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Experimental aspects of low-latitude pulsations – A review

J. Verő

Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences, Sopron, Pf. 5, H-9401 Hungary

Abstract. This paper reviews results mainly from the past 3 years. In the first part the connection between interplanetary medium/solar wind and pulsation parameters is dealt with. The effects due to modification of the primary waves in the magnetosphere, i.e., propagation and field line resonances, are summarized in Sect. 3. A survey of a few specific questions (ionospheric effects, man-made pulsations, etc.) and of some recent results on low-latitude Pi 2 conclude the review.

Key words: Geomagnetic pulsations – Low-latitude phenomena – Solar wind-magnetosphere coupling – Hydromagnetic waves – Magnetosphere – Pi 2 pulsations

1 Introduction

Within the more than one-century-long history of geomagnetic pulsations, there were several intervals of increased interest which stressed the clarification of some more or less essential problems. Over about the last 10 years there has been a rise in interest due to discoveries of the connections between pulsation parameters and parameters of the interplanetary medium. In recent years several investigations have been carried out at low-latitude (below the auroral zone, i.e. roughly below $L \sim 3$) ground stations and arrays because it was thought that they would carry clearer information than high-latitude or outer-magnetospheric ones (Yumoto, 1985a, b). One problem with the low-latitude pulsations is that corresponding satellite data cannot be obtained; therefore, ground-based data are of special importance.

2 Connections between Pc 3–4 pulsations and the solar wind

2.1 Connection between Pc 3–4 amplitudes and solar wind velocity

Since it was first suggested that the solar wind controls the pulsation amplitudes, this relationship has been nearly unanimously accepted. Many details remain, however, to be clarified. Odera (1984b) computed correlations between the amplitudes of about 100 Pc 3 and Pc 4 events and the solar wind velocity (V_{SW}) with the result that at $L \sim 2.8$ (Eskdalemuir) the correlation factor was 0.43 for Pc 3 and only 0.13 for Pc 4, and at $L \sim 2.4$ (Cambridge) both correlations were nearly zero. Wolfe et al. (1985) found correlation coefficients of 0.08–0.50 for 9 low-latitude stations (hourly averages) with higher values in an open magnetosphere (with negative, southward B_z), but the main factor governing pulsation activity was B_x, and not V_{SW}. In the case of longer (daily) averages, the correlation is closer, e.g., Střeštik (1984) found a value of 0.6 both for Pc 3 and Pc 4 at $L \sim 2.0$ (Fürstenfeldbruck).

Verő et al. (1985) found at $L \sim 1.9$ (Nagycenk) that the exponent x in the function $A = c\,V_{\mathrm{SW}}^x$ (A is the amplitude of the pulsation, c a constant) depended on the period of the pulsations studied (Fig. 1). For short periods the exponent is greater than 2; for periods around 60 sec it is less than 1 or even nearly zero. This corresponds to a shift

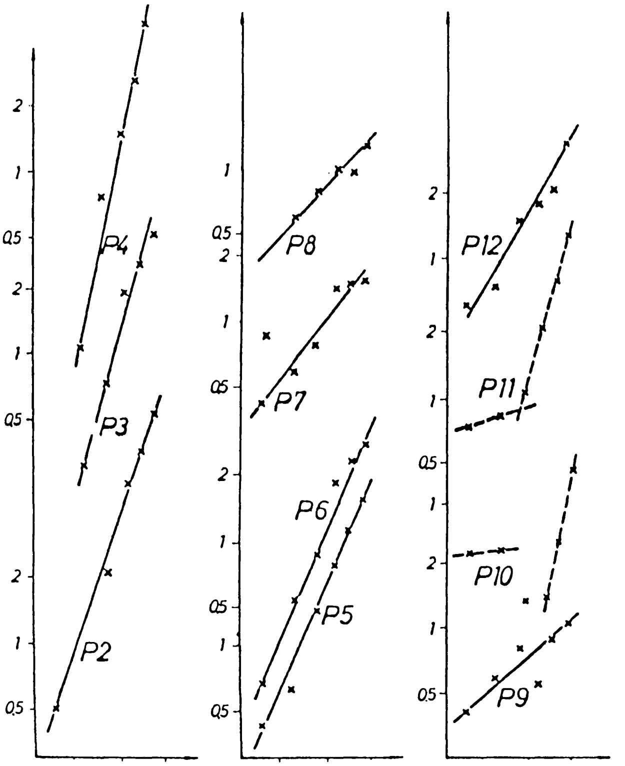

Fig. 1. Average amplitudes of the pulsations in 11 period bands (P2, 5–10 sec; P3, 10–15 sec; P4, 15–20 sec; P5, 20–25 sec; P6, 25–30 sec; P7, 30–40 sec; P8, 40–60 sec; P9, 60–90 sec; P10, 90–120 sec; P11, 2–5 min; P12, 5–10 min) as a function of solar wind velocity at $L \sim 1.9$ (Verő, 1980)

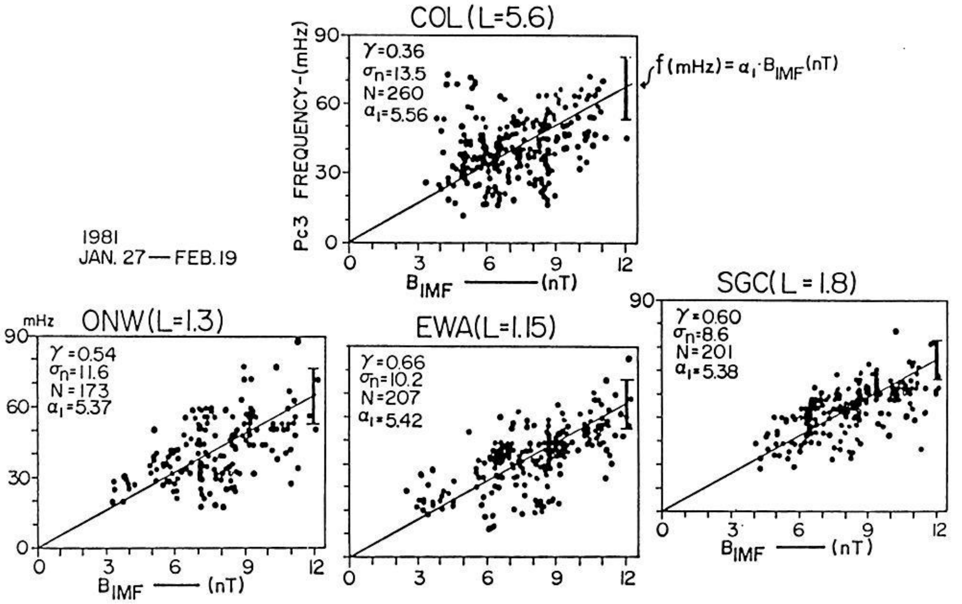

Fig. 2. Scatter plots of daytime Pc 3–4 frequencies at four globally coordinated stations against IMF magnitude from Jan. 27 to Feb. 19, 1981 (a very quiet interval). The *solid lines* indicate the function $f(\mathrm{mHz}) = \alpha_1\, B_{\mathrm{IMF}}(\mathrm{nT})$. γ and δ_n are the linear correlation coefficient and the standard deviation ($\pm \Delta f$ mHz) of the observed value from the computed one, respectively (Yumoto, 1985b)

in the pulsation periods toward shorter ones for high V_{SW} (see Sect. 2.2).

Plyasova-Bakounina (1985) found an asymmetry between morning and evening hours in the relationship between V_{SW} and the amplitude of solar-wind-controlled pulsations. Adopting a Kelvin-Helmholtz (KH) source she supposed that at a given V_{SW} the higher evening activities are due to the different directions of the magnetospheric convection at the dusk and dawn sides. This increases V_{SW} at the magnetopause in the evening and decreases it in the morning hours, i.e., the limit of the driving instability is attained more often at dusk.

The connection between pulsation amplitudes and V_{SW} changes little during the solar cycle (Verő, 1981; Polyushkina and Potapov, 1983); the deviations were found to be less than 10% of the values expected on the basis of the relationship between solar wind velocity and pulsation activity. The connection is, however, disturbed during the solar maximum by the winter minima of the pulsation activity due to ionospheric screening (see Sect. 4).

This stability is somewhat surprising as Troitskaya and Bolshakova (1984) found different pulsation types in different solar wind conditions. For instance, quiet, homogeneous, high-velocity solar wind generates regular Pc 3, and more variable solar wind, mixed Pc 3–4. The occurrence of these conditions does change quite strongly within the solar cycle.

The better correlations for averages from longer time intervals may be due to the elimination of IMF effets which change on a much shorter time scale than V_{SW}. In longer time intervals, the IMF effects are averaged out from the results, and therefore correlations become better.

2.2 Connection between interplanetary magnetic-field magnitude and pulsation periods

As clear as the connection between IMF magnitude and pulsation periods seemed to be at the time of its discovery, much controversy has developed around it. Because the time scale of IMF variations is shorter than those of V_{SW}, an hourly basis is often insufficient for correlation studies.

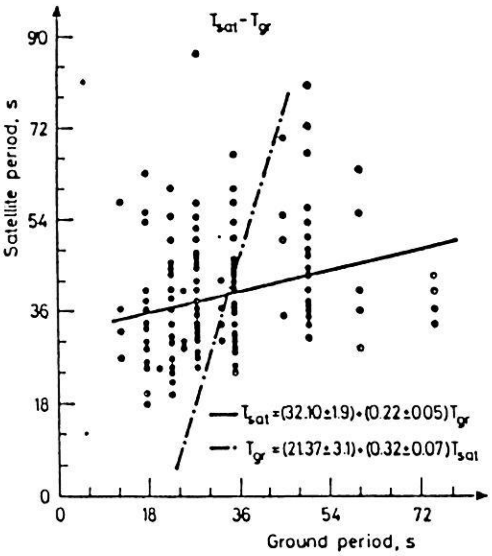

Fig. 3. Scatter plot of measured periods (T_{sat}) of waves in the solar wind on board, the ISEE-2 satellite and measured periods (T_{gr}) on the ground at Nagycenk ($L \sim 1.9$) (Odera, 1984a)

If two or more spectral peaks are superimposed the "period" of a time series (pulsations) within an interval can be defined in several ways. Thus, the "period of pulsations" is an ambiguous notion if several spectral components appear simultaneously. Both these facts mean serious problems in investigations involving pulsation periods.

Based on a study including globally coordinated low-latitude stations ($L \sim 1.15$–1.8), a high-latitude station (Collage) and the GOES-2 satellite, Yumoto (1985a) found correlation coefficients of 0.54–0.66 between B and F (frequency of the pulsations) at low-latitude stations; in College it was 0.36, and for GOES, 0.70 (Fig. 2). He attributed the low-latitude increase in the correlation to a filtering effect during magnetospheric propagation, when localized waves in the high-latitude ionosphere and magnetosphere are effectively removed. Yumoto's data refer to spectral peaks from 20-min-long periods of the records.

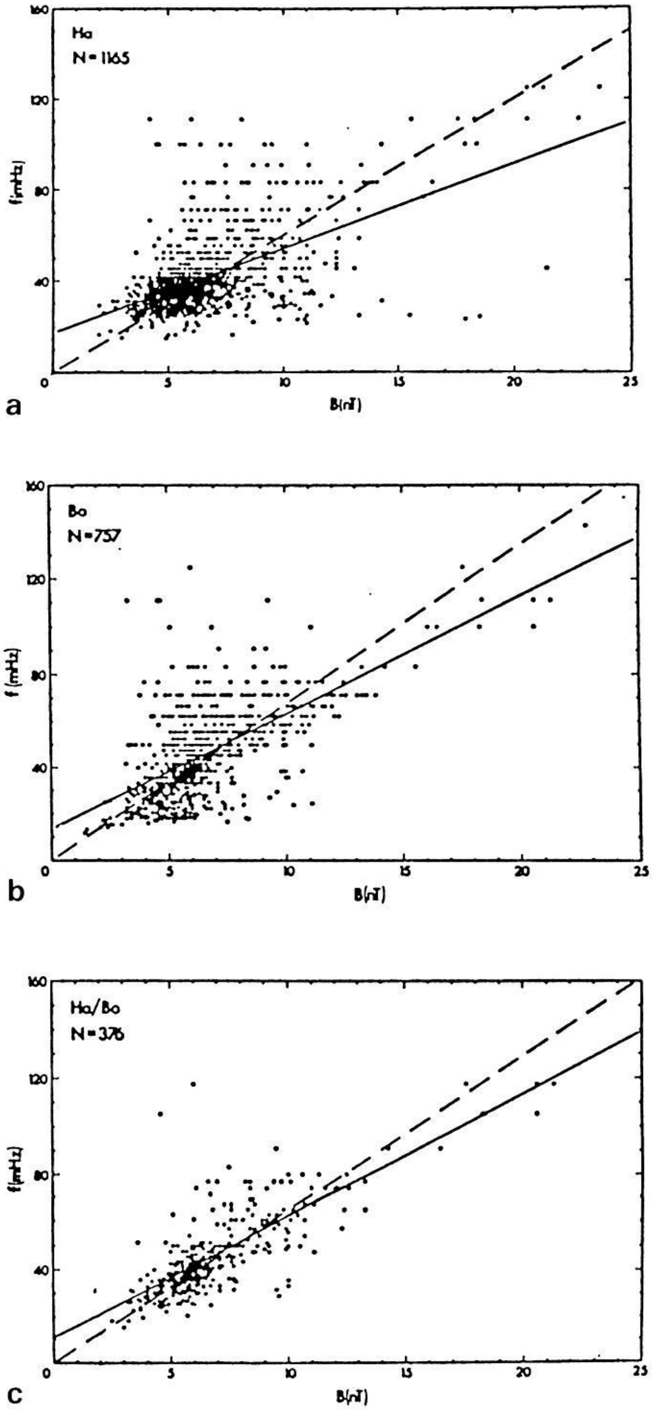

Fig. 4a–c. Scatter plots of ground pulsation frequencies against IMF magnitude. **a** Data from station Ha alone, **b** data from station Borok alone, **c** data when period at Hartland $\simeq$ period at Borok (dotted line, $F=6B$; full line, $F=c_1B+c_0$, with the free constants c_0 and c_1) (Green et al., 1983)

Odera (1984a) compared pulsation periods from Nagycenk ($L \sim 1.9$) with those onboard ISEE-2 and found rather low correlation (Fig. 3). He considered the differences only partly due to differences in response of the instruments.

From a wider data basis, Odera (1984b) found the best-fitting regression lines between $F=1/T$ (Pc 3) and B of the form $F=c_0+c_1B$, i.e., not forced through the origin. This idea is shared by Green et al. (1983; Fig. 4). As their statistical treatment was very careful, the form given by Green et al. and Odera must be taken into account. We suppose that at least a part of the deviations from the $F=cB$ law is due to an effect of V_{SW} (or Kp). Figure 5 shows data from Nagycenk for selected ranges of the solar wind velocity as amplitudes vs B. At lower V_{SW} values, the $c \cdot B$ law is correct at least up to a B value of 10 nT, but with increasing V_{SW}, the change in T vs B becomes less and less evident (Fig. 6). In the limits, at a solar wind velocity below 300 km/s, the $F=cB$ law is correct in a rather wide range of B while at very high velocities (>700 km/s) there is little or no dependence of F on B. If different values of V_{SW} occur in a sample, the correlation decreases, and depending on the amount of higher V_{SW} values, the regression line does not cross the origin. It is characteristic that Yumoto's (1985a) data are from a time interval of quiet and very quiet magnetic conditions with the exception of a single day.

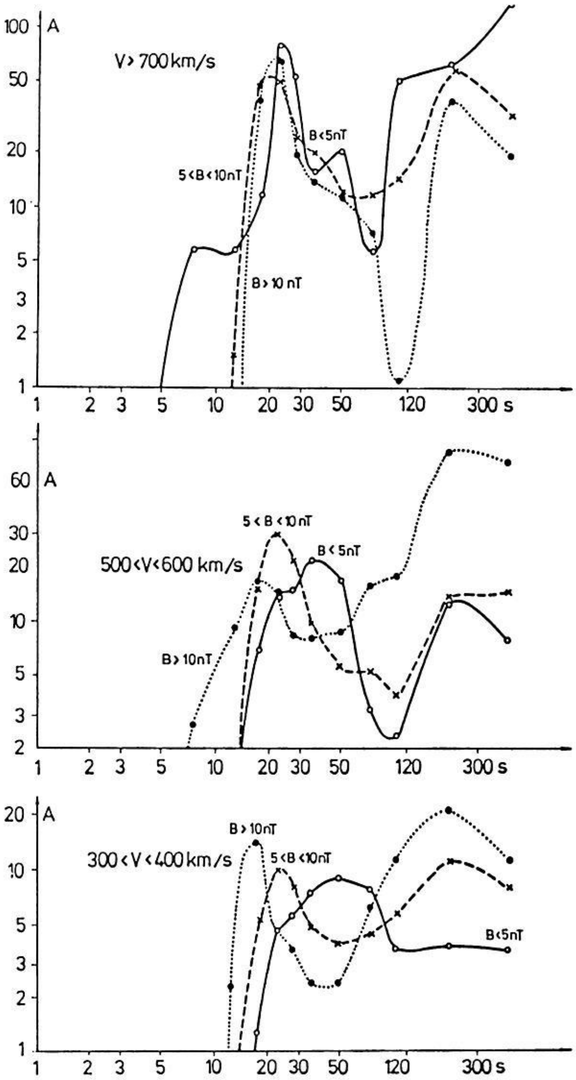

Fig. 5. Pulsation amplitudes at the observatory Nagycenk ($L \sim 1.9$) at different solar wind velocities and at different values of B. The three panels correspond to three discontinuous ranges of V_{SW}, increasing from bottom to top

An intriguing problem is how to select solar-wind-controlled pulsations. As supposed by Gul'elmi et al. (1973)

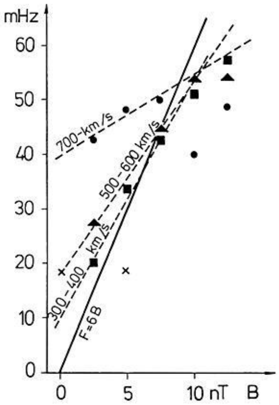

Fig. 6. Peaks in amplitude distribution of Fig. 5 against B at different solar wind velocities and the corresponding linear approximations

and Plyasova-Bakounina et al. (1982) and accepted by Odera and Stuart (1985), the correlation between B and F can be significantly improved if pulsations are used whose periods coincide at distant stations (of distances more than 20° in longitude, surpassing the supposed dimension of inframagnetospheric pulsation sources). They used data from Borok ($L \sim 2.9$) and Hartland ($L \sim 2.4$) and then from Cambridge ($L \sim 2.5$) and Faroes ($L \sim 4.4$) with the result that the connection improved for pulsations with identical periods at both stations (Fig. 7).

This selection is very difficult to harmonize with Cz. Miletits's (1980) result that regular pulsations have a strong latitude dependence of periods corresponding to a field line resonant amplification of certain periods. Accepting the latitude dependence of periods, however, the criterion of the period identity would exclude a very essential part of the pulsations from the direct $F-B$ connection for which a reasonable fit with the predicted periods is evident. This problem will be discussed in Sect. 3.1.

2.3 Connection between the cone angle and Pc 3–4 amplitudes

The cone angle, $\Theta = \cos^{-1}(B_x/|B|)$, was shown by Saito (1964) and Bolshakova and Troitskaya (1968) to control Pc 3–4 activity. After some initial discussion, the existence of such a control became generally accepted; nevertheless, there are many controversial points within this dependence.

As the two main factors controlling pulsation activity, the solar wind velocity V_{SW}, and the cone angle Θ have very different time scales for the variations (typical value for V_{SW}, around one day; for Θ, some tens of minutes to a few hours), the changes in the Pc 3–4 activity due to these two factors can be quite easily separated. Switches, i.e., sudden changes in the activity, are connected to changes in Θ, while smooth changes, e.g., in daily averages, are mostly due to changes in V_{SW}. Thus, in addition to looking for correlations between Θ and pulsation amplitudes, the immediate effect of switch-offs and switch-ons can be found, too.

Wolfe et al. (1985) found a decrease by about a factor of 3 between the cone angles of 30° and 90° (Fig. 8), and the correlation coefficients between pulsation power and Θ were rather high, -0.4 to -0.8.

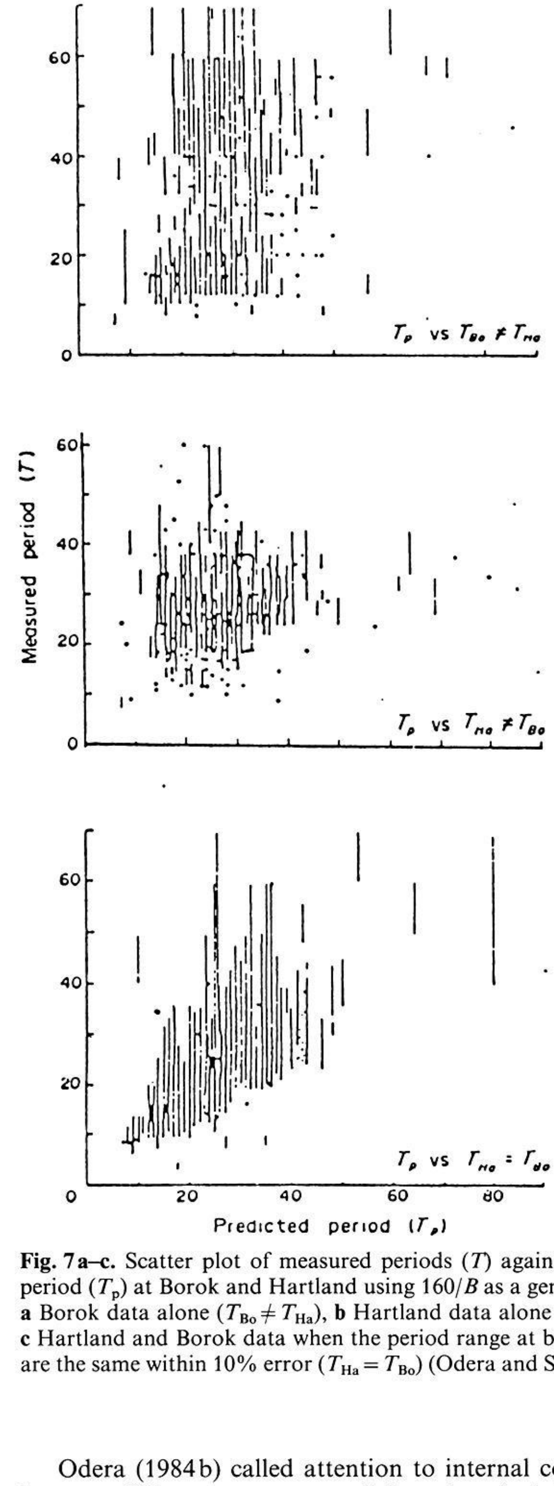

Fig. 7 a–c. Scatter plot of measured periods (T) against predicted period (T_p) at Borok and Hartland using $160/B$ as a general model. **a** Borok data alone ($T_{Bo} \neq T_{Ha}$), **b** Hartland data alone ($T_{Ha} \neq T_{Bo}$), **c** Hartland and Borok data when the period range at both stations are the same within 10% error ($T_{Ha} = T_{Bo}$) (Odera and Stuart, 1985)

Odera (1984b) called attention to internal correlations between different parameters of the solar wind. Θ depends both on V_{SW} and B. In his sample, Θ increases from 35° to 55° for V_{SW} values of 300 and 600 km/sec, and from 45° to 55° for B values of 4 and 12 nT. The correlation between V_{SW} and Θ may contribute to lower correlations in certain samples between V_{SW} and pulsation power if the cone angle effect is neglected. Moreover, Odera (1984b) found also correlations of -0.45 between Pc 3 power and Θ and of -0.35 between Pc 4 power and Θ, in accordance with the previously mentioned results. Without continuing the enumeration of correlation results, two effects should be mentioned which are of particular interest.

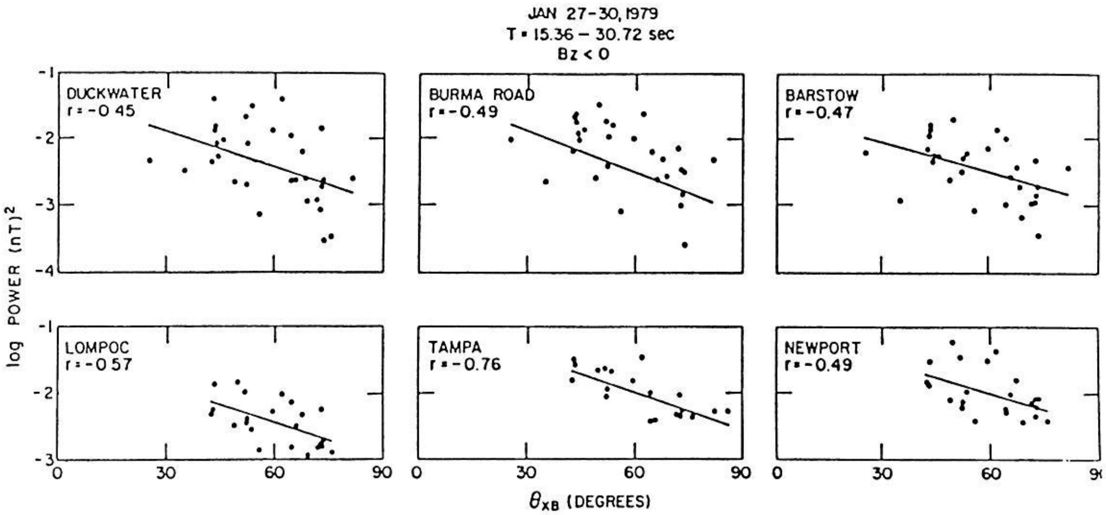

Fig. 8. Scatter plots of log power (15.36–30.72-sec band) vs cone angle Θ_{XB} for all $L=2$ (and $L=3$ at Newport) dayside stations of the AT & T Bell Laboratories and AFGL networks. Correlation coefficients (r) are also indicated. (Wolfe et al., 1985)

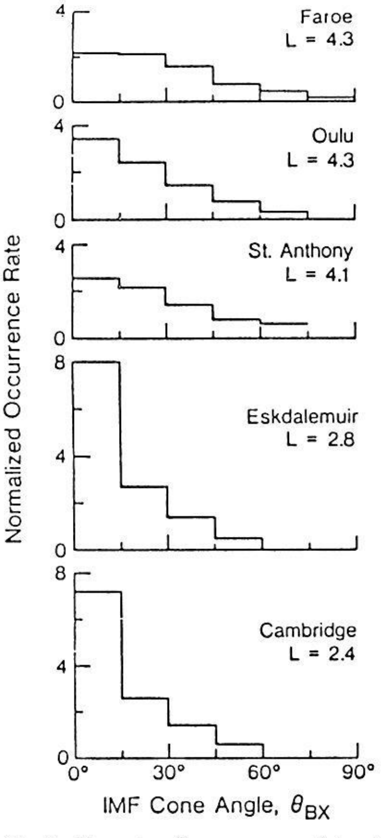

Fig. 9. The rate of occurrence of dayside Pc 3–4 pulsations at five IGS stations as a function of the cone angle. The rates have been normalized by the rate of occurrence of orientations of the IMF during the period of survey (Russell et al., 1983)

The first one is from Russell et al. (1983) who found a significant change in the cone angle effect with latitude in the sense that the effect was felt at larger Θ at higher latitudes (Fig. 9). The sharp dependence at low L on Θ reflects the dependence of upstream wave amplitudes at the nose of the magnetosphere on Θ, while at high L the weak effect should be due to a shift of the stream lines which convect the waves from the magnetopause and indicates cross-stream line propagation.

The other, controversial point is the cone angle optimum. Generally, an optimum at 0° is accepted, but the number of cases around $\Theta=0°$ is quite low; therefore, in smaller samples values around 0° are mostly lacking (see, e.g., Wolfe et al.'s and Odera's data). At Nagycenk ($L\sim1.9$), from the data of two years, a maximum in amplitude at 30° was found in the period of 15–30 sec, but a similar investigation at the Uzur observatory at similar latitude failed to confirm this result (Verő et al., 1985). The cause of this difference lies neither in a difference in the period ranges (which does not exist) nor in a difference in the processing method. The Nagycenk values for cone angles of 0°–20° are averages for about 200 hand-scaled amplitudes.

Switch-ons and switch-offs are conspicuous events; perhaps this is why a considerable amount of research has been concentrated on them. Anyway, in satellite and ground data both simultaneous and noncoinciding events can be found. A characteristic positive example is presented by Yumoto et al. (1984) and Yumoto (1985a) for three stations and several switches. Odera (1984a, b) presented on the contrary a few cases in which switches in the solar wind were absent in ground records (Fig. 10). His figure contains data from Cambridge (at $L\sim2.5$) and ISEE-2. The switch-off and switch-on sequence around 0800 UT on December 3, 1977, was clearly present on ISEE-2 and much less evident and shorter at the ground station. Nagycenk records, however, are more similar to the ISEE-2 spectra than to the Cambridge ones. Both frequency ranges and the switches are evident there as shown in Fig. 10 by dotted areas. The interruption of the activity at ~25 mHz lasts on ISEE-2 for about 90 min, at Cambridge for about 15 min, and at Nagycenk for about 120 min.

Wolfe et al. (1985) discussed a time interval with evidence both of an association and lack of it between interplanetary conditions and ground-based hydromagnetic energy at low latitudes. They found two consecutive switch-on/switch-off sequences, identified at stations between $L\sim2$ and $L\sim4$. Both events were connected with the IMF. The first event occurred after a short deviation in the IMF direction; the second followed a change of the IMF direction (Figs. 11 and 12). The duration of the disturbance at the ground station was longer than in the solar wind within roughly identical period ranges.

Holló and Verő (1985a) selected events on an hourly basis from IMF data when Θ changed from unfavorable to favorable and vice versa. The simultaneous changes in the activity of several period ranges are shown in Fig. 13. For Pc 3, the average changes are 30%–45% both for switch-offs and switch-ons, but the latter have a more uniform change in all period ranges studied. Two hours after the switch-on, amplitudes return to the previous level. In switch-offs, the amplitudes remain low for a longer time. This corresponds to Wolfe et al.'s (1985) result where the high activity events were of rather short duration (less than 1 h).

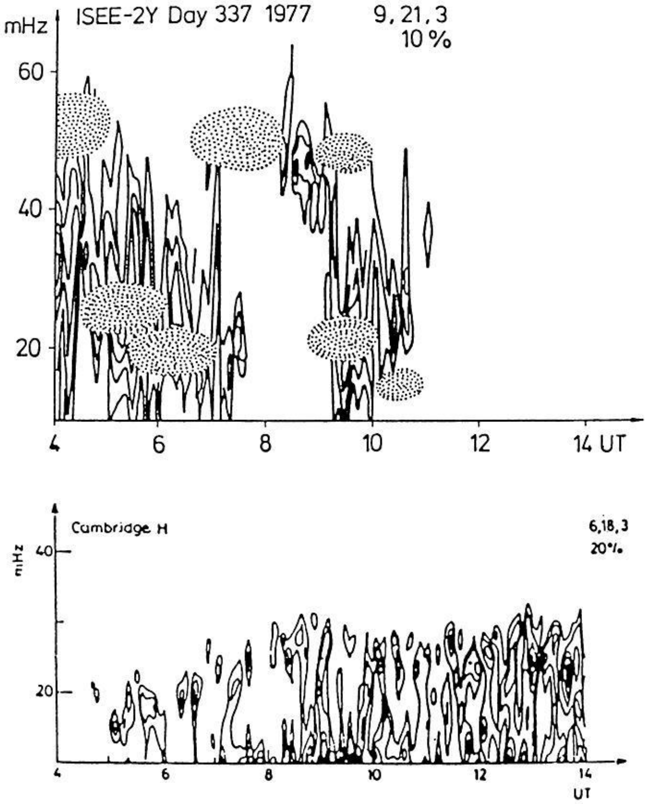

Fig. 10. Dynamic spectra of waves in the solar wind (*top panel*) and the simultaneous Pc 3–4 pulsations on the ground (*bottom panel*) for 0400–1400 UT on day 337 at Cambridge. The active pulsation periods in Nagycenk are shown by dotted areas for comparison (after Odera, 1984a)

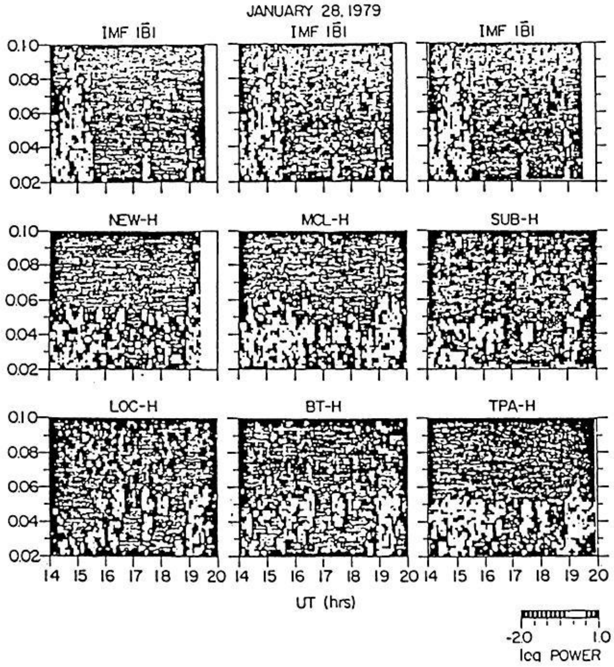

Fig. 12. Comparison of dynamic power spectra of magnetic field data measured in the interplanetary medium and at ground stations (*H* component) near $L\sim2$ and $L\sim3$ across the USA. Enhancements in ground-measured Pc 3 wave power occur simultaneously with enhancements for these same frequencies in the magnetic field power in interplanetary field at 1730 UT and 1900 UT (Wolfe et al., 1985)

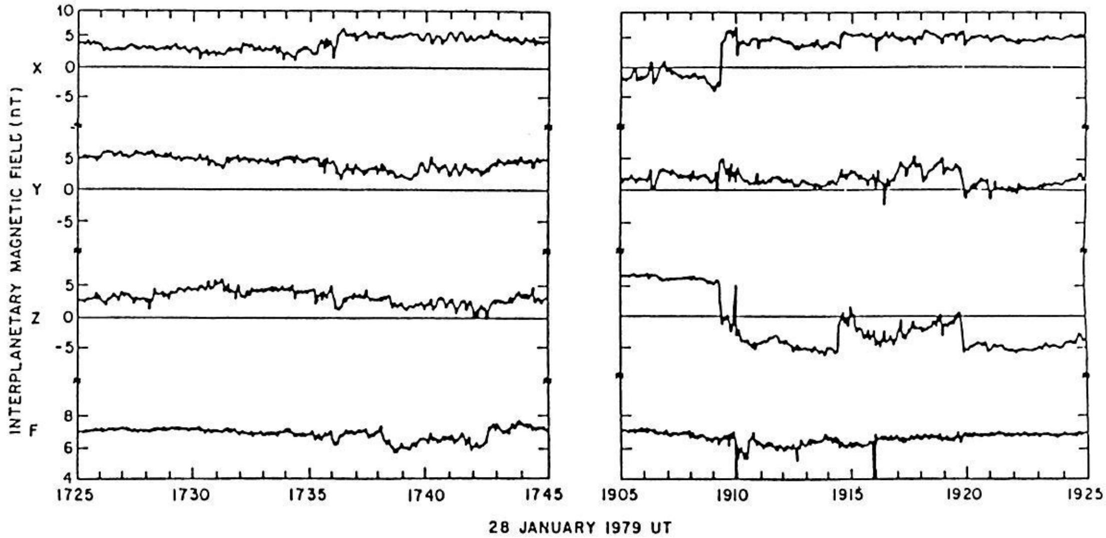

Fig. 11. Interplanetary magnetic field data in solar-magnetospheric coordinates and total field magnitude for two time intervals. *Left panel*, abrupt changes in the field occurred near 1735 UT; *Right panel*, changes in the field begin near 1910 UT (Wolfe et al., 1985)

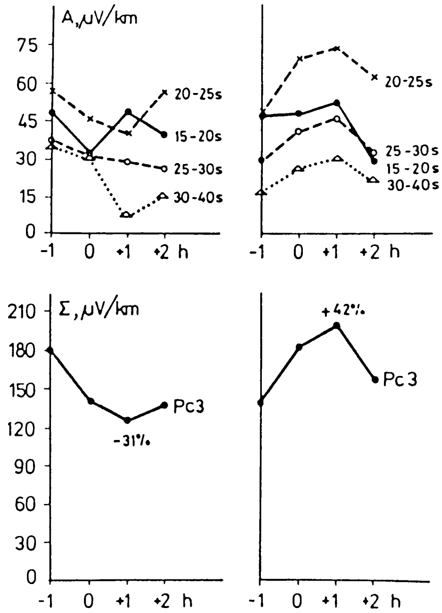

Fig. 13. Effect of switch-offs (*left*) and switch-ons (*right*) selected on the basis of IMF data (cone angle changes) at $L \sim 1.9$ in narrow period bands (*top*) and in the full range of Pc 3 (*bottom*) (Holló and Verő, 1985a)

If for synchronization similar switch-like events in ATS 6 records are used (Halló and Verő, 1985b), only those occurring between 0600–1200 UT (0700–1300 LT in Nagycenk, with the difference in LT between Nagycenk and ATS being 8 h) were present at the ground station. Afternoon events were poorly correlated; the events were synchronous mostly only at periods of 15–30 sec. It seems that the inward propagating upstream waves can be seen in favorable situations at a synchronous orbit, too.

Summarizing these observations, solar wind velocity and cone angle control at least a significant part of Pc 3–4 pulsations. The effects of V_{SW} on the activity are more important on longer time scales; on shorter ones the Θ effects prevail. Both connections are, however, disturbed by other factors. Higher solar wind velocities promote the occurrence of shorter Pc 3 periods for which the Θ control is stronger than for longer Pc 4 periods. The upper limit of favorable cone angles changes with the L value, i.e., it is less at lower L. Switches are sometimes very complicated events, and only a fraction of them can be identified in the solar wind, on synchronous-orbit and at ground-based stations.

Pulsation periods are controlled by B, but the exact form is not yet clear, and the solar wind velocity may also disturb this connection. At low V_{SW}, the $F = cB$ law may be valid, and the fit deteriorates at higher V_{SW}.

2.4 Comparison of observations with predictions for the upstream wave source

It should be mentioned first that there are evidently waves present in the low-L magnetosphere which do not follow the usual pattern of waves from the upstream source. To mention only a few, low-latitude Pc 4 exists irrespective of IMF (e.g., Gul'elmi, 1974), resonances of localized field lines may be excited also at very low B values with periods of around 20 sec at $L \sim 2$ (Verő, 1980), and Pi-type pulsations excite Pc 3–4-type pulsations (Sect. 6). In spite of all this, low-latitude pulsations reflect better interplanetary conditions than high L pulsations do (Yumoto, 1985a, b).

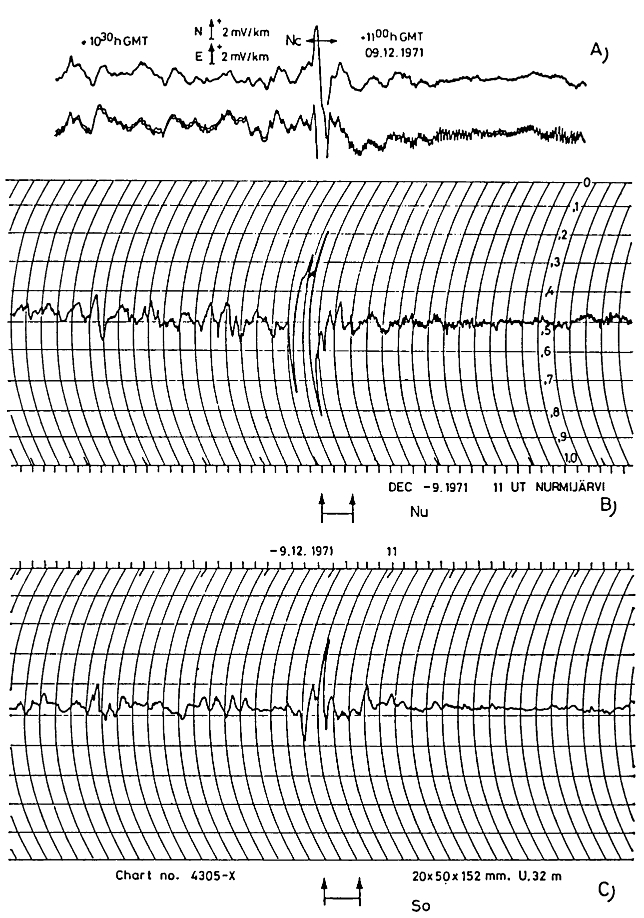

Fig. 14. Earth-current record from Nagycenk ($L \sim 1.9$) and induction records of Nurmijärvi ($L \sim 3.3$) and Sodankylä ($L \sim 5.0$) of a SI (1054 UT) followed after an interruption of pulsations by a change of the pulsation regime around 1102 UT (Tátrallyay and Verő, 1973; Verő, 1975)

Magnetosonic upstream waves excited by the anomalous Doppler-shifted, ion-cyclotron resonance with the narrowly reflected ion beam in the Earth's foreshock explain at least two of the three major connections between Pc 3–4 and interplanetary conditions, i.e., the period dependence on B and the Θ effect on the amplitude (Yumoto, 1985b). As these connections are clearer at low latitudes, some waves having other properties than the upstream source (e.g., waves due to a KH instability) in the outer magnetosphere are filtered out during inward propagation. Solar wind velocity may also influence pulsation periods (Yumoto et al., 1984; Yumoto, 1985b; Sect. 2.2).

The most easily identifiable events at geostationary orbits ($L \sim 6.6$, GOES 2, ATS 6) and on the ground, namely switches, indicate that there is no general coincidence of pulsations at the two sites. Events may be observed at synchronous orbit without a counterpart on the ground when the corresponding wave is localized or filtered out during propagation, and only on the ground when the satellite does not see the corresponding low-amplitude wave which is amplified at lower L values.

In the context of the interplanetary medium, an earlier observation should be mentioned. Geomagnetic SI impulses indicate sudden changes in the interplanetary medium. The pulsation activity often ceases at such SI (Tátrallyay and Verő, 1973; Verő 1975). After a few minutes pulsations with other periods appear in a part of the events, corresponding to the new situation. The reappearance of the activity is, however, delayed by several minutes (Fig. 14), and the time interval without pulsations may correspond to the growth time of the upstream source in the new situation. This idea does not conflict with Hoppe et al.'s (1981) result that changes in the ion population and of the upstream waves are quite simultaneous. Here, the interval is between a change in the IMF and the corresponding change of ions and waves.

The solar wind control of the pulsation amplitudes is not included in the original upstream source theory. As this control is quite stable in the long run (Verő, 1981; Polyushkina and Potapov, 1983), in complete solar cycles any of the following mechanisms may contribute to it: an increase of hydromagnetic noise with V_{SW} initiating the beam cyclotron instability in high velocity streams; weaker attenuation of the waves in a narrower magnetosheath at higher V_{SW}; a more transparent magnetosphere (Verő et al., 1985).

3 Propagation of upstream waves to low latitudes

In recent years, the number of in situ magnetospheric measurements of pulsations has increased rapidly, partly due to the discovery of the presence of several harmonics in the pulsation spectra at synchronous orbits (Takahashi et al., 1981). In the outer magnetosphere there is a wide variety of waves, including radially inward propagating, compressive waves and guided transverse waves, both of azimuthal and radial polarizations. Waves propagating from the magnetopause region excite field line resonances up to the sixth harmonic at $L \sim 6.6$. The compressive propagating waves reach lower L shells, and there they may excite surface waves on the plasmapause, and in the plasmasphere, trapped oscillations ($L = 1.7\ L_{pp}$), fundamental ($L = 1.7-2.6$), and higher harmonic ($L = 2.0\ L_{pp}$) standing oscillations (Yumoto, 1985b). ($L_{pp} = L$ value at the *p*lasma *p*ause.) Only a part of the waves observed at high L shells reach lower L. This fact explains the sometimes poor correlation between high- and low-latitude observations. The observational problems which need clarification include the identification of waves which can reach low latitudes, the low-latitude structure of pulsation periods which contributes to the selection of the mechanism being active there, the problem of the harmonic structure at low latitudes and its connection with the primary source and the harmonic structure at high L values, as well as polarization characteristics of the waves.

3.1 Dependence of Pc 3–4 parameters on latitude

The dependence of pulsation parameters on latitude is quite a delicate problem. Complications are due to the sometimes rapidly changing parameters which may be smoothed out by averaging over longer distances (or times). Anyway, closely spaced stations in the meridional direction are necessary for this problem, and the visual determination of "average" periods may be of equal value or even superior to power spectra. Dynamic spectra are best used for the detection of temporal variations.

It has been known for a long time that Pc 3–4 periods change sometimes rapidly with geomagnetic latitude or L value even at low latitudes (Voelker, 1962, 1963). Quite a great number of studies have been published but mostly were based on little data. The main effects found should be summarized, based mainly on a chain of stations in central Europe consisting of 6 stations between 43° and 64° geomagnetic latitudes (Cz. Miletits, 1980), in the following:

1. There are two groups of Pc 3–4 pulsations; the first one has periods rapidly changing with latitude (4%–10% change for one degree of latitude), the other has constant or nearly constant periods (less than 4% change for one degree of latitude).
2. The group with latitude-dependent periods has at $L \sim 2$ mostly periods of about 20–30 sec and regular waveforms (one sharp peak in the spectrum). The constant period group has a much wider period range (12–100 sec) and less regular waveforms.
3. Pc 4 occurrence frequency and amplitude decrease quickly toward lower latitutes around $L \sim 2$.
4. Pc 3 with regular waveform sometimes appears on the background of irregular Pc 4.
5. The change of the period with latitude is monotonic, but discontinuous; the period changes quickly within short distances, and then remains nearly constant.
6. The amplitude increases around $L \sim 2$ smoothly with the latitude to about $L \sim 2.5$ (50°–55°) where in certain cases a maximum occurs. Plyasova-Bakounina et al. (1985) found that solar-wind-controlled pulsations have an amplitude maximum within the polar cap at about 74°–77°(corresponding to a $K-H$ source) while those of magnetospheric origin have the amplitude peak at much lower latitudes. However, at low L the solar-wind-controlled pulsations prevail.

The fact that the most regular pulsations have the greatest latitude dependence sometimes leads to subjectively produced predominance of this group in selected samples. On the average there are more pulsations with constant rather than with latitude-dependent periods (the ratio is about 1:1.5 to 1:2 in occurrence frequency).

From the effects listed, Wolfe et al. (1985) confirm, for example, 3 and in part 6. The events presented by Lanzerotti et al. (1981) in their Fig. 7a and b have a latitude dependence at the 10% upper limit given in 1.

Accepting such a latitude dependence, the problem is that it should be reconciled with the dependence of the pulsation periods on B. In spite of the rather strong frequency decrease at higher latitudes, the coefficient c_1 in $F = c_1 B$ is not latitude dependent (Fig. 15). In Fig. 15b the two straight lines from Fig. 15a are redrawn in the form of $c_1 = f(L)$ to enable a comparison with experimental data.

Another observation difficult to understand with the latitude-dependent periods is why the $F-B$ relationship improves when events are considered with equal periods at two stations. Odera and Stuart (1985) used data at $L \sim 2.4$ (Hartland) and 2.9 (Borok), corresponding to a latitude difference of about 4°, and as Fig. 7 shows, the fit was much better when the periods were the same. As they accepted only those cases in which the periods differed by less than 10%, events with 4%–10% change in period for one degree of latitude are excluded from this comparison.

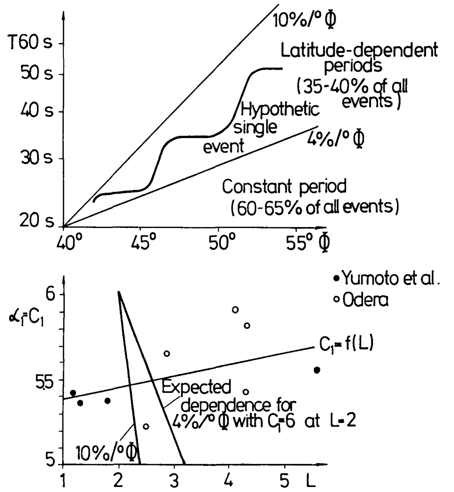

Fig. 15. Observed extrema of the period change vs. latitude in the group with latitude-dependent periods with indication of the real variation (*top*). Values of the c_1 factor in the equation $F = c_1 B$ at various L values from Yumoto et al. (1984) and Odera (1984b), and the limiting straight lines from Fig. 15 top transformed into a system of (L, c)

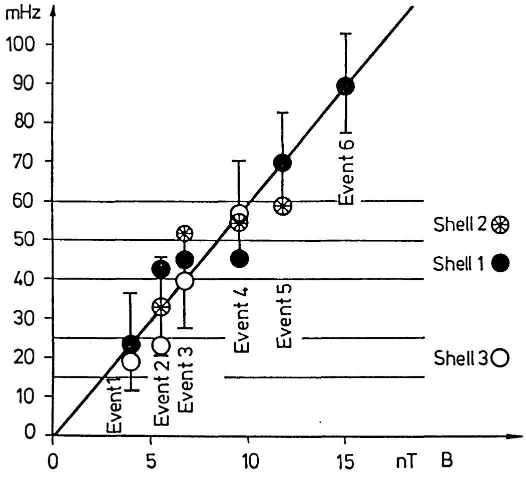

Fig. 16. Scheme of the shell resonances with conservation of the *B* dependence of the pulsation periods. It is supposed that stations with resonant periods outside the primary compressive wave spectrum see the original frequency, other stations see their own resonant period. Three shells and six events are indicated; the observed period for each shell is identified by the corresponding symbols

These seemingly contradictory facts can be partly understood within the following scheme.

The upstream source produces waves centered at a frequency corresponding to $F = 6B$, but in a wider range (Varga, 1980). Yumoto et al. (1985) found a range of frequencies active between $F = 4.5B$ and $F = 7.5B$. Individual shell resonances are possible within this range. Shells are not constant formations; they shift both in extent and position. Thus, there is some scatter in the periods observed, but the average for a certain L value is just $6.0B$.

Figure 16 summarizes the situation. Events 1–6 correspond to different B values as indicated on the ordinate axis. The straight line corresponds to $f_0 = 6B$; three shells are investigated which have resonant periods 40–50 mHz, 50–60 mHz and 15–25 mHz, respectively. The (constant) width of the source spectrum is supposed to be ± 12 mHz around the central frequency f_0 of each event. In case of, for example, event 3, $B = 6.7$ nT, $f_0 = 40$ mHz, and the range is 28–52 mHz. Shell 3 has a resonant period outside of this range, shell 1 is fully within the range 40 ± 12 mHz, and shell 2 is partly within. Therefore, the characteristic frequency of shell 3 (dots in Fig. 16) is equal to $f_0 = 40$ mHz, that of shell 1 is at say 45 mHz, and that of shell 2 at 51 mHz. In such a case all three shells have nearly the same frequency, and this corresponds to $f_0 = 6B$, as Odera and Stuart (1985) observed. In case of event 2, shells 1 and 3 are within the range of 35 ± 12 mHz, so they experience different periods (corresponding to the shell resonance) and cannot be fit to the $f_0 = 6B$ equation. Both the primary upstream waves and those from field line resonances should have the possibility to reach the ground, they correspond to the following two classes of pulsations. Regular, narrow-peaked pulsations with periods of about 20–30 sec at $L \sim 2$ are due to shell resonances. Longer period Pc 4 could propagate through the whole magnetosphere to the ground with the nearly unchanged original spectrum of the upstream waves. (Surface waves at the plasmapause cannot cause this Pc 4, as the close correlation with interplanetary parameters would be hardly possible.) In the case of sudden changes, field lines get excited even outside of the primary spectrum. The period changes more or less quickly at the boundary of neighboring shells, otherwise it remains nearly constant.

There are several possibilities to detect certain parameters of the shells. One of these possibilities is the phase (or polarization) change. Lanzerotti et al. (1981) quite often observed phase and polarization changes at closely spaced stations. Gough and Orr (1984) found similar changes, too, but they argued that due to damping of the waves, the phase changes are partially smoothed out at such boundaries, and there is no complete phase reversal (by 180°) when crossing the shells. Baransky et al. (1985) used $\mathrm{grad}_M H$, the gradient of the H amplitudes in meridional direction to determine the frequency of the shell ($\mathrm{grad}_M H$ changes its sign just at this frequency).

Yumoto et al. (1984) listed the possible waves from the upstream source at low latitudes. The main contribution should come from fundamental standing oscillations in the plasmasphere (regular waves with latitude-dependent periods) and directly from compressional waves (less regular waves without latitude dependence of periods). Higher harmonic waves in the plasmasphere will be considered in the next section. Waves originating at the plasmapause are probably of less importance at low latitudes, and for other modes no observational evidence is known.

3.2 Harmonic structure of pulsations at low and high latitudes

The harmonic structure of high L-pulsation spectra has been discovered by Takahashi et al. (1981) using ATS 6 data. There are also early indications for a low-latitude harmonic structure of Pc 3–4 pulsations (Stuart and Usher, 1966; Ádám et al. 1972). At the ground, equally spaced frequencies were found to be active at one station or at the stations of an array. The harmonic structure was, however, by no means unambiguous (see also Ansari and Fraser, 1985a).

A comparison of ground-based daily indices for differ-

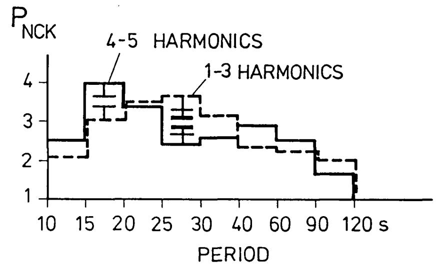

Fig. 17. Activity of some period bands in Nagycenk expressed by the daily indices P_{Nck} for each period range; if there are different numbers of harmonics present in ATS records, 90% and 99% confidence limits are indicated for two period bands (Holló and Verő, 1985b)

ent period ranges with the number of harmonics on ATS 6 (Holló and Verő, 1985b) has shown that if there are more than three harmonics in the ATS 6 spectra, then the ground-pulsation spectrum is broader, too (Fig. 17). (The number of harmonics can be quite easily counted for a full day as in such a case the absence of a harmonic, e.g., due to the position of the satellite at a node, can be detected.) In such a case the ground activity in the ranges of 10–20 sec and 40–90 sec is higher; if there are less harmonics, the activity is concentrated at the ground station into the 20–40-sec range. There are many features which differ in the two records, the most characteristic being the regular daily variation of the period lacking at the ground station. These results led to the conclusion that the harmonic structure on ATS 6 records is only correlated with ground data to the extent that it indicates the width of the primary spectrum.

3.3 Phase and polarization characteristics of low-latitude pulsation

It has been already mentioned that polarization changes may be used for the detection of resonant shells. Recently, several studies were devoted to the polarization characteristics of low-latitude pulsations to help clarify problems connected with the magnetospheric wave sources.

The polarization sense of the low-latitude pulsations has two rather characteristic changes during the day. The first one is at sunrise and may be connected to the ionospheric *E* layer. At this time the polarization changes from an "identical" to a "mirror" situation at conjugate stations (Yumoto, 1985b). This change is, however, rather difficult to study as it coincides with the rapid growth of Pc 3 amplitudes, and thus prior to it, mostly low-amplitude pulsations exist. The second change is around local noon, when the morning left-hand polarization changes to a right-hand or linear one on the northern hemisphere. This change should be understood as true in a statistical sense, as exceptions occur (more often in the afternoon) and even the time of the transition changes. Fraser and Ansari (1984) also found the same situation in the southern hemisphere (Fig. 18), while Yumoto et al. (1985) found opposite polarizations there. The noon reversal of the polarization is accompanied by a number of other changes, e.g., rotation of the polarization ellipse, characterized by low amplitudes in the H_y component in the afternoon, etc. These changes are not connected with the change of any ionospheric parameter, i.e., they should be characteristic for the pulsation source.

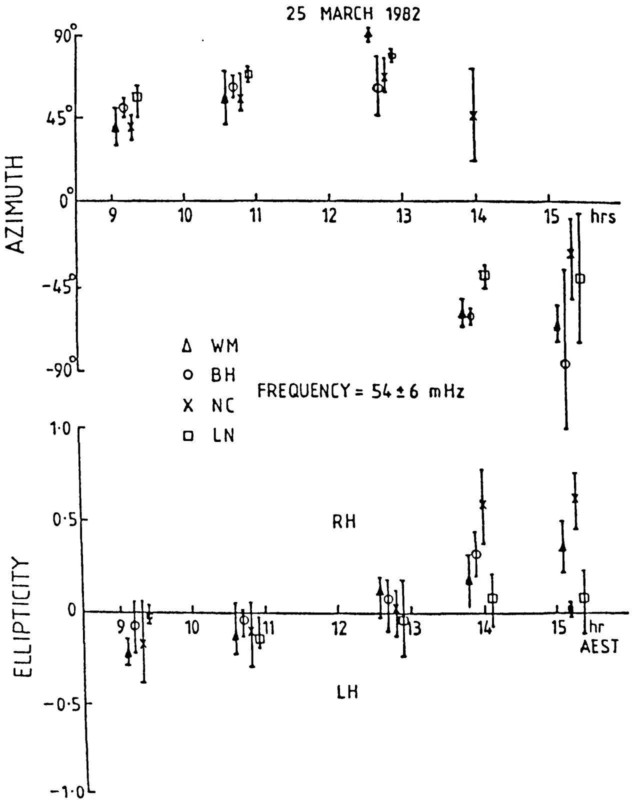

Fig. 18. Diurnal variation in polarization azimuth and ellipticity for March 25, 1982, at four Australian stations (NC, BH, WM at $L \sim 1.8$; LN at $L \sim 2.6$). AEST is within ± 1 h LT for all stations. Positive (negative) azimuth indicates a major axis in the NE (NW) quadrant. Error bars indicate the standard deviation (Fraser and Ansari, 1984)

Wave numbers deduced from phase differences of coherent waves at several separated stations were recently published by Fraser and Ansari (1984) and Sutcliffe (1985). The direction of propagation changes sign before local noon, between 0900 and 1100 LT. Azimuthal wave numbers are in the range of 3–6, at least in the morning hours. This value is in accordance with theoretical calculations for the upstream wave source (Yumoto, 1985b). Nevertheless, the results in this field are contradictory in several points, and some authors think that the observations can be better explained by a $K-H$ source (e.g., Southwood, 1983). This may be, at least partly, due to sudden jumps in the parameters of the pulsations over limited areas, as described by Sutcliffe and Boshoff (1985) for the frequency and by Ansari and Fraser (1985b) for phases. Such jumps indicate sudden changes in the resonant conditions over limited areas. The phase studies are also rendered more difficult by period changes with the latitude.

3.4 Types of HM waves observed at low-latitudes during the day

An essential part of Pc 3–4 events have periods which change rapidly, monotonically and discontinuously with the *L* value. In spite of magnetospheric modification, the pulsation periods are correlated to the *B* value of the IMF, and thus the source should be sought outside the magnetosphere. The width of the coherently excited shells lies at a few to about 10 ° in latitude (some tenths of L). The monotonic increase indicates that waves of higher harmonic numbers occur seldom (or they are everywhere the same higher harmonic). Exceptions do exist, as Sutcliffe and Boshoff (1985) have shown. Thus, the $F = 6B$ law remains valid in a rather wide range of frequencies (about 10–100 sec). This is in favor of a direct propagation of the upstream waves to the ground. Waves propagating compressionally in the magnetosphere and locally amplified waves by field line resonance would thus be the two main types present at low latitudes around $L \sim 2$. Other mechanisms have less importance there, but their share increases rapidly with latitude.

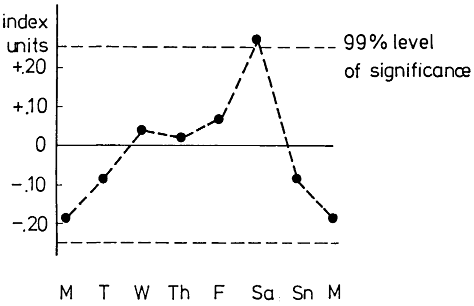

Fig. 19. Deviation of the pulsation activities on different days of the week at Nagycenk from the average of four years (1958, 1970, 1974, 1984). 99% confidence level of the deviations is indicated

4 Ionospheric effects from/on pulsations

Most studies on the ionospheric modification/origin of pulsations, whether theoretical or experimental ones, refer to high latitudes. Several effects are expected due to ionospheric modification, but only a few are experimentally confirmed.

The best-known effect from the ionosphere is the rotation of the polarization ellipse by 90°, resulting in a mutual substitution of the components H and D.

Ionospheric damping, as a decrease in consecutive amplitudes was studied by Hughes and Southwood (1976a, b) and experimentally by Gough and Orr (1984). The latter compared computed waveforms with measured ones and concluded that in addition to Joule heating, another mechanism contributes to the damping which is therefore stronger than computed on the basis of the Joule heating. Such mechanisms may be coupling between adjacent flux tubes or energy loss to plasma populations in the magnetosphere. The damping is accompanied in the ionosphere by a "smearing" (Poulter and Allan, 1985) which means an averaging of spatially rapidly changing characteristics, e.g., latitudinal period changes.

The ionosphere may also screen pulsations when they propagate downward. There are many computations for the amplitude ratios above and below the ionosphere, but mostly for periods shorter than Pc 3–4. Verő (1981) and Verő and Menk (1986) were able to show that if a certain limit in f_0F2 is surpassed (10–11 MHz), pulsations are locally screened (amplitudes decrease by a factor of about 0.6). The screening does not originate in the outer magnetosphere as opposite hemispheres experience screening in respective local winter, also not from the ionosphere, as the screening does not follow the daily variation of f_0F2. Thus, only a region of intermediate position, i.e., the upper ionosphere-lower plasmasphere where the shell resonances take place, can be the source region of this screening.

Disturbances and fields in the ionosphere associated with pulsations have been reported from the Chatanika incoherent radar (Doupnik et al., 1977) and from the Scandinavian STARE (Walker et al., 1979). Lathulliere et al. (1981) reported on Pc 3–4 waves in the incoherent scatter facility at Saint Santin in France and concluded that they had a very short horizontal wavelength. Menk et al. (1983) used a high-resolution, computer-controlled phase path ionosonde at $L \sim 2.1$ and detected changes by some tens of meters in the height of the reflection point which were correlated with Pc 3–4 bursts (Pi 2 had effects greater by one order of magnitude). Sutcliffe and Poole (1984) detected oscillations in the ionospheric Doppler velocity using the Grahamstown chirp ionosonde in South Africa. To explain the results, both variations in the ionospheric refractive index due to the transient oscillating magnetic field and a vertical drift in the ionosphere as a whole due to $\mathbf{E} \times \mathbf{B}$ were necessary.

Lanzerotti et al. (1981) attributed the already mentioned frequent changes of the polarization pattern of Pc 3–4 at closely spaced stations to ionospheric effects. Such polarization jumps are at all times usual, e.g., magnetotelluric field work would be hardly possible without changing polarization.

5 Man-made pulsations

Without speaking about the artifical generation of pulsations by radio waves, an interesting observation by Tsirs and Loginov (1985), who found a Thursday minimum in Pc 1 and Pi 2 activities, is mentioned here. They referred to Fraser-Smith and Roxburgh (1969) when they pleaded for a human origin of this weekly variation. A survey of the Nagycenk daily pulsation indices from 4 years between 1958 and 1984 (this index characterizes the daily average amplitude of pulsations, see e.g., Verő, 1981) indicated a Saturday maximum in all years (Fig. 19), deviating somewhat from Tsirs and Loginov's result; the Saturday peak is, however, significant at a 2% level. As the effect was present in 1958, and it was strongest from the years studied just then, it cannot be due to satellite transmissions.

6 Some recent observations of Pi 2 at low latitudes

The current wedge model (McPherron et al., 1973) has been accepted at least as a working hypothesis for the basis of the organization of Pi 2 observations at subauroral latitudes. The primary process is essentially short-circuiting the enhanced cross-tail current by field-aligned currents (FAC) and currents in the auroral ionosphere. The model offers a natural system of coordinates centered at the center of the current wedge and the width of the wedge between the upward and downward FAC is characterized by the values of $\Delta H = 0$. An other local and substorm-centered system of coordinates can be deduced from the polarization pattern of Pi 2; Lester et al. (1983, 1984) have shown that the two systems coincide if there is no preexistent current system which would shift the two systems with respect to each other. If Pi 2 on a quiet background is selected, there then is seldom any difference between the two systems. In case of such events, Lester et al. (1983, 1984) found polar-

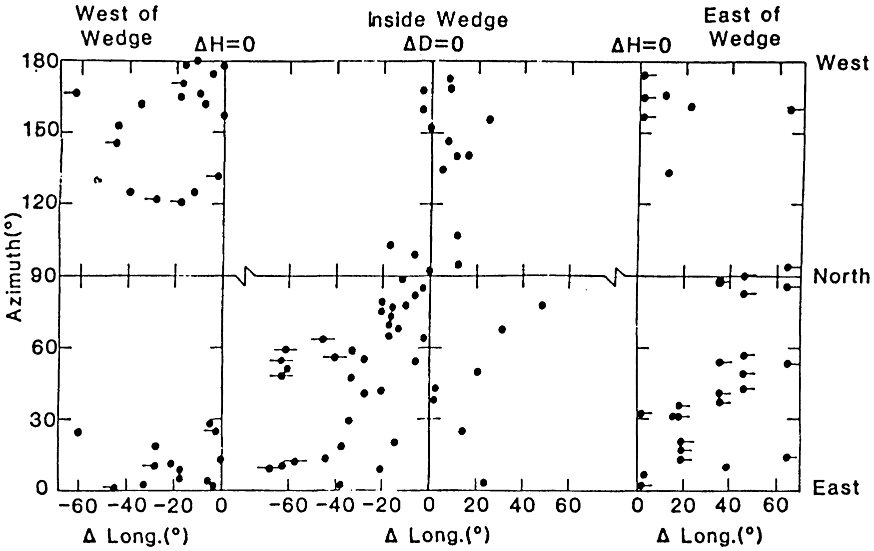

Fig. 20. Azimuth of the major axis of the horizontal polarization ellipse plotted against longitude for Pi 2. The left, center, and right panels correspond to points west, inside, and east of the wedge, respectively (Lester et al., 1983)

ization patterns and a number of other characteristics of Pi 2 which correspond to expectations on the basis of the current wedge model. Figure 20 is a summary of the results: it shows that the direction of the major axis of the polarization ellipse changes according to predictions within the wedge from E-W through the NE quadrant to N-S, then through the NW quadrant again to E-W, and the polarization is predominantly counterclockwise. This is confirmed by Lanzerotti and Medford (1984) who found constantly counterclockwise polarization at latitudinally spread stations. W of the wedge there are more cases in the NW quadrant, E of it in the NE quadrant, and the polarization is in the majority of cases counterclockwise here as well with more clockwise-polarized events than within the wedge. The angular azimuthal wave number indicated westward propagation with more exceptions occurring E of the wedge. Lester et al. (1984) interpreted the results as the consequence of the superposition of two circularly polarized waves propagating azimuthally in opposite directions with different amplitudes (Southwood and Hughes, 1985). These waves are generated by a partially reflecting boundary west of the model system. These surface waves would be responsible for the observed characteristics of Pi 2, e.g., the E-propagating wave (E of the wedge) is due to reflection from the western current. The eastern current causes less reflection as it is more distributed longitudinally.

Among the few features not explained by this model, the frequency changes in certain events are the most significant ones. They occur both inside and outside the wedge, and they can be explained by field line resonances or localized surface waves at the plasmapause.

As the sequence of events organized in the substorm-defined system of coordinates can be transferred into a local time-dependent system, even if the centers of substorms have rather great time spread, similar results are expected for the LT variations of the direction of the major axis of the polarization ellipse with the center of the substorm substituted by a LT around 23 h. This is in reality what was found by Lanzerotti and Medford (1984).

The westward travelling surge greatly modifies Pi-2 properties at auroral latitudes, but at lower latitudes less, as, for example, the counterclockwise polarization of Samson and Rostoker (1983) is shown to be in accordance with the results of Lester et al. (1984). The former authors supposed a lower-latitude, second Pi 2 source region but they found only an increase in amplitudes toward the equator around 60° as no low-latitude stations were used. This increase leads sometimes to an amplitude maximum around 55°.

By comparing data from the AFGL network (the same, as used by Lester et al., 1983, 1984) with magnetospheric Pi 2, Singer et al. (1983) found that Pi 2 has much narrower occurrence in longitude (sometimes less than 30°) on synchronous orbit than on the ground (here up to 60°). They found a clear difference between low- and high-Kp situations, as in latter cases the events were quite often seen both at synchronous orbit and on the ground, while in quiet conditions only the ground stations experienced Pi 2. They supposed that the position of the source region (plasmasheet) is responsible for this difference, and the inner edge is beyond synchronous orbit at low Kp. The difference in the longitudinal extent should be due to the transformation of low-amplitude compressional waves (below the detection limit) into resonant modes similarly to dayside Pc 3–4. Maltsev and Lyatsky (1984) computed a period of 100 sec for the surface wave on the plasmasheet, corresponding to the typical period of Pi 2.

Sastry et al. (1983) identified daytime Pi 2 at Indian equatorial stations. The period of their cases, however, is shorter than normal Pi 2 periods, being around 30 sec.

The possibility that Pi 2 can trigger Pc 3–4 pulsations in the sunlit hemisphere has been suggested by Yanagahira and Shimazu (1966) and Holló and Verő (1970). Propagation is more likely toward the west, i.e., afternoon hours are more favorable for Pi 2-triggered Pc 3–4. These Pc 3–4 may be identical with Voelker's Pse (Pulsational single effects) (1962, 1963). Such "transformed" Pi 2 or Pse are amplified 1.5–3.5 times at equatorial latitudes relative to somewhat higher latitudes (Sastry et al., 1983).

The mentioned role of field line resonances in Pi 2 is also supported by the observation that noiselike, continuous Pi 2 may have smooth transitions both in morning and evening hours from/into Pc 3–4 (Verő, 1964).

As a conclusion, the problem of the generation of low-latitude pulsations seems to be near to a solution. There are, however, a number of problems which need further experimental and theoretical work. Such problems are, for example, the conditions of the propagation of upstream waves through the magnetopause and the magnetosphere, the nature of low-latitude field line resonances and their changes, the form of the connection between frequency of pulsations and IMF *B* magnitude, the complex nature of ionospheric modification, and the postulated low-latitude additional source for Pi 2.

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