J. Geophys. 48, 1–6 1980

Journal of Geophysics

Original Investigations

The Analysis of Simultaneous Observations of Nighttime Pi Pulsations on an East-West Profile

L.N. Baranskiy[1], V.A. Troitskaya[1], I.V. Sterlikova[1], M.B. Gokhberg[1], N.A. Ivanov[2], I.P. Khartchenko[3], J.W. Münch[4], and K. Wilhelm[5]

[1] Institute of the Physics of the Earth, Academy of Sciences, Moscow, USSR
[2] Geophysical Institute of the Ural Scientific Centre, Sverdlovsk, USSR
[3] Siberian Institute of Terrestrial Magnetism, Academy of Sciences, Irkutsk, USSR
[4] University of Siegen, D-5900 Siegen 21, Ferderal Republic of Germany
[5] Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau 3, Federal Republic of Germany

Abstract. Magnetic pulsations of the types Pi 1 and Pi 2 were observed on a profile consisting of five stations between Lindau and Novosibirsk (87.5 to 155.0 deg geomagnetic longitude and 49.7 to 54.0 deg geomagnetic latitude). The Pi events were analysed with respect to their propagation characteristics. The frequency-time analysis demonstrated that individual Pi pulsation events attained their highest frequencies near local magnetic midnight. In addition, it was found that the east-west component of the horizontal disturbance vector exhibited a larger frequency shift than the north-south component. The phase variations observed were indicative of a propagation along the profile. The polarization of the pulsations generally was elliptical with a left-hand rotation of the disturbance vector and local time dependent direction of the major axis. All findings support the conclusion that the propagation of the two components is governed by different conditions. The phase velocities of the events ranged from 100 to 500 km/s.

Key words: Magnetic Pi pulsations – Hydromagnetic wave propagation.

1. Introduction

Irregular geomagnetic pulsations of the type Pi are known to occur in close relation to magnetospheric substorm onsets. They predominantly are night-time phenomena and exhibit a pronounced/latitudinal dependence of their amplitude variations with an absolute maximum near the auroral zone and a relative maximum near the plasmapause location. On the basis of this evidence, it was concluded that the primary excitation process is operating on auroral magnetic field lines and that the plasma density gradient at the plasmapause gives rise to a secondary resonance effect (Jacobs, 1970; Kuwashima, 1978). The observations on the polarisation properties of the Pi pulsations are by far more controversial than those on the amplitude characteristics. It is likely that phase reversals across boundary lines in longitude and in latitude, such as the auroral zone or the plasmapause, substantially complicate the issue, as the interpretation of a given measurement depends on the accurate spatial determination of the appropriate boundary with respect to the observation site. A detailed description of the properties of Pi 2 pulsations and the corresponding theoretical interpretations was recently given by Kuwashima (1978) supported by a compilation of the relevant literature.

In order to further the understanding of mid-latitude Pi pulsations and their propagation characteristics, an observational programme was performed at five sites with geomagnetic latitudes between 49.8 and 54.0 deg and geomagnetic longitudes reaching from 87.5 to 155.0 deg. The corresponding McIlwain parameters L were smaller than 2.9. Consequently, all stations were located south of the plasmapause for magnetically quiet and moderately disturbed time intervals, thus eliminating any complications by the expected polarisation reversals across this boundary.

2. Methods of Observation and Data Analysis

The observations used in this study were made by compensation-type pulsation magnetometers described elsewhere (Wilhelm, 1966; Wilhelm et al., 1977). In summary, both pulsations and variations of the geomagnetic field were recorded in both components H and D of the horizontal disturbance vector. The amplitude and phase response curves of all recording systems as a function of the pulsation period were nearly identical, showing 3-dB points at periods of 1 and 150 s.

Data were recorded both on paper charts and digital magnetic tapes. Special features of the magnetic tape recordings were sampling times of 0.4 and 3.2 s for pulsation and variation channels, respectively, and a resolution of the digitization of 0.03 nT in the frequency range corresponding to the plateau of the response function. Internal crystal clocks and frequent comparisons with radio time signals maintained a very good time accurancy at the widely separated stations. The time adjustments required typically were of the order of 40 ms and never exceeded 100 ms giving an indication of the synchronism achieved.

Five identical instruments were operated on a profile reaching from Lindau, FRG, to Novosibirsk, USSR. The stations and their geomagnetic coordinates are listed in Table 1.

The experiment was conducted from August 1–October 25 1974 as a joint venture of the Max-Planck-Institut für Aeronomie and the Institute of the Physics of the Earth. A more detailed description of the project was given by Münch et al. (1975) and first results were published by Troitskaya et al. (1976a and b).

0340-062X/80/0048/0001/$01.20

Table 1. List of stations

Station	Nomenclature	Geomagnetic latitude, deg	Geomagnetic longitude, deg	L-parameter	Local magnetic time at 00:00
Lindau	LIN	49.8	87.5	2.40	02:00
Kaliningrad	KNG	52.1	98.0	2.65	02:42
Borok	BOR	54.0	114.0	2.89	03:48
Sverdlovsk	SVE	52.5	135.5	2.70	05:12
Novosibirsk	NOV	49.7	155.0	2.39	06:30

The pulsation recordings of the *H* and *D* components designated in this paper by P_H and P_D, respectively, stored on magnetic tape in a digital data format were processed using a computer programme by Grusdeva et al. (1974), which carried out an analysis of the spectral contents of the pulsation signals with respect to time. The principle of the mathematical formalism can be summarized as follows:

Let $U(t)$ denote the time dependent signal of the pulsation activity, an estimate of the spectrum of the signal $s(\omega)$ as a function of the angular frequency averaged over a time interval τ can then be obtained by

$$s(\omega)=\int_0^{\tau} U(\vartheta)\exp(-i\omega\vartheta)\,d\vartheta. \tag{1}$$

The interval τ has to be chosen in accordance with the accuracy of the estimate and the time resolution required. Using narrowband filters, the time dependent change of the spectrum can be computed by

$$Y(t,\omega_\nu)=\frac{1}{\pi}\int_0^{\infty}\left[\int_0^{\tau} U(\vartheta)\exp(-i\omega\vartheta)\,d\vartheta\right] \cdot\exp[i\omega t-\alpha(\omega-\omega_\nu)^2/\omega_\nu^2]\,d\omega \tag{2}$$

with discrete values of $\nu=1 \dots N$, where ω_ν is the central frequency of the ν-th filter. The factor α determines the slope of the filter response curve. In the calculation presented here, α and N were chosen to be equal to 25 and 30, respectively. Discrete time series of the P_H and P_D components and of the horizontal magnetic disturbance $P=(P_H^2+P_D^2)^1/_2$ were separately treated according to Eq. (2). The magnitude $r=|Y(t,\omega_\nu)|$ of $Y(t,\omega_\nu)$ solely depends on the amplitude of the filtered signal and, similarly, the argument of $Y(t,\omega_\nu)$ is related to the phase φ. The quantities r_{P_H}, r_{P_D} and r_P as well as φ_{P_H} and φ_{P_D} were thus obtained, by which the pulsation activity could be characterized. In addition, the phase difference $\varphi_{P_H}-\varphi_{P_D}$ is of interest for a comparison of the horizontal components. The magnitudes r were plotted in (t, T)–planes with a time resolution corresponding to $\tau=6.4$ s. The pulsation period T instead of the frequency was used here for reasons of simplicity. In these plots, contour lines of constant pulsation activity could be drawn thus delineating wave packets of the Pi pulsations. Furthermore, the largest amplitude for each individual frequency band could be determined.

3. Observations and Results of the Data Analysis

Two examples of the dynamic spectra of Pi events recorded simultaneously at all five stations have been compiled in Figs. 1 and 2. Inspection of auroral zone magnetograms showed that the centre of the substorm activity related to Fig. 1 was located near northern Scandinavia (geomagn. long. 120 deg) starting at 18:45 UT. The amplitude signal of the pulsation activity between 18:45 and 18:46 UT was largest at Borok. The event in Fig. 2 resulted from a substorm of more than 500 nT negative depression in the *H* component over Iceland and Greenland. In addition, four other cases of simultaneous Pi events were analysed that could clearly be identified at all observation sites in the time interval from October 18–22, 1974. In Fig. 3 some of these events are depicted as functions of time. The two features that are most apparent from Figs. 1 and 2 are the different positions of the wave packets in the (t,T)-domain for different stations and the displacement between the P_H and P_D components relative to each other. In

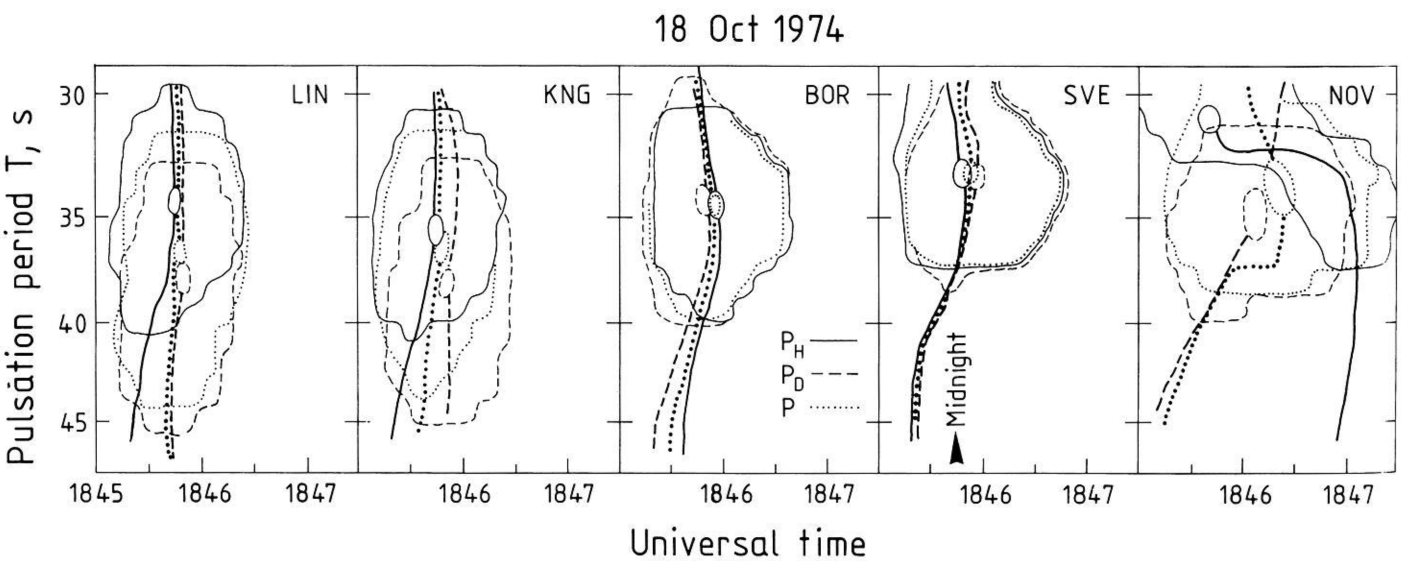


Fig. 1. Dynamic spectra of a Pi pulsation event on October 18, 1974 at 18:46 UT. Amplitude contours of the pulsation components (for details see text) are given in a universal time-pulsation period co-ordinate system together with the location of the amplitude maxima

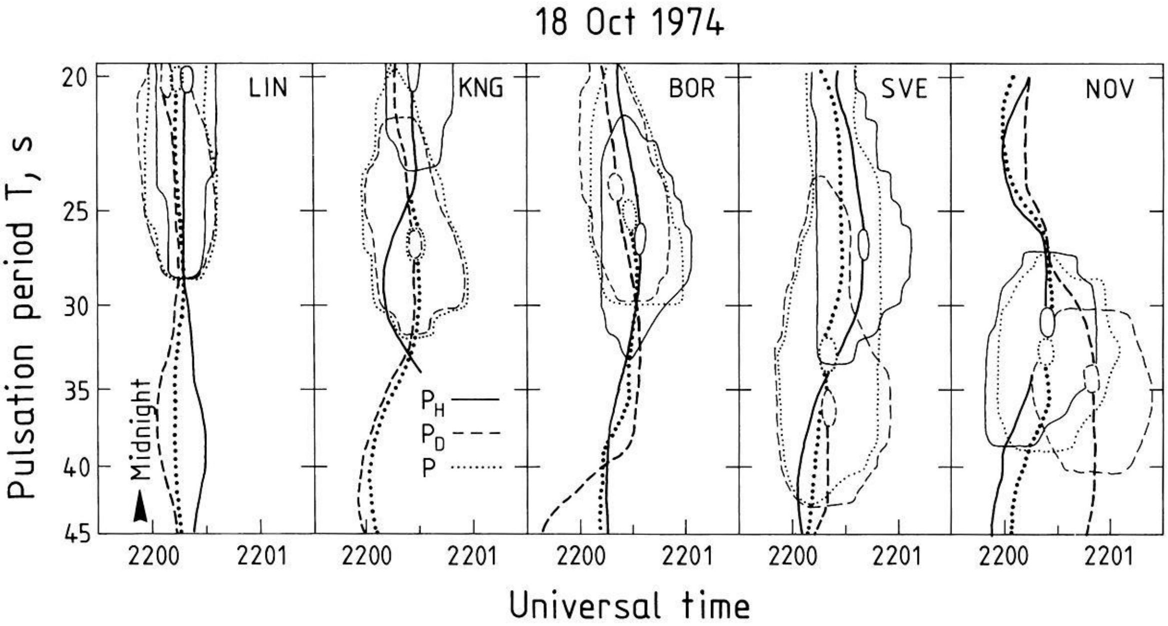


Fig. 2. Dynamic spectra of a pulsation event on October 18, 1974 at 22:00 UT

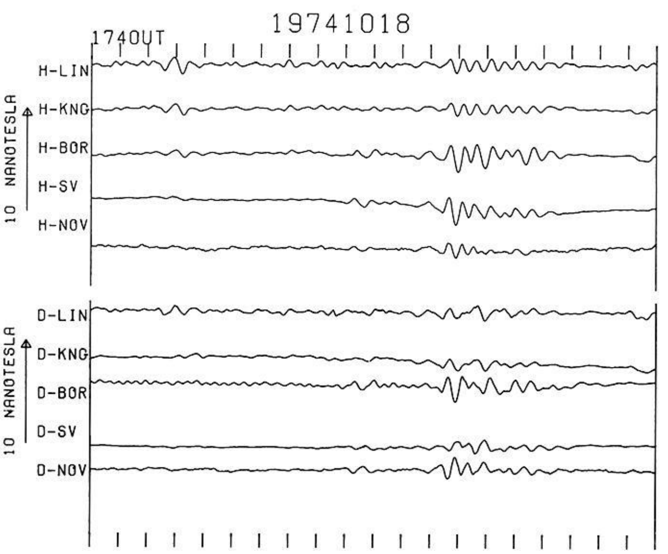


Fig. 3. Amplitude-time displays of Pi pulsation events in both the *H* and *D* components as observed at the five observational sites. The *arrows* point in the positive direction and have a length corresponding to 10 nT. The time span shown is 20 min starting at 17:40 UT on October 18, 1974

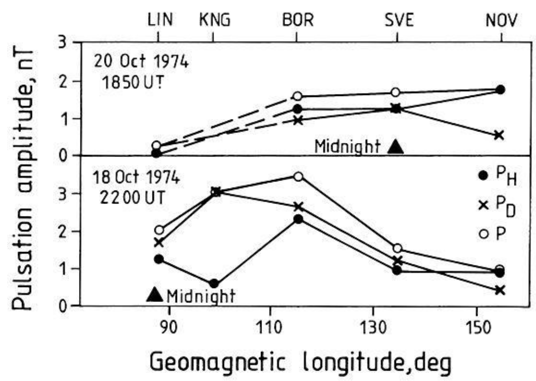
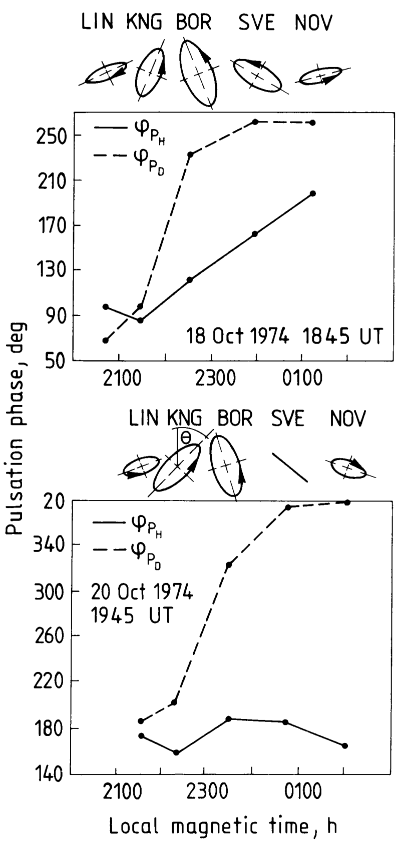


Fig. 4. Mean peak pulsation amplitude of two Pi events as a function of geomagnetic longitude

particular, there is a tendency towards a shift of the position of the wave packets to longer periods with increasing distance from magnetic midnight. Beginning at stations near local magnetic midnight where the positions of the wave packets of the P_H and P_D components almost coincide, this shift of the main period of the Pi pulsations increases with distance from the midnight meridian and is significantly stronger for the P_D than for the P_H component, causing the large displacement of the wave packets in the (t,T)-domain of the P_D relative to the P_H component at stations located sufficiently far from the magnetic midnight meridian.

In order to establish the distribution of the intensity of a Pi event along the profile the following method was applied: For each event, an area in the (t,T)-plane was defined that contained the peak values of the amplitudes at all five stations. Over this area, the average amplitude values were then calculated for different stations. The amplitude information thus obtained could directly be used in comparing the different observation points. This was done in Fig. 4, showing two examples of the distribution of the average amplitude peaks of the quantities P_H, P_D, and P along the profile. The maxima of these distributions exhibit a weak tendency to follow local magnetic midnight. In addition, it could be noticed in these and other examples not subject to the restriction made in this paper of simultaneous occurrence at all five stations that Borok normally showed the largest amplitudes. This seems to reflect the fact that the stations were not precisely located along a constant latitude profile but that the central stations lay at higher latitudes (see Table 1). Taking into account the increase of Pi 2 amplitudes with increasing latitude of typically 0.2–0.9 nT/degree (Baranskiy et al., 1974), which is a large gradient as compared to the weak longitudinal dependence, we can presume



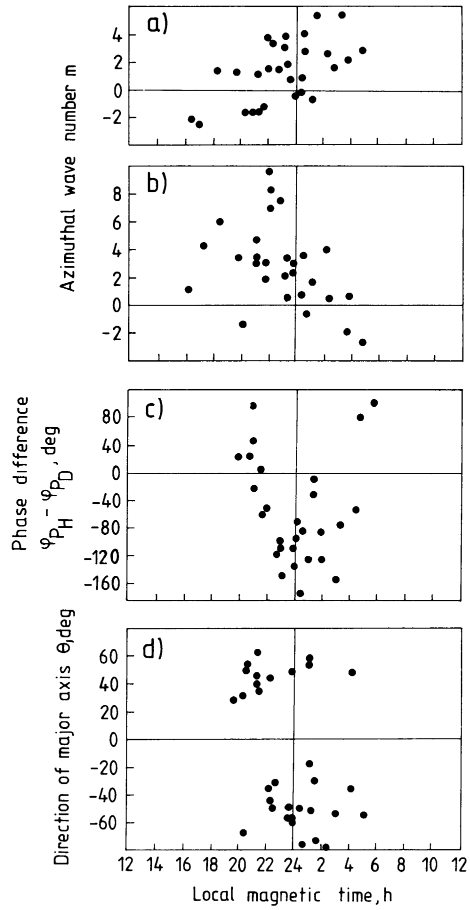


Fig. 5. Variation of the pulsation phase for both components along the observation profile for two events. Also given are schematic polarization ellipses and the sense of the rotation of the disturbance vector

Fig. 6. Dependence of Pi wave parameters on local magnetic time

that the Pi amplitudes at the stations BOR, KNG, and SVE are usually larger than those at the stations LIN and NOV mainly because of their geomagnetic location.

In order to investigate the shape of the Pi waves and their variations in space along the chain of stations considered here, it was necessary to study the phase relations of the P_H and P_D components. For each individual wave packet the phase relationship turned out to be rather stable. This allowed the determination of the average phase values at all stations. For two pulsation events the resulting phase curves as a function of local magnetic time are given in Fig. 5.

Also indicated in this figure are the polarisation ellipses for each station. When assessing the phase dependence of Pi pulsations on local time, it should be remembered that the phase of sinusoidal waves propagating in one direction along the profile would linearly change in this direction. It can be seen that this ideal case is only a very crude approximation for some portions of the propagation path. The observed nonlinear changes of the phases point to more complicated wave structures and changes or even reversals of the phase velocity. The polarisation ellipses support earlier investigations (Baranskiy et al., 1970; Björnsson et al., 1971) that Pi 2 pulsations are characterized by a dominant left-hand rotation of the disturbance vector in the horizontal plane and the change of the sign of the orientation angle θ around midnight. In order to reveal some of the statistical properties of Pi pulsation events, the information obtained for all events studied here have been compiled in Fig. 6 as a function of local magnetic time. An important parameter is the phase difference between pairs of stations. It was taken positive when the phase angle of the signal at the eastern station was greater than that at the western station. The resulting phase difference could only be determined modulo π and was selected to lie between $\pm\pi$. Any ambiguity could be excluded by the assumption that the change of the phase along the profile of stations was continuous. The azimuthal wave number m could then be defined by $m = \Delta\varphi/\Delta\lambda$ where $\Delta\varphi$ is the difference of the phase of the signal at two neighbouring stations and $\Delta\lambda$ is the difference of their longitudes. The scatter plots of m exhibit little systematic behaviour both for the H (Fig. 6a) and D (Fig. 6b) component. Most of the values are positive and seem to have a tendency to change sign around midnight for both components. Should this indication be supported by further investigations, it would mean that the phase velocity of the P_H signal is directed towards local magnetic midnight whereas the P_D signal is directed away from it.

The dependence of the phase difference between the P_H and P_D signals on the local magnetic time is displayed in Fig. 6c. This difference characterizes the direction of the rotation of the disturbance vector of the pulsations in the horizontal plane. A right-hand rotation will lead to positive values of $\varphi_{P_H} - \varphi_{P_D}$ and a left-hand rotation correspondingly results in negative values.

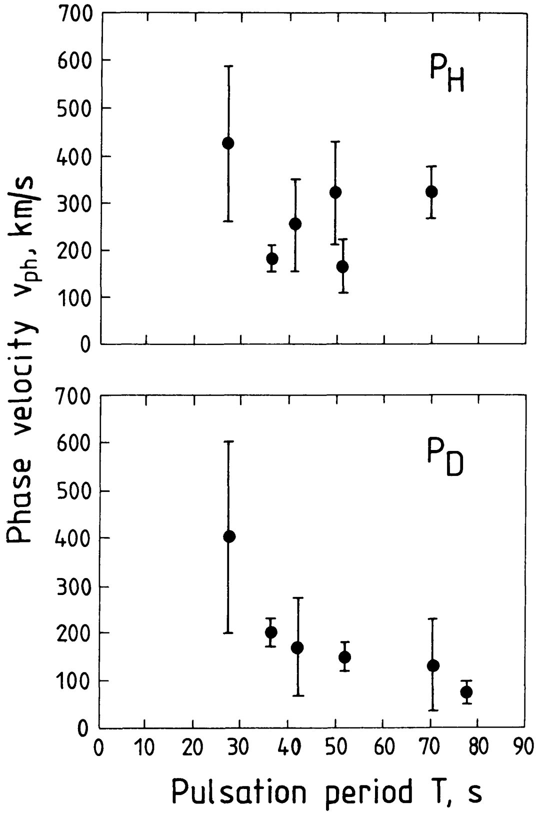


Fig. 7. Phase velocities of the two horizontal wave components as a function of the pulsation period

It follows that the rotation of the horizontal vector of Pi pulsations is predominantly negative in the 21:00 to 04:00 local magnetic time interval and positive both before and after this interval.

Finally, the dependence of the angle of the major axis of the polarisation ellipses with the north direction on local magnetic time is presented in Fig. 6d. The angle is positive, if the axis of the ellipse is pointing into the north-east quadrant and negative, if it is deflected to the west. The scatter diagram does not indicate a clear local time dependence. However, the mean local times of the positive and negative clusters have significantly different values of 22.3 and 0.6 LMT, respectively, confirming earlier findings of Baranskiy et al. (1970) that a change of the sign of the angle θ in the vicinity of the midnight meridian is a common feature for Pi pulsation events.

Figure 7 summarizes the findings on the phase relationships of Pi pulsations in mid-latitudes by presenting the phase velocities separately both for the H and D components. A decrease of the phase velocity with increasing pulsation period seems to be indicated at least for the D-component.

4. Discussion

Observations of Pi pulsations along a latitudinal profile extending over 60 deg in longitude were carried out for the first time. Of special interest is the value and the direction of the Pi phase velocity. The figures obtained are in good agreement with calculations of the azimuthal wave number by Lanzerotti and Fukunishi (1974) and with a Pi 2 generation model suggested by Chen and Hasegawa (1974). However, the interpretation cannot be unambiguous before a moving source, possibly related to the westward travelling surge of a magnetospheric substorm event (Pytte et al., 1976; Kisabeth and Rostoker, 1973), can definitely be excluded. Further investigations taking into account the auroral Pi activity will be required to solve this problem.

Other results of this investigation of Pi pulsations are the discoveries of the pulsation period increase on either side of the midnight meridian and the polarisation splitting. The different spectral composition and the dependence of the azimuthal wave number on local magnetic time as well as the differences of the intensity distribution of the H and D components of the Pi pulsations can all be considered as evidence that the primary hydromagnetic disturbance experiences different conditions of propagation for the H and D components.

In conclusion, it may be useful to compare these findings with results obtained for pulsations in the 8–25 mHz band (Mier-Jedrzejowicz and Southwood, 1979) and for dayside pulsations Pc 3 and Pc 4 (Green, 1976). The values of the azimuthal wave numbers obtained for nighttime events were comparable to the ones reported here, whereas Pc 3 and Pc 4 pulsations had slightly larger wave numbers indicating shorter wave lengths for Pc 3 and Pc 4 than for Pi waves.

Acknowledgements. The observations discussed in this paper were made during a compaign jointly sponsored by the Deutsche Forschungsgemeinschaft and the Academy of Sciences of the USSR. The significant contributions of B.N. Kazak and R. Schmidt during the field operations are greatly acknowledged.

References

Baranskiy, L.N., Shchepetnov, R.V., Afanas'Yeva, L.T., Zybin, K.Yu., Hillebrand, O., Sanker Harayan, P.V.: Intensity distribution of Pi 2 pulsations along the geomagnetic meridian and on the night side of the earth. Geomagn. Aeron. **14**, 743–746, 1974

Baranskiy, L.N., Vinogradov, P.A., Raspopov, O.M.: Polarization of geomagnetic pulsations of the Pi 2 type. Geomagn. Aeron. **10**, 743–745, 1970

Björnsson, A., Hillebrand, O., Voelker, H.: First observational results of geomagnetic Pi 2 and Pc 5 pulsations on a North-South profile through Europe. Z. Geophys. **37**, 1031–1042, 1971

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

Green, C.A.: The longitudinal phase variation of mid-latitude Pc 3–4 micropulsations. Planet. Space Sci. **24**, 79–85, 1976

Grusdeva, N.P., Levshin, A.L., Pisarenko, V.F., Pruchkina, F.J.: Spectral time analysis of seismic waves. Theor. Comput. Geophys. Nauka 5–15, Moscow, 1974

Jacobs, J.A.: Geomagnetic micropulsations. In: Physics and Chemistry in Space, Vol. 1, J.G. Roederer and J. Zähringer, eds.. Berlin, Heidelberg, New York: Springer 1970

Kisabeth, J.L., Rostoker, G.: Current flow in auroral loops and surges inferred from ground-based magnetic observations. J. Geophys. Res. **78**, 5573–5584, 1973

Kuwashima, M.: Wave characteristics of magnetic Pi 2 pulsations in the auroral region – Spectral and polarization studies. Mem. Nat. Inst. Polar Res., Series A, No. 15, Tokyo, 1978

Lanzerotti, L.J., Fukunishi, H.: Relationships of the characteristics of magnetohydrodynamic waves to plasma density gradients in the vincinity of the plasmapause. J. Geophys. Res. **80**, 4627–4634, 1975

Mier-Jedrzejowicz, W.A.C., Southwood, D.J.: The East-West structure of mid-latitude geomagnetic pulsations in the 8–25 mHz band. Planet. Space Sci. **27**, 617–630, 1979

Münch, J.W., Wilhelm, K., Troitskaya, V.A., Kazak, B.N., Baranskiy, L.N.: Observations of geomagnetic micropulsations on a mid-latitude east-west-profile. Kleinheubacher Berichte **18**, 123–132, Darmstadt, 1975

Pytte, T., McPherron, R.L., Kokubun, S.: The ground signatures of the expansion phase during multiple onset substorms. Planet. Space Sci. **24**, 1115–1132, 1976

Troitskaya, V.A., Baranskiy, L.N., Gokhberg, M.B., Münch, J.W., Wilhelm, K., Voelker, H., Siebert, M., Hillebrand, O., Ivanov, N.A., Vinogradov, D.A.: Preliminary results of the german-soviet experiment on simultaneous registrations of geomagnetic pulsations on meridional and latitudinal profiles. Kleinheubacher Berichte **19**, 545–552, Darmstadt, 1976a

Troitskaya, V.A., Baranskiy, L.N., Gokhberg, M.B., Sterlikova, L.V., Belen'kaya, B.N., Münch, J., Wilhelm, K., Voelker, H., Siebert, M., Hillebrand, O., Kharchenko, I.P., Ivanov, N.A., Kopytenko, Yu.A.: Preliminary results of a soviet-german experiment on synchronous recording of geomagnetic pulsations on meridional and latitudinal station profiles. Geomagn. Aeron. **16**, 558–561, 1976b

Wilhelm, K.: Registrierung and Analyse erdmagnetischer Pulsationen der Polarlichtzone sowie ein Vergleich mit Bremsstrahlungsmessungen. Mitt. a.d. MPI f. Aeronomie, Nr. 27. Berlin, Heidelberg, New York: Springer 1966

Wilhelm, K., Münch, J.W., Kremser, G.. Fluctuations of the auroral zone current system and geomagnetic pulsations. J. Geophys. Res. **82**, 2705–2716, 1977

Received September 7, 1979; Revised Version December 19, 1979