0$ in a coordinate system in which Λ, the azimuthal coordinate, increases towards the east. As Southwood et al. (1969) showed for a westward travelling wave, protons with an inward-directed density gradient are a possible population of resonant particles. Using the center angular frequency of the pg event analysed, $\omega = 20 \cdot \pi$ mHz, in (4) we get two resonance energies, a low and a high one (Southwood et al. 1969). For the lower energy the disturbance frequency approximately equals the bounce frequency of the protons, and we have for the energy, W, of the resonant particles $W \sim 13$ keV.

Using an expression for ω_D as given by Hamlin et al. (1961) and ignoring a slight dependence of ω_D on the equatorial pitch angle (see Southwood et al. 1969), we have

$$\omega_D \approx -\frac{2 \cdot L \cdot W}{q \cdot B_0 \cdot R_E^2}. \tag{5}$$

Here L, W, and q are the McIlwain parameter, the energy, and the electric charge, respectively, for the particles under consideration; B_o is the equatorial geomagnetic flux density at the earth's surface; and R_E is the earth's radius. ω_D as calculated by Hamlin et al. (1961) involves only the gradient and the curvature drifts. For such low energy particles as the resonant protons (see above) the drift velocity is not governed by gradient and curvature drifts alone, but we also have to take into account an $\mathbf{E} \times \mathbf{B}$ drift because of the dawn-dusk magnetospheric electric field (Schulz and Lanzerotti 1974, p. 6f). This drift is to the east on the morning side and therefore lowers the westward drift velocity as computed by Hamlin et al. (1961). For the angular velocity $\omega_{E \times B}$ that is related to the $\mathbf{E} \times \mathbf{B}$ drift it follows

$$\omega_{E \times B} = \frac{E}{B_o} \frac{L^2}{R_E} \text{ [rad/s]} \tag{6}$$

with E denoting the magnitude of the dawn-dusk field. A typical value is $E \sim 5 \cdot 10^{-4}$ V/m (Brice 1967). With $L = 6.6$ (this corresponds, e.g., to the L value of MAT) and putting $\omega_{TOT} = \omega_D + \omega_{E \times B}$, where ω_{TOT} is now the drift velocity of a trapped particle because of gradient and curvature drifts as well as the $\mathbf{E} \times \mathbf{B}$ drift. From (5) and (6) and putting in the above values we get $\omega_{TOT} \sim -2.6 \cdot 10^{-5}$ rad/s which agrees roughly with the measured apparent angular velocity, $\omega_A = -6.8 \;\; 10^{-5}$ rad/s. On the other hand, now putting $\omega_{TOT} \sim \omega_A$, we may estimate in the same way the dawn-dusk field to have been $3.1 \cdot 10^{-4}$ V/m.

Therefore, starting from the resonace condition (4) one finds a clear relation between the observed drift velocity of the disturbance center in the A component and the drift of the trapped protons if not only gradient and curvature drifts are considered but an $\mathbf{E} \times \mathbf{B}$ drift is also taken into account. The idea that the observed signal moves with the same velocity as the resonant particles may also explain the regularity and large amplitudes of pgs because then the disturbance has time to build up.

No good explanation can be given for the different drift behaviour of the B component. We suggest that some unknown influence of the ionosphere on a magnetospheric pulsation signal might be a reason for that difference. How the relative motion of the pulsation source against the ionosphere is of importance still has to be investigated.

The period drift of a giant pulsation (see Fig. 9) may also be discussed in terms of the bounce resonance mechanism. We propose that a change of the resonance condition (4) is responsible for the period change as is probably the case for IPDPs (*I*ntervals of *P*ulsations with *D*iminishing *P*eriods, see review by Jacobs 1970). IPDPs are believed to be caused by ion cyclotron instabilities, and a change of the resonance condition is caused, for example, by an inward convection of the resonating protons which results in an increase of the particle gyration frequency (Heacock et al. 1976).

A bounce resonance between protons and a magnetic disturbance results in a radial diffusion of the resonant particles. As Dungey (1964) showed, a meridional magnetic field disturbance, b_N, results in a zig-zag motion of the bouncing particles (see Dungey's Fig. 1), and the particles experience a change of their L value with time (Dungey, 1964),

$$\dot{L} = \frac{b_N \cdot v_{\parallel} \cdot \cos^3 \Theta \cdot L^3}{B_o R_E} \tag{7}$$

where $v_{\parallel}$ is the particle's velocity parallel to the ambient field and Θ is the colatitude of the particle's gyration center. As Southwood et al. (1969) showed for a westward travelling wave, as observed in our case, there must be an inward-directed gradient of the proton density for the instability to arise. This means that L has to increase during the event because the protons cannot diffuse against the density gradient. With $b_N = 10$ nT and an equatorial pitch angle of, for example, 80° one finds for 13 keV protons (such protons have a bounce period of about 100 s, see above): $\dot{L} \approx 4 \cdot 10^{-3}$ s^{-1}. This corresponds to a frequency decrease of $\delta f \sim 4 \cdot 10^{-2}$ mHz/s, a value which is much larger than the observed one. A more refined discussion of the diffusion described and a consideration of non-linear effects may result in better coincidence of theoretical and observed values. In agreement with Green (1979), who suggested that a radial motion of the source region might be the cause of the frequency change, we propose that radial diffusion of the resonant particle distribution might be the reason for such a radial motion and a possible explanation of the observed period drift.

The results of the polarisation analysis in the present paper (compare Fig. 8) and the earlier works of Hillebrand (1976) and Green (1979) show that the fieldline resonance theory as described by Southwood (1974) and Chen and Hasegawa (1974) is strictly not applicable to pgs because at the resonance region they show linear polarisation in the direction of the B component and not in that of the A component as predicted by the theory (Southwood 1974; Walker et al. 1979) and as observed, for example, for pc 4–5 pulsations (Green 1978). The fieldline-resonance model also does not predict the existence of the meridional separator line. In agreement with Rostoker et al. (1979) we believe the observation that the disturbance is largest in the B component and is strongly localised in space (Fig. 5a, b) to be best described by the guided poloidal mode (Orr and Matthew 1971; Radoski 1967). However, as Chen and Hasegawa (1974) pointed out, this mode does not have a resonant coupling with, for example, a surface wave at the magnetopause. This also shows the restricted applicability of the fieldline resonance theory. Only the sense of rotation of the horizontal disturbance vector on both sides of the demarcation line is as predicted by the model. For a westward travelling wave we find clockwise rotation north of the resonance and counterclockwise rotation south of it (Southwood 1974; Fig. 8 of the present paper).

There is another possible mode in the magnetospheric plasma having fieldline-resonance-like behaviour (Southwood 1977). For the ring-current plasma, Southwood showed the existence of a compressional mode which is strongly localised. The disturbance vector of this mode is mainly in the meridional direction if phase propagation occurs in E-W direction. Considering the ionospheric rotation of a magnetospheric signal as described by Inoue (1973) and Hughes (1974), the observed larger amplitudes of the B component as compared to the A component, combined with a purely westward phase propagation, and the strong localisation in space are in agreement with the properties of the Southwood mode. The strong localisation of this mode is an effect of the magnetic and pressure changes being in counterphase. Just this anticorrelation was found observationally by Hughes et al. (1979) for pg-like disturbances seen by ATS 6.

The strong localisation in E-W direction is of some importance for statistical studies of pgs. For example, an analysis of the occurrence of pgs and of the distribution of the pulsation period should not be done in relation to local time of a magnetometer station (Harang 1936; Green 1979) but in relation to local time of the pg center. To find this center a dense magnetometer array is necessary. The localisation may also explain the different results of Annexstad and Wilson (1968) and Green (1979) concerning conjugate behaviour. While the events that Green (1979) analysed were of small amplitude and showed odd-mode characteristics, Annexstad and Wilson (1968) reported on pgs with amplitudes up to 40 nT as seen also for the event reported in this paper, and even-mode characteristics. Therefore the present author believes that Green (1979) measured the conjugage behaviour somewhere in the periphery of the pg region where properties may be different from those in the center region.

In recent years apparent azimuthal wave numbers have been derived from observations by several workers (Green 1976; Olson and Rostoker 1978; Mier-Jedrzejowicz and Southwood 1979). From a study of a large number of pc 4–5 pulsation events Olson and Rostoker (1978) derived the following relation between the apparent azimuthal wave number, m, and the frequency, f, of a pulsation event: $m=(1.4\pm0.4)\cdot f+0.26$, where f is measured in mHz. The apparent azimuthal wave numbers as measured for the present event (see Table 1) are in accord with the above-mentioned relation which shows that there is no significant difference between the wave numbers of normal pc 4–5 pulsations and the giant pulsation analysed in this paper. A corresponding result was found recently by Rostoker et al. (1979) using observations of four pg events.

Concerning the meaning of apparent azimuthal wave numbers, Green (1976) believes them to give us information about magnetospheric properties of a pulsation event. An apparent azimuthal wave number, $m\sim20$ for example, corresponds to an apparent horizontal phase velocity on the ground $v_{ph}\sim8$ km/s, at auroral latitudes. Phase velocities of the same order of magnitude have also been derived theoretically for phase propagation in the ionosphere, perpendicular to the earth's magnetic field, of waves in the extraordinary mode, for example (Prince and Bostick 1964). As Hughes (1974) showed, the behaviour of a magnetic disturbance in the atmosphere is quasi-static and the phases on the ground are a direct image of the phases in the ionosphere. We therefore suppose apparent azimuthal wave numbers, as measured in the present work, and associated apparent horizontal phase velocities to be controlled by ionospheric rather than by magnetospheric conditions.

Equivalent current systems (Fig. 11) have earlier been used by Obertz and Raspopov (1968) to explain, for example, the phase differences in the N-S component of pc 5 pulsations on an N-S profile. From Fig. 11 we see that the equivalent currents of the pg analysed may be interpreted as a system of moving current vortices as proposed by Obertz and Raspopov (1968) (see Fig. 12). If the periodic change of the disturbance vectors in time is explained by a moving periodic structure in space then, for a period of 100 s and a longitudinal extent of a single current vortex of about 10° (see above), one arrives at a velocity of 8 km/s for the motion of the periodic current system. The measured velocity is (8.3 ± 2.7) km/s.

A system of current vortices as shown in Fig. 12 may be generated by moving field-aligned currents. As Fukushima (1976) shows in an ionosphere with laterally homogeneous electric conductivity, the equivalent ionospheric currents of an incident field-aligned current and the Pedersen current cancel each other in their magnetic effect at ground, so that one only measures the curl-like Hall currents at the earth's surface. Whether such moving field aligned currents periodically incoming or outflowing in E-W direction, are realistic needs more investigation by means of magnetospheric and ionospheric measurements. However, there is still one argument which restricts the applicability of a current model as proposed by Obertz and Raspopov (1968) to pgs: From Fig. 3 we know that the event lasted about 30 periods in time which means a longitudinal extent of the whole current system of about 300°. This seems to be in contrast to the observed localisation.

Conclusions

One of the main results of the present paper is the observation of a westward drift of the disturbance center in the A component. This observation is in contrast to the work of Eleman (1967) and shows the advantage of a dense two-dimensional magnetometer array in pulsation studies.

The evidence for a bounce-resonance instability as a possible mechanism for explaining the drift and also the measured increase in period is suggestive but not categorial. For further decision one needs more information about the magnetospheric plasma distribution during a pg event. To clarify the result that the drift velocity of the disturbance center in the A component agrees roughly with the drift velocity of the resonant protons, one needs a more thorough analysis of the dynamical behaviour of the proposed instability, as has been done in the case of the ion-cyclotron instability by Jacobs and Watanabe (1966) to see whether it is a convective or a non-convective one.

As Southwood et al. (1969) pointed out, a bounce resonance, for example, requires an even-mode oscillation of the fieldline and therefore the conjugate behaviour of giant pulsations is of some interest. Because of the different results of Green's (1979) and Annexstad and Wilson's (1968) analysis of conjugate behaviour of pgs this question must be treated again with magnetometer stations showing better conjugacy and lying under or very close to the pulsation center and not somewhere at the periphery of the pg region.

The observation of a moving pulsation region may be of some interest regarding the question of the influence of the ionosphere on a magnetospheric signal. The motion of the magnetospheric radiation source relative to the ionosphere may explain the different behaviour of the two horizontal components. In future analyses a separation of both the drifting and stationary parts of the observed signal should be studied to get more insight into the dynamical properties of the pulsation center.

Localised compressional waves in the ring current region as described by Southwood (1977) show some features observed with the present pg event, namely the strong localisation and the predominance of the B component at the resonance region.

More information about the spatial polarisation characteristics of this mode is needed for a detailed comparison. For example, it would be interesting to know about the existence of a meridional separator line within this mode as was observed in the polarisation pattern of the present event (Figs. 7 and 8).

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