GEOMAGNETIC MICROPULSATIONS AND DIAGNOSTICS OF THE MAGNETOSPHERE

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(Received 18 September, 1967)

Abstract. Plasma oscillations in a wide range of spectrum exist in the magnetosphere. Part of them penetrate the ionosphere and are recorded on the earth's surface. In the range of frequencies from millihertz to several hertz, the so-called micropulsations (ULF) are observed. In the range from hundred of hertz to several kilohertz the low-frequency emissions (VLF) are registered. Both types of emissions contain interesting and important information on the physical parameters of the magnetosphere and on the processes developing in it. The following paper describes the main problems of the diagnostics of the magnetosphere, which are based on the surface observations of micropulsations.

In the first part of the paper, a short summary of theoretical conceptions on micropulsations is given. The main part of the paper describes the methods of diagnostics of the location of the boundary of the magnetosphere, of cold-plasma concentration in the outer regions of the magnetosphere, as well as of the energies and fluxes of fast charged particles in the geomagnetic trap. Some experimental results of the diagnostics of the parameters of the magnetosphere are given. Advantages and deficiencies of the existing methods of surface diagnostics are discussed, and the directions of further investigations are traced.

1.0. Introduction

1.1. Spectrum of the Natural Electromagnetic Emissions

Electromagnetic waves of a very low frequency fall on the Earth's surface from the cosmic space. These waves were called 'geomagnetic micropulsations', and were observed for the first time at the Kew Observatory, around a hundred years ago. The systematic and intensive study of micropulsations only began in the period of the International Geophysical Year (1957–1958).

The geomagnetic micropulsations are due to the ionocyclotron and hydromagnetic waves in the magnetosphere of the earth. The spectrum of their frequencies is extended from millihertz, to approximately one kilohertz. The lowest frequency of this range is the smallest frequency of the proper oscillations of the magnetosphere, and the upper is the gyrofrequency of the protons in the lower layers of the polar ionosphere. On the frequencies 3–5 hertz, however, there exists a sharp decline in the spectrum of the oscillations, due to the fact that those falling from above the waves are strongly absorbed in the ionosphere, and are practically not observed on the earth's surface. Besides, on the frequencies greater than approximately 5 hertz the level of atmospheric disturbances is very high, and this circumstance also makes the registration of emissions of cosmic origin difficult (Figure 1). Therefore, as a result of analysis of the experimental materials, it was established, that the upper border of the micropulsations frequency range is located around frequencies of several hertz.

Beginning from the frequencies of several hundred hertz, the ionosphere again

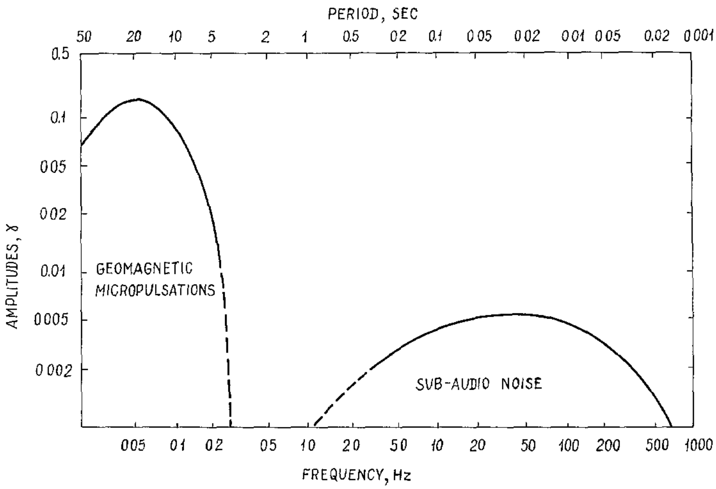

Fig. 1. Spectrum of the natural low frequency emissions in California (Campbell, 1959).

becomes transparent, and the level of cosmic noise rises. At these frequencies, the lower border of the VLF range* (very low frequency) is located. The maximal intensity of the VLF emissions falls at the frequencies of several kilohertz. In the range of VLF, the so-called whistlers – electromagnetic signals generated by lightnings and propagating along the field lines in the outer space – are observed. The VLF emissions in general are generated by fast particles in the space surrounding the earth. The character of their propagation is similar to whistlers.

VLF emissions are propagated in the form of electron-cyclotron, or as they also have been called, spiral waves of right-hand polarization. It would seem that this property could be used as an indication, which could help to distinguish VLF emissions from micropulsations (if we identify them with iono-cyclotron and hydromagnetic waves in the magnetosphere). However, in the medium with smoothly changing parameters, the spiral waves propagating in the direction of the magnetic-field augmentation can generally be continuously transformed into the fast magneto-acoustic waves, because in the two component plasma they form essentially the one and the same branch of the dispersion curve.

The iono-cyclotron waves have a left-hand polarization and form the other branch of the dispersion curve. Nevertheless, some of their general properties are similar to spiral waves. For instance, both undergo a strong magnetic focusing, and as a result of it, their trajectories in the magnetosphere form enormous arcs, which are based by their ends on the conjugate regions. Moreover, in a multicomponent plasma, the waves of the one type can be transformed with the change of polarization into the waves of the other type in the regions of intersection of the dispersion curves (Stix, 1962).

* Similarly to the VLF emissions, micropulsations in the range of frequencies from millihertz to several hertz are sometimes called ULF emissions (ultra low frequencies).

If, lastly, we remember the possibility of VLF and micropulsations generation by the one and the same stream of energetic particles, and the possibility of mutual transformation of waves as a result of non-linear processes, it becomes evident that these two types of phenomena are essentially connected with each other (BRICE, 1965). The aim of this paper, however, is to consider the micropulsations only in consequence with their classical definition, that is, oscillations of the electromagnetic field of the earth in the range 10^{-3} – 5 Hz.

Geomagnetic micropulsations attract, in recent time, permanently increasing attention, because they are an interesting natural phenomenon and an excellent indicator for investigations of conditions of generation and propagation of the electromagnetic waves in plasma. At the same time, the interest in micropulsations is due to the fact that they are also a source of information on the state of the magnetosphere and on the properties of solar corpuscular streams. Being generated at very high altitudes, the hydromagnetic waves transfer to the earth's surface valuable information on the physical properties of cosmic space. Therefore, the observation of micropulsations can become one of the tools in the diagnostics of properties of corpuscular streams and, of the properties of the magnetosphere in the regions of the waves generation and on the ways of their propagation to the earth's surface. An undoubted advantage of such observations is the possibility of continuous tracing of the state of the magnetosphere by means of relatively simple equipment.

The following survey deals with the problems of diagnostics of the magnetosphere by means of surface observations of micropulsations. In spite of the fact that the investigations in this direction are mainly of a methodical character, their survey may help to give some idea of the perspectives of further research.

1.2. CLASSIFICATION OF GEOMAGNETIC MICROPULSATIONS

An important problem in the investigation of micropulsations is the description and classification of the observed types of oscillations and of the conditions in which they are generated. The classification is necessary in order to express the great variety of oscillations in a limited number of clearly identifiable types of pulsations.

In the latter, three essentially independent principles of classifications have been discussed:

(1) Classification on morphological properties (periods, amplitudes, time of occurrence, etc.);

(2) Correlative clasification (based on connection with other types of phenomena – magnetic storms, aurora, VLF emissions, etc.);

(3) Genetical classification (based on mechanism of generation).

Due to the fact that the true origin of micropulsations still remains a mystery in many respects, the genetical classification, which in other circumstances would be the best one, cannot serve as a base of a general classification. The correlative principle, unfortunately, also cannot be used as a base, because a clearly expressed correlation is not observed for all types of pulsations. This is a reason why the morphological principle was widely used in recent years. As a base of a general classification it allows one to elaborate a convenient and a definite subdivision of the observed pulsations on types.

The first generally adopted classification was introduced in 1957 by the IAGA Committee N10 before the I.G.Y. The micropulsations were divided into three classes: Pc – pulsations continuous, Pt – pulsations trains, and Pg – giant pulsations.

The typical records of continuous pulsations Pc and pulsation trains Pt are given in Figure 2. The range of periods for these pulsations is ~ 10–150 sec. Their amplitudes in middle latitudes changes from case to case, from fraction to several gammas (TROITSKAYA, 1964).

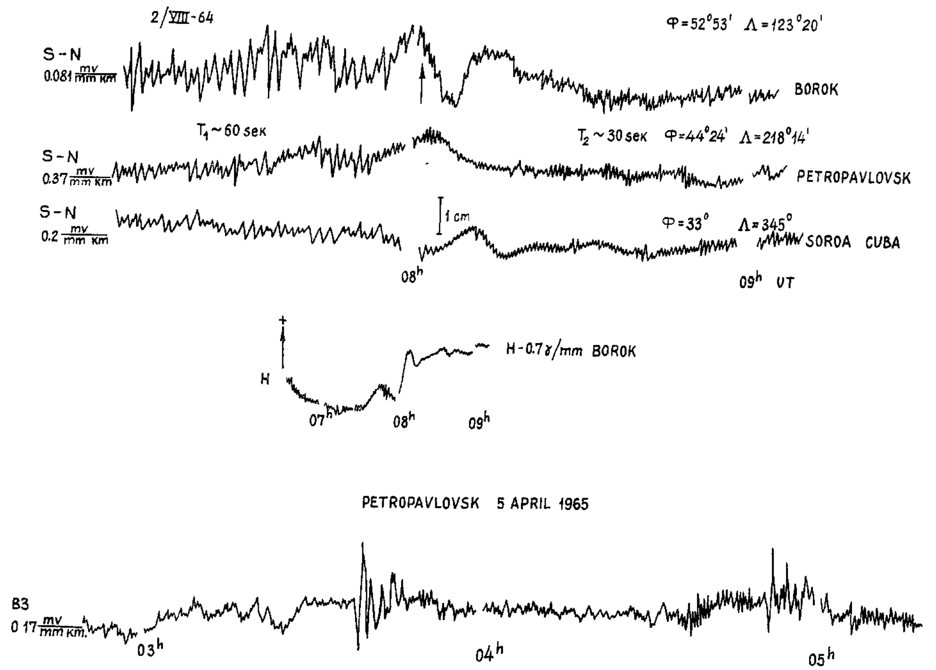

Fig. 2. Geomagnetic micropulsations of the types Pc 2–4 and Pi 2.

Pulsations of these types are observed practically every day on very great surfaces of the earth. The continuous pulsations Pc are registered during the day, and the pulsation trains Pt occur in the night hours, revealing a distinctive correlation with the magnetic bays. The giant pulsations Pg are typical for the auroral zone. The local character of occurrence, the augmentation of the period of oscillations with the latitude of the point of observation, and a strong correlation of pulsations observed simultaneously in the conjugate points are typical for these pulsations. Pg have great amplitudes (up to tens of gammas) and long periods (up to several hundreds of seconds).

The investigations of micropulsations during the I.G.Y. and the following years have shown that the classification adopted in 1957 needs to be widened and detailized.

First of all, micropulsations of the 'pearl' type (Pc 1 due to the new classification) were revealed and systematically investigated at many observatories (TROITSKAYA, 1961). The record of this type of pulsations really suggests a pearl necklace (Figure 3). The pearls are observed sporadically in the range of periods 0.2–5 sec. The period of repetition of pearls is, on average, $1\frac{1}{2}$–2 min. The amplitude is relatively small from several to several tens of milligrammes. A remarkable property of the pearls is revealed in their alternative occurrence in the Northern and Southern hemispheres (Figure 3).

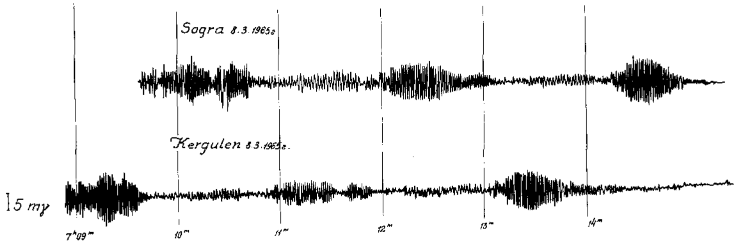

Fig. 3. Example of Pc-1 record (pearls).

Many of the important properties of pearls were revealed in the course of their analysis on the sonograph, which allows the dynamical properties of the signals to be obtained (TEPLEY and WENTWORTH, 1962). Figure 4 shows a typical sonogramme of the series of pearls. It is seen distinctly, that the series consists of separate tones of rising frequency.

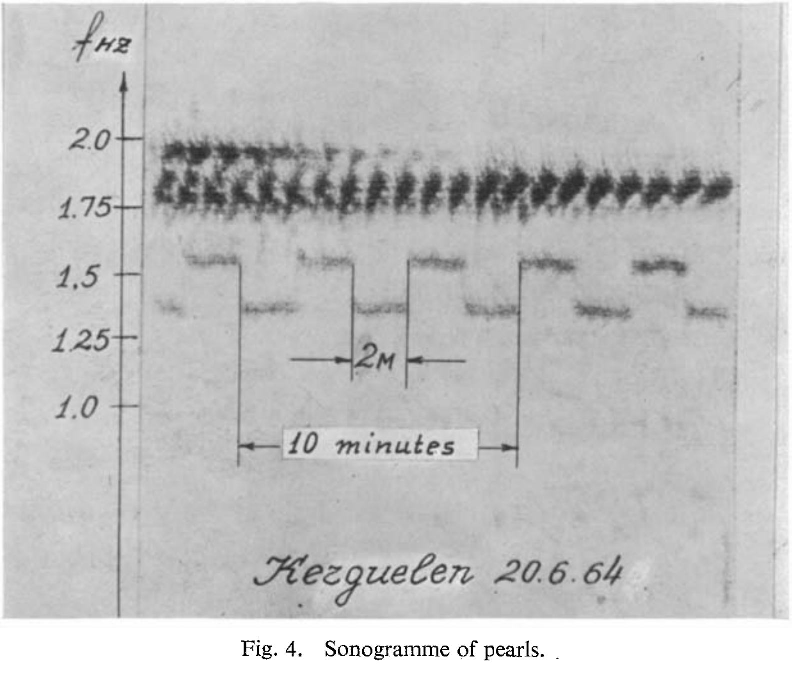

Fig. 4. Sonogramme of pearls.

In the new classification pulsations of irregular form with the periods falling mainly in the range 1–15 sec were introduced. They are generated mainly in the evening and night hours, and their amplitude is maximal in the aurora zone. They were called Pi 1 (in the literature they are sometimes also named 'sip'). The Pi-1 pulsations are strongly correlated with variations of aurora intensity, bursts of X-rays in the stratosphere, and other corresponding phenomena.

We have also to mention here the specific disturbances which present the intervals of pulsations diminishing on periods (IPDP). They are typical for the main phase of the magnetic storms, and are connected with processes developing in the radiation belt. Morphologically, they consist of a mixture of pulsations of Pi-1 and Pc-1 types (TROITSKAYA, 1961).

Investigations of these and other types of micropulsations were conducted independently by different groups of authors, who often gave different nominations to the micropulsations belonging practically to one and the same morphological or genetical type.

For instance, the terms Pg and Lpc were introduced to nominate pulsations not differing very much from pg. In some papers, also, the pearls were called oscillations of *A*-type, hydromagnetic emissions, etc. To bring order to this situation, at the XIIIth General Assembly of IUGG (August, 1963, Berkeley, Calif., U.S.A.) a new broadened classification of micropulsations was elaborated and adopted (JACOBS *et al.*, 1964). The pulsations were divided into two main groups: regular and irregular. The regular oscillations are characterized by quasi-sinusoidal periods and the stability of the regime. They were called 'Pc'. The Pc group itself is divided into five spectral subgroups. The group of irregular pulsations contains two subgroups (Table I).

The correspondence between the new and the earlier classifications is established in the following way: Pc 1 – pp, Pc 3 – pc, Pc 5 – pg, Pi 1 – sip, and Pi 2 – pt.

The experience obtained in the years following the adoption of the new classification showed the necessity of further detailization in the subdivision of micropulsations on types. For instance, the frequency range for Pi-2 pulsations must be

TABLE I
Classification of Micropulsations

Type	Range of periods (sec)
	Continuous pulsations
Pc 1	0.2 – 5
Pc 2	5 – 10
Pc 3	10 – 45
Pc 4	45 – 150
Pc 5	150 – 600
	Irregular pulsations
Pi 1	1 – 40
Pi 2	40 – 150

widened to the interval 20–240 sec, and inside this range several subgroups, similar to the Pc-type group have to be introduced (SCHEPETNOV, 1966). Further on, the morphological studies of pearls have shown that there exist reasons to divide them into two groups: pulsations with periods less than 2 sec and pulsations with periods greater than 2 sec. Whereas the oscillations of the first group are usually observed globally, the pulsations of the second group occur more or less locally (TROITSKAYA, 1964).

Some additional information on micropulsations will be given in the text as far as necessary. The detailed description of the geomagnetic micropulsations is given in special surveys (TROITSKAYA, 1961, 1964, 1967; KATO and SAITO, 1962; JACOBS and WESTPHAL, 1963; TEPLEY, 1965; GENDRIN, 1965).

1.3. ELECTROMAGNETIC SOUNDING OF PLASMA

The sounding of plasma by electromagnetic waves is a classical method of measuring its parameters – density, temperature, ions content, etc. Up to date, a variety of surface and satellite methods of the electromagnetic sounding of plasma in the cosmic surroundings of the earth have been elaborated. It is convenient to divide these methods into the high-frequency (HF) and the low-frequency (LF) ones. This division is based on the fact that the plasma frequency ω_{0e} in the magnetosphere greatly exceeds the gyrofrequency Ω_e of electrons. Therefore, the propagation of waves in the band $\Omega_e < \omega \lesssim \omega_{0e}$ becomes impossible (Figure 5). To the left of the opacity band we have the low-frequency range, and to the right – the high-frequency one.

The high-frequency waves are used in the ionospheric sounding of plasma concentration below the level of maximum ionisation of F_2 layers. In this high-frequency range the powerful radars operate which allows investigation of the parameters of plasma higher than the main maximum, by means of the incogerent backscatter

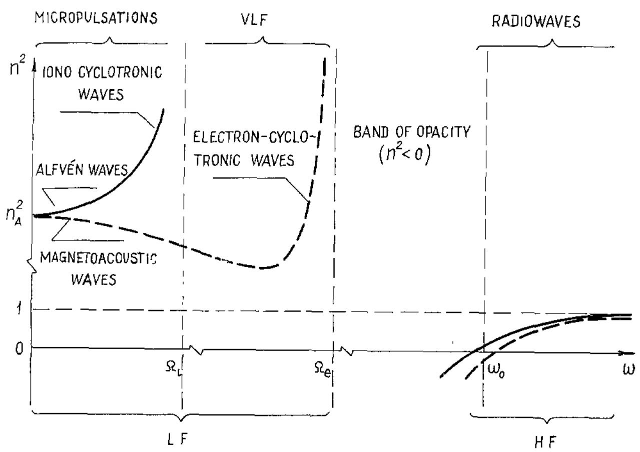

Fig. 5. Low-frequency (LF) and high-frequency (HF) ranges of waves in the magneto-active plasma. The figure shows the dispersion curves in the cold magneto-active plasma (longitudinal propagation). The band of opacity is indicated ($n^2 < 0$) dividing the ranges HF and LF.

method. The high-frequency waves are also used in investigations of plasma utilizing the Doppler shift of the frequency of the radio transmitter installed on a satellite, the Faraday rotation of the plane of polarization, etc.

In general, high-frequency methods of sounding utilize the artificial electromagnetic fields. At the same time, methods in which electromagnetic emissions of natural origin can be used gratis, present doubtless, practical interest. These emissions are, for instance, VLF emissions and micropulsations. The success of utilization of whistlers for the diagnostics of the plasma concentration in the magnetosphere is well known. Beginning from 1953, when on the eve of cosmic-space investigations, Storey made the first qualitative estimate of electron concentration on high altitudes, whistlers and other VLF emissions are widely used in the electromagnetic methods of the sounding of the magnetosphere.

The application of micropulsationsfor the aims of the diagnostics of the magnetosphere is a natural prolongation of this direction of research. In spite of the fact that the frequencies of the micropulsations and of the VLF emissions differ to several orders of magnitude, the methods of diagnostics utilizing these natural electromagnetic fields possess, in a number of cases, a formal and physical similarity. The similarity of these methods is most distinctly revealed in the diagnostics of 'thermal' plasma concentration on dispersion of whistlers, and on dispersion of micropulsations of Pc-1 type, as well as by estimation of the parameters of the distribution function of energetic particles on the character of the waves amplification in the exosphere.

At the same time, the observations of micropulsations make possible the diagnostics of such an important parameter of the magnetosphere as the location of the boundary of the magnetosphere. There exist no other surface methods of diagnostics of this parameter of the magnetosphere.

Up to date three main directions of investigations of the magnetosphere utilizing micropulsations can be formulated:

(1) Determination of the location of the boundary of the magnetosphere;

(2) Diagnostics of cold-plasma concentration in the far regions of the magnetosphere;

(3) Diagnostics of energetic particles in the magnetosphere.

Unfortunately, the general quantitative theory of geomagnetic micropulsations is far from being elaborated. Only some basic principles of physical interpretation of micropulsations are formulated, and mechanisms of generation for some types of pulsations are suggested. Therefore, different empirical and semi-empirical methods are widely used in the diagnostics of the state of the magnetosphere. The experimental observations show that there exist some interesting interconnections of micropulsations with processes developing in the outer space. As an example can serve the so-called intervals of pulsations diminishing on periods (IPDP). In spite of the fact that the theory of the IPDP is not yet elaborated, the data already gathered allow one to state that these intervals are a sensitive indicator of processes developing in the geomagnetic trap.

Before describing the methods of diagnostics of the magnetosphere, the authors thought it useful to give a short summary of the theoretical conceptions of the origin of micropulsations.

It is necessary to stress that the listed bibliography does not embrace all the investigations conducted in this field of research. A great number of scientists participate in the experimental and theoretical investigations of micropulsations but in the frame of this paper it was not possible to make a due estimate of the importance of contribution of many of them. The main attention was given to the investigations which, directly or indirectly, were connected with the problems of diagnostics of the magnetosphere.

2.0. The State of the Theory of Geomagnetic Micropulsations

2.1. Preliminary remarks

This paragraph contains some of the theoretical conceptions on micropulsations, which are connected in some measure or other with the problem of diagnostics of the magnetosphere.

The theoretical investigations of micropulsations are hindered by some of their specific peculiarities. The length of waves in the low-frequency part of their spectrum (that is Pc 3 – Pc 5, Pi 2) is comparable with the dimensions of magnetosphere. Therefore, the correct solving of the problem requires application of numerical methods.

At the highest boundary of the frequency range (Pc 1) the wavelengths are significantly smaller than the linear dimensions of the magnetosphere. Therefore, methods of geometrical optics can be used in studying their propagation. But even in this case, at low altitude (that is lower than 2–3 thousands of kilometres), these methods are no longer applicable.

Moreover, the physical conditions in different parts of the magnetosphere are quite different. Above the ionosphere, that is higher than 500 km, the number of collisions between the particles is few, and consequently the absorption (or the amplification) of waves is determined only by kinetic effects.

In the ionosphere the number of collisions between ions and electrons and with neutral molecules is great, this leads to the dissipation of hydromagnetic waves falling from outer space. In the far regions of the magnetosphere the frequencies of the shortest periodic pulsations of pearl type (Pc 1) become comparable with gyrofrequencies of ions and this leads to dispersion effects. Therefore we have to deal with a medium, where electrodynamical parameters change in space in a complicated manner and moreover depend on the frequency and direction of the wave propagation.

When the generation of micropulsations is discussed it is generally admitted that micropulsations are produced as a result of different types of plasma instabilities in the magnetosphere or its boundary. The conditions of generation and the increase of growth of small disturbances can be investigated in detail in the linear approximation. However, the determination of the amplitude of stationary oscillations requires elaboration of the non-linear theory. Nevertheless the general direction of the future theory of micropulsations has been traced already.

2.2. Proper oscillations of the magnetosphere

The problem of proper oscillations of the magnetosphere was formulated for the first time by DUNGEY (1954). In the case of axial symmetry the oscillations are divided into two independent types: the poloidal and the toroidal oscillations (see Appendix 1). The toroidal oscillations arise on magnetic surfaces formed by the rotation of field lines around geomagnetic axis. It is important that different surfaces oscillate independently of each other.

The problem of eigenvalues for toroidal oscillations was solved, for cases of different indications of plasma distribution in the magnetosphere, both by numerical and approximate analytical methods (DUNGEY, 1963; OBAYASHI, 1958; WATANABE, 1961; WESTPHAL and JACOBS, 1962; MACDONALD, 1961; CAROVILLANO and RADOSKI, 1967). In Table II, taken from the paper of WESTPHAL and JACOBS (1962), the dependence of the period of the main mode of toroidal oscillations T_1 from the polar angle v_0 is given.

TABLE II

Dependence of the Period of the Main Mode of the Toroidal Oscillations from the Polar Angle

v_0	T_1, sec
10°	4.3×10^5
15°	1.9×10^4
20°	2.0×10^3
25°	3.8×10^2
30°	1.2×10^2
35°	39
40°	17
45°	8.9
50°	5.2
55°	3.8
60°	6.5
65°	16
70°	29
75°	41
80°	32

The equation of toroidal oscillations was obtained using a number of simplifying suggestions. In reality, all these suggestions can be disputed to some degree or other, and therefore it is difficult to expect the generation of toroidal oscillations in the magnetosphere in a pure form. Nevertheless some types of micropulsations, and namely Pc 5 and partly Pc 4, clearly reveal the basic properties of toroidal oscillations. (The augmentation of the period of oscillations with the latitude and a strong correlation of oscillations in magnetically conjugated points.) Therefore, it may be assumed that micropulsations of these types can be described in some approximation by equation of toroidal oscillations.

The poloidal oscillations embrace all, or a significant part of the resonating volume. Therefore they are usually identified with micropulsations of Pc 2 – Pc 4 types, which may practically be observed on a global scale.

The proper oscillations of the magnetosphere can be generated in different ways. One of the main mechanisms is the hydrodynamic instability of surface waves, which arise in the course of sweeping of the magnetosphere by the solar wind (DUNGEY, 1963; MOSKVIN and FRANK-KAMENETSKII, 1967). The surface waves are transformed as a result of linear and non-linear processes in the Alfvén and magneto-acoustic oscillations of the magnetosphere on the day side. In this way the continuous pulsations are generated. As regards the pulsation trains (irregular pulsations Pi 2) on the night side, it is probable that they are generated as a result of impulsive action on the magnetosphere of different plasma instabilities in the neutral sheet of the magnetospheric tail.

2.3. GENERATION AND PROPAGATION OF MICROPULSATIONS OF Pc-1 AND Pi-1 TYPES

In this section we shall consider the waves with relatively short wavelengths, which are significantly less than the linear dimensions of the magnetosphere (Pc 1 – Pi 1). Micropulsations of Pc-1 type differ from other groups of continuous pulsations by the mechanism of generation. The proper oscillations of the magnetosphere are generated as a result of instability of hydrodynamic type, whereas kinetic instability of distribution of energetic particles in the magnetosphere is responsible for Pc 1.

The main specific property of the plasma surrounding the earth which determines the form of the tensor of dielectric permeability $\varepsilon_{\alpha\beta}(\omega)$ and the character of solutions of the dispersion Equation (43) is the existence of several types of ions with different ratio of the charge to the mass (see Appendix 2). As a result of this, the dispersion curves $n^2(\omega)$ have additional zero's and poles in the vicinity of gyrofrequencies of heavy ions.

Ions of oxygen, nitrogen, helium and hydrogen exist up to altitudes of ~ 1000 km. The frequency of micropulsations for these regions in the Alfvén range is: $\omega \ll \min\{\Omega_i\}$, where Ω_i = girofrequency of ions. The existence of heavy ions is taken into account in the expression for the density in the formula of Alfvén velocity.

Due to the dipole-like character of the geomagnetic field, the gyrofrequency of the ions of given type diminishes with the distance from the earth as $1/L^3$ and at some altitude becomes equal to the frequency of the wave. For instance, the Alfvén wave propagating upwards with a frequency 1 cycle/sec reaches the poles of the refraction index at the gyrofrequencies of ions O^+ and N^+ at the distance $L \approx 3$. But at such distances the ions O^+ and N^+ are practically absent. The ions of He^+ present an exception – their existence was discovered up to the heights of ~ 30000 km with relative concentration $\xi \approx 1\%$ (TAYLOR *et al.*, 1965). Just at these altitudes is reached the pole on the gyrofrequency Ω_{He^+} of the square of refraction index for the ionocyclotron waves (L-mode) which propagate upwards with a frequency of 1 Hz. Therefore, for the analysis of propagation in the magnetosphere of waves in the range of 1 Hertz, one can adopt a model of plasma consisting of electrons, protons and a small amount of one-charged helium ions. At the periphery of the magnetosphere it may be required to take into account the α-particles, the relative concentration of which in the interplanetary medium is of the order of 10%.

The general expressions determining the refraction index $n(\omega)$ of the magneto-active plasma are given in Appendix 2. With their aid, choosing an appropriate model of the magnetosphere, one can solve the eiconal equation describing the direction of rays in the magnetosphere. A correct solution of the eiconal equation must have a rather complicated form. An essential and simplifying circumstance is the fact that the energy of the Alfvén and ionocyclotron waves (L-mode) is well canalised by the magnetic-field lines, whereas the magnetoacoustics wave (R-mode) are propagated more or less isotropically. This circumstance is very evidently reflected in Figure 6, which shows the surfaces of the index of refraction for the electron-cyclotron (L-mode) and iono-cyclotron (R-mode) waves (JACOBS and WATANABE, 1964).

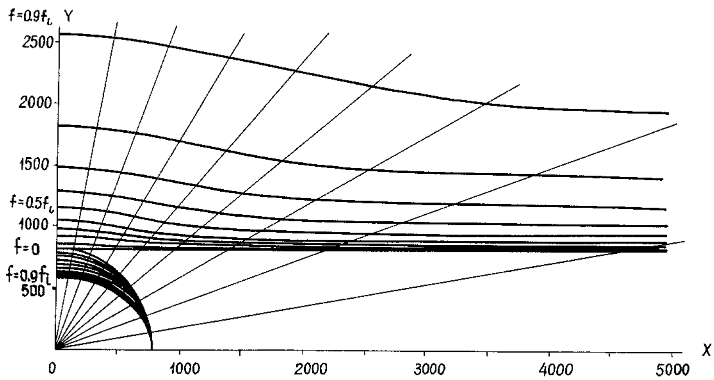

Fig. 6. The surfaces of the index of refraction in the homogeneous magneto-active plasma. Axis y is parallel to the external magnetic field. The numerical values of the indexes of refraction are plotted on the axes x and y. The curves are calculated as typical for the far regions of the magnetosphere values of electron concentration and intensity of the external magnetic field.

The external homogeneous magnetic field is directed along the y-axes and has the intensity 170γ, corresponding to the intensity of the geomagnetic field in the far regions of the magnetosphere. In calculations of the refraction index n, plotted on the axes x and y, it was suggested that plasma consists of two components – electrons with concentration $N = 10^2$ cm^{-3} and one type of ion (protons). The upper group of curves shows the dependence of refraction index of the iono-cyclotronic waves from the frequency and the direction of propagation. The values of the wave frequency f are shown in Figure 6 in the fractions of the ions gyrofrequency $f_i = \Omega_i/2\pi$, and the angle between **H** and **k** is the angle between the radius vector and the axis y. The value of n is equal to the length of the radius-vector up to its intersection with the corresponding curve. The lower group of curves shows the similar dependence for the electron-cyclotron waves. All this picture is, of course, symmetrical in respect of the y-axis, and therefore the values of the refraction index on a given frequency form some surface. The normal to this surface gives the direction of the vector of the group velocity $\mathbf{V}_g = \partial\omega/\partial\mathbf{k}$ which, in the non-dissipative medium, coincides with the direction of waves energy flow (Stix, 1962). The figure shows that the direction of the rays of iono-cyclotron waves does not significantly deflect from the direction of the magnetic field at practically any frequency and any direction of the waves normals.

Dowden (1965) and Gurnett and Shawhan (1966) have shown that this deflection never exceeds 12.3°. It is well known also that in the Alfvén region of frequencies ($\omega \ll \Omega_i$) the vector of the group velocity of L-waves simply coincides with the direction of the external magnetic field. When wave packets of the type L are propagating in the magnetosphere their frequency ω is approaching the gyrofrequency of the ions Ω_i on the relatively small parts of the trajectory. Therefore, the arising deflection of the ray from the tangent to the field line is small, and the family of the trajectories of waves of this type can be approximated by the field lines of the geomagnetic field.

The direction of the vector of the group velocity of the magneto-ionic waves (R-type) in the homogeneous medium does not differ greatly from the direction of the wave normal – the waves propagate isotropically (Figure 6). The calculation of the trajectories of magneto-ionic waves in an inhomogeneous medium with slowly changing parameters (magnetosphere) was done by Sugiura (1965). The magnetic focusing of waves evidently does not exist in this case. For accomplishing the magnetic focusing of magneto-ionic waves, a special distribution of plasma with sufficient sharp gradients of density transverse to the external geomagnetic field, is necessary (Booker, 1962). Such gradients exist, for instance, in 'ductes' – layers of higher concentration elongated on geomagnetic-field lines; in the region of the 'knee', etc. It is necessary to note, however, that the question of canalisation of the magneto-ionic waves by such formations in the magnetosphere is not yet sufficiently investigated.

Speaking about pearls, we can explain the fact of antiphase appearance of the signals in conjugate points by propagation along the field lines of narrow wave packets of Alfvén type (Obayashi, 1965; Jacobs and Watanabe, 1964). Let us see how this point of view helps to understand other properties of pearls, for instance the slope of structural elements on spectrogrammes in respect of the time axis. But first it is necessary to mention the character of refraction of the Alfvén and iono-cyclotron waves. If, at the surface of the earth, the wave starts at an angle θ_0 to the geomagnetic field, then, the angle θ diminishes as it propagates upward, the vector $\mathbf{k}$ being the closer to the field line, the closer is the frequency of the wave to the gyrofrequency of the ions (Stix, 1962; Dowden, 1965). This circumstance gives the right to use the approximation of longitudinal propagation ($\theta = 0$) in the calculation of the time of the group delay for the pearls

$$\tau(\omega) = \int \frac{\mathrm{d}l}{V_g(\omega)}, \qquad V_g = \frac{c}{\partial\omega n/\partial\omega}. \tag{1}$$

The integral is taken along the trajectory of the signal. The group velocity in the hydrogen plasma is equal* (OBAYASHI, 1965).

$$V_g^{\pm} = V_a\left(1 \pm \frac{\omega}{\Omega_i}\right)^{3/2}\left(1 \pm \frac{\omega}{2\Omega_i}\right)^{-1}. \tag{2}$$

Here $V_a = H/\sqrt{4\pi m_i N}$ is the Alfvén velocity.

The upper sign refers to the waves of the right-hand polarization, and the lower to the waves of the left-hand polarization. In calculation of the time of group delay for pearls it is necessary, in consequence to the above statement to take the lower sign. OBAYASHI (1965) and JACOBS and WATANABE (1964) succeeded in explaining the tones of rising frequency on the spectrogrammes of pearls by the effect of the 'magnetic shore': the frequency of the signal propagating upwards along the field line approaches the gyrofrequency of the ions and due to the dispersion the signals diffuse. The low-frequency components of the signal arrive before the high-frequency ones, and a signal of a rising tone is observed on the earth's surface.

Choosing an appropriate model of the exosphere one can, using Equations (1) – (2), calculate the theoretical spectrogrammes $\tau(\omega)$ and compare them with the experimental ones. Figure 7 gives an idea on the dynamic spectrum of the signals

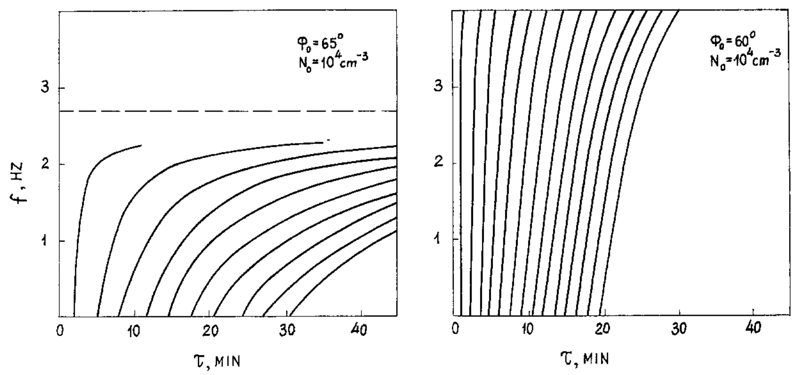

Fig. 7. The theoretical spectrogrammes of pearls. The figure represents the dependence on frequency of the time of group delay of waves packets propagating along the field lines $L = 4.0$ and $L = 5.6$. It is suggested that the waves are mirrored back in the magnetically conjugate regions. The dotted line on the left-hand figure shows the value of gyrofrequency of protons in the summit of the field line.

propagating along two typical trajectories (field lines). One of them intersects the earth's surface on the latitude $\phi_0 = 60°$ and the other on the latitude $\phi_0 = 65°$ (OBAYASHI, 1965). The signal is momentarily generated at one end of the field line, and is registered at the other end. The calculations are made on the assumption that the geomagnetic field is a dipole field and the plasma concentration depends on the geocentrical distance r as $N = N_0(r_e/r)^3$ where r_e is the earth radius and $N_0 = 12000$ cm^{-3}.

* Equation (2) is valid also for the proton-helium plasma everywhere, except a narrow-frequency band in the region of the helium gyroresonance.

The figure shows several successive echoes of the signal arising due to the reflection of waves in the magnetically conjugate regions. The diminishing of the slope of the structured elements obtained to the time axis for the theoretical spectrogramme is observed practically only at the end of the pearls series, when the amplitude of the signals diminish. In the middle of the series the slope of the structured elements often remains constant, and at the beginning of the series it can even augment, completely contradicting the predictions of the theory. In the paper of WATANABE (1966) an endeavour is made to explain this peculiarity by the non-linear effects of propagation. The linear theory of dispersion is, as it seems, applicable only at the end of the series of pearls.

Let us now consider the kinetic effects in the exosphere. In the approximation of the cold plasma, which was used up to now, it was suggested that the charged particles are at rest in the absence of waves. Under the influence of the waves field the particles are oscillating, but on average, no exchange of energy between the wave and the particle takes place. In the real plasma the particles are moving and, if they are in resonance with the wave, an effective exchange of energy takes place between them.

The condition of resonance for a wave and a particle moving with the velocity u along the external magnetic field is well known (GINSBURG, 1960; STIX, 1962)

$$\omega = S\Omega + ku\cos\theta, \qquad S = 0, \pm 1, \pm 2, \ldots, \tag{3}$$

where Ω is the gyrofrequency of the particle. The kinematic meaning of the relation (3) is that in the system of coordinates in which the Larmor center of the particle is at rest, the frequency of the wave is either zero ($S=0$) or is a multiple of the particle gyrofrequency ($S\neq 0$). If $S=0$, the relation (3) coincides with the condition of Cherenkov emission; if $S>0$, then (3) is a formula of normal, and by $S<0$, of abnormal Doppler effect for an oscillator with the frequency Ω.

The character of interaction of waves with resonance particles depends on the form of the distribution function of particles. For instance, for the Maxwellian distribution the interaction leads to the damping of waves. But if the relations (57) do hold, then one can neglect the effect of damping, because the resonance takes place for the exponentially small number of particles (see Appendix 3). For the case of resonance of the iono-cyclotronic wave with protons the condition of applicability of the approximation of cold plasma is described by the inequality $|1-\Omega_i/\omega| \gg (V_T/V_a)^{2/3}$ where $V_T=\sqrt{2T/m_i}$ is the mean thermal velocity of ions. The Alfvén velocity in the exosphere is $V_a \approx 10^8$ cm/sec, the temperature $T\approx 10^4$ °K, $V_T \approx 10^6$ cm/sec, and $(V_T/V_a)^{2/3} \approx 0.03$. From here, in particular, it follows, that if the frequency of pearls is not too close to the gyrofrequency of ions, then the thermal plasma of the exosphere may be considered as a cold one.

However, in the magnetosphere in addition to the thermal plasma, there exist energetic particles – the particles of the radiation belts, aurora particles, solar cosmic rays, etc. Their interaction with hydromagnetic and iono-cyclotronic waves leads, in definite conditions, to the forming of the instability that is conducive to the growth of the oscillations. Let us consider the conditions necessary for growth of transverse waves of small amplitude, propagating along the external magnetic field in cold plasma containing a small amount of energetic particles. The waves are circularly polarized, and the resonance arises on the first harmonic of the particles gyrofrequency ($S = \pm 1$). For the effective exchange of energy between waves and particles it is necessary, that in addition to the condition (3), the following polarization rule is fulfilled: in the system of coordinate where the Larmor centre of the particle is at rest, the direction of gyrorotation of the particle coincides with the direction of rotation of the electric vector of the wave. This leads to the definite relations between the type of resonance particles, type of the wave and the character of the Doppler effect (Table III; JACOBS and WATANABE, 1966).

TABLE III

Additional Conditions of Resonance

Type of particles	Type of wave	Character of Doppler effect, S	Direction of particle movement along the external magnetic field in respect of direction of wave propagation
Electrons	R	$+1$	Antiparallel
Electrons	L	-1	Parallel
Protons	R	-1	Parallel
Protons	L	$+1$	Antiparallel

Combining the resonance condition (3) and the dispersion relation (46), one can, taking into account the data of Table III, build the dependence of the resonance velocity of particles from the wave's frequency (GINTZBURG, 1961a, b, c; GENDRIN, 1965; JACOBS and WATANABE, 1966). From Figure 8, it is seen that in the frequency range lower than the ions gyrofrequency, the resonance electrons in the conditions of the magnetosphere must be ultrarelativistic (JACOBS and WATANABE, 1966). Due to the fact that the amount of such particles in the magnetosphere is very low, it is usually suggested that the main agents responsible for Pc-1 generation are the energetic protons.

As regards the mechanism of Pc-1 – Pi-1 generation, there does not exist a unanimous opinion. CORNWALL (1965) put forward the hypothesis that pearls (Pc 1) are generated due to the cyclotron instability of protons of the outer radiation belt. If we assume that the distribution of protons on pitch angles α is described by a function $\sim \sin^{\mu}\alpha$, where μ is the parameter of the distribution, then if $\mu > 0$, the growing waves will be waves of the left-hand polarization in the frequency range

$$\omega < \Omega_i \frac{\mu}{\mu + 1}.$$

As in the proton belt $\mu \approx 1$–2 (DAVIS and WILLIAMSON, 1963), the $\omega/\Omega_i < 0.5$–0.6, where Ω_i is the gyrofrequency of the protons in the summit of the field lines. (The

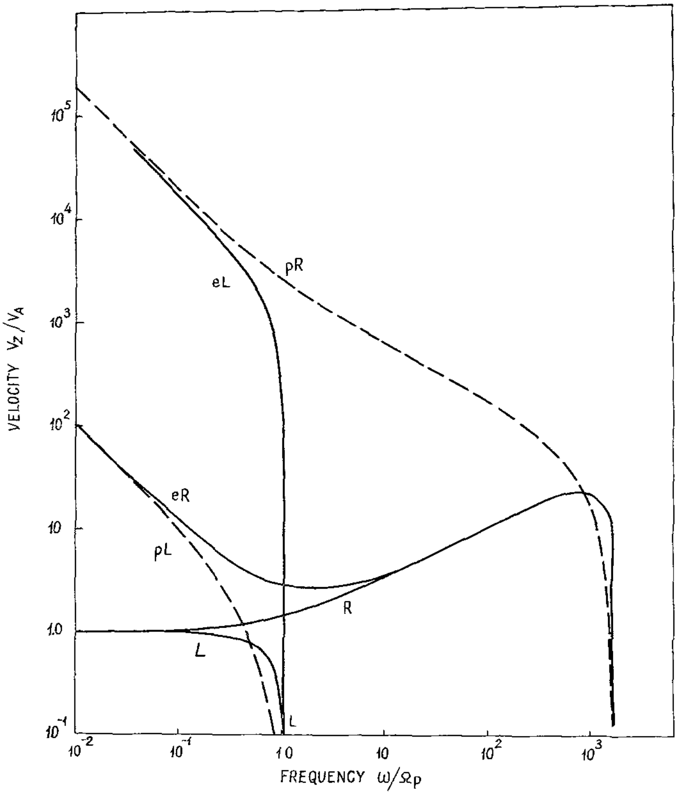

Fig. 8. Dependence of the resonance velocity of electrons (e) and protons (p) from the frequency of transverse waves of the left- and right-hand polarizations. The figure also shows the frequency dependence of the waves phase velocity (indexes R and L).

instability develops most quickly in the equatorial plane.) The maximal coefficient of amplification takes place at the frequencies

$$\omega_m \approx \Omega_i (V_a/W_{\parallel})$$

where $W_{\parallel}$ is the average longitudinal velocity of protons (see also Appendix 3). For instance, if $L \approx 4$, $\Omega_i \approx 47$ rad/sec, $V_a \approx 7 \times 10^7$ cm/sec, $W_{\parallel} \approx 7 \times 10^8$ cm/sec and $\omega_m \approx 4.7$ rad/sec, that is, it falls in the frequency range of pearls (Pc 1).

LIEMOHN (1967) has conducted in the linear approximation detailed calculations of the coefficient of amplification of the transverse waves in the outer radiation belt for a different hypothesis on the steepness of the spectrum of particles energies, and degrees of the anisotropy of their distribution on pitch angles. CORNWALL (1966), KENNELL and PETSCHEK (1966) and TVERSKOY (1967) have founded the base of the quasi-linear theory of the instability of the proton belt. The results of all these investigations clearly show that the instability of the proton belt in respect of growing iono-cyclotron waves may exist. It is not very probable, however, that as a result of this instability micropulsations of the pearl type arise. The pearls are usually narrow-band signals, whereas the proton belt is unstable in a rather wide range of frequencies. The widening of the spectrum arises from the natural scattering of particles on velocities, but mainly due to the inhomogeneity of the magnetosphere. If we assume, that $V_a \sim L^{-3/2}$ then, due to the fact that in the proton belt $W_{\parallel} L^{3/2} = \text{const}$, we get the following dependence of ω_m from L: $\omega_m \sim L^{-3}$. Going out from this dependence and taking into account the character of particle fluxes distribution on L shells, one can conclude that the range of growing waves exceeds at least an octave (Appendix 4). It is also difficult to understand how the instability of the proton belt would lead to the formation of regular quasi-sinusoidal signals, alternatively and periodically appearing in the conjugate regions.

One can draw interesting and fruitful analogies between hydromagnetic and VLF emissions (BRICE, 1965). It is known, for instance, that the cyclotron instability of the electrons of the outer radiation belt is revealed in the form of broad-band emission – the so-called hiss, in the range of kilohertz (GERSHMAN and TRACHTENGERTZ, 1966). Similarly, it is natural to identify the hydromagnetic emission of proton belt with the continuous broadband emission which was observed by TEPLEY and AMUNDSEN (1965) at night in the frequency range ~0.5 Hz (GUL'ELMI, 1966d, 1967a).

The mechanism of pearls generation must be of some other type. A number of authors suggest that pearls are generated as a result of cyclotron or Cherenkov instability of almost monoenergetic proton bunches, sporadically injected into the magnetosphere (TEPLEY and WENTWORTH, 1963; GENDRIN, 1965; JACOBS and WATANABE, 1966; OBAYASHI, 1965; GUL'ELMI, 1966d; BRUNELLI and LYATSKY, 1967). In spite of the fact that this point of view could explain some of the morphological properties of pearls, the existence in the magnetosphere of the bunches of protons with suitable properties needs to be seriously proved itself.

The cyclotron instability of energetic protons is not the only possible mechanism of the micropulsation generation in the range of Pc 1 – Pi 1. NISHIDA (1964) suggests that the bursts of irregular pulsations Pi 1 observed with maximal intensity in the auroral zone on the night side, are due to the instabilities of electron bunches with energies of particles around 1–10 keV, which are injected in the upper atmosphere (see also Section 5.3) GUL'ELMI (1967a) suggests, that some types of Pc-1 micropulsations observed in high latitudes in noon hours could be a result of the development of the drift-cyclotron instability (MIKHAILOVSKII, 1963) in the narrow transition layer on the periphery of the sunlit magnetosphere. However, a detailed analysis of the instability of drift-cyclotron waves in the magnetosphere as a possible mechanism of micropulsations generation is not yet fulfilled. The mechanism of the generation of the intervals of pulsations diminishing on periods IPDP, which occur in the main phase of the magnetic storms also remains unexplained. The early solution of this question is very important because the IPDP contain essential information on the non-stationary processes developing in the geomagnetic trap.

2.4. PROPAGATION OF WAVES IN THE IONOSPHERIC LAYERS

The influence of the ionosphere on the micropulsations is due to two types of processes:

firstly, the high frequency of collisions between the particles leads to the dissipation of the falling-from-above hydromagnetic waves, and secondly, the sharp vertical inhomogeneity of the ionosphere favours the canalisation of waves, that are their propagating along the ionospheric layers. The dependence of the coefficient of hydromagnetic-waves penetration through the ionosphere from the waves frequency and from the state of the ionosphere is illustrated in Figure 9 (PRINCE and BOSTICK, 1964).

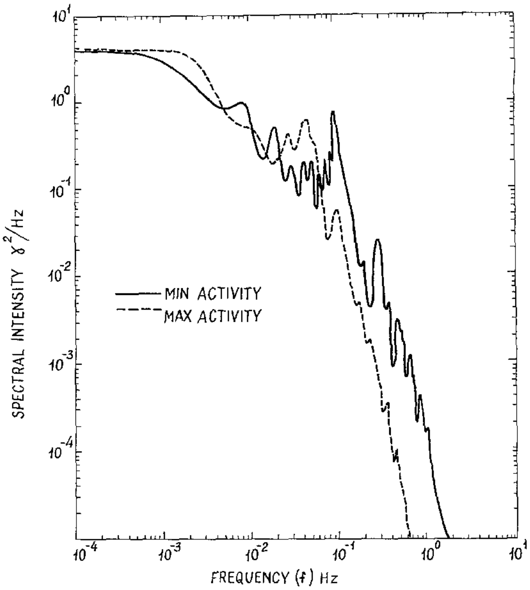

Fig. 9. The theoretical spectrum of magneto-acoustic oscillations of the magnetosphere. In calculations of the spectrum it was suggested that the plane magneto-acoustic waves fall on the magnetosphere at the height of 68000 km and propagate to the earth in the equatorial plane. As a model of the earth's surface a plane sheet is taken, 50 km thick, lying on an ideal conducting base and having the conductivity 100 Ω *m*.

The general dropping of the coefficient of penetration with the augmentation of the frequency is due to the dissipation of the hydromagnetic energy in the ionosphere as a result of collisions between the particles (KARPLUS *et al.*, 1962; AKASOFU, 1965). The resonance maxima arise as a result of hydromagnetic waves reflections from the earth's surface and from the sharp gradient of Alfvén velocity at the height of around 1000 km (JACOBS and WATANABE, 1962).

The dissipation of waves leads in principle to the additional warming of the ionosphere (DESSLER, 1965). Up to date there is no generally adopted opinion as regards the effectivity of such source of the ionospheric warming. It seems that the warming by hydromagnetic waves, if in general it plays some role in the heat balance of the ionosphere, is possible only by waves of great amplitudes which can occur during strong magnetic disturbances.

In numerical calculations of the curves presented in Figure 9, the ionosphere and the exosphere were approximated by a number of horizontal layers, the magnetic field was taken parallel to the plane of stratification, and the direction of propagation of plane waves was taken perpendicular to the plane of stratification. This case takes place approximately when the waves propagate towards the earth's surface near the plane of the geomagnetic equator. In some papers the calculations of the coefficient of penetration of vertically falling waves were conducted for the case when the magnetic field is perpendicular (polar propagation, FIELD and GREIFINGER, 1965) and for the case when the magnetic field is directed under some angle to the horizon (middle latitude propagation) (KARPLUS *et al.*, 1962).

The coefficient of reflection from the ionosphere of the waves with periods from 10 and more sec differ little from unity. In the Pc-1 range, the coefficient of reflection is less than unity, and in general diminishes with rising of the frequency. It is interesting to note that the frequency dependence of the coefficient of reflection in this range has narrow minima located in the vicinity of its maxima (FIELD and GREIFINGER, 1965).

Due to the vertical inhomogeneity of the ionosphere, the waves of different types become, in general, mutually interconnected. It leads to the situation in which the falling-from-above Alfvén waves are partly transformed into the magneto-acoustic ones, which may be trapped in the ionospheric waveguide.

The conception of the existence in the ionosphere of the hydromagnetic waveguide follows from a number of qualitative considerations. The vertical profile of the refraction index for magnetoacoustic waves $n(z) \approx c/V_a \sim \text{const} \cdot N^{1/2}(z)$ repeats the profile of plasma concentration, that is, it has a maximum at a height around 300 km (Figure 10). Due to the fact that, as it is known from the geometrical optic, the rays

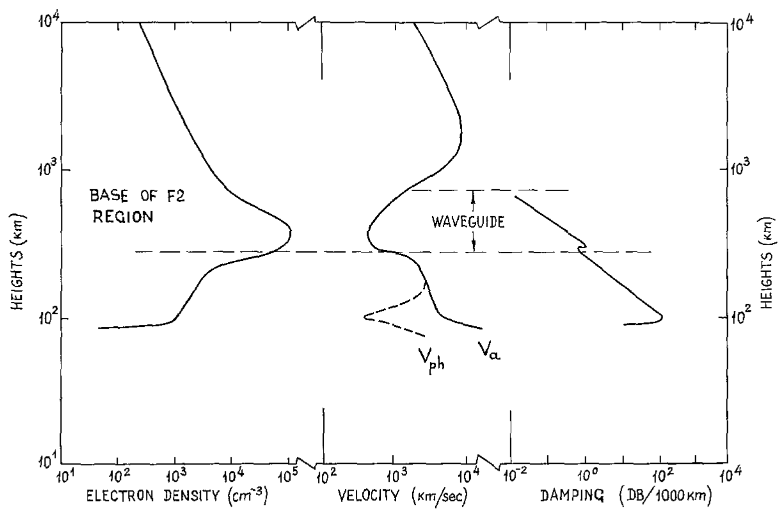

Fig. 10. Properties of the hydromagnetic waveguide in the ionosphere. The figure shows the vertical profiles of the phase velocity and the weakening of isotropic hydromagnetic waves with frequency 1 Hz in the ionosphere (for the night hours during the minimum of solar activity) (TEPLEY and LANDSHOFF, 1966).

are bent in the direction of augmentation of refraction index, the magnetoacoustic waves will concentrate in the plane around $z \approx 300$ km.

But such an explanation is not quite a correct consideration, because in the range of micropulsations the wavelengths are comparable to or exceed the thickness of the ionosphere. The character of waves propagation along the ionospheric layers can be cleared up only by means of solving the corresponding diffraction problem. Making estimate calculations, one can use the known solutions for wave propagation in a plane-parallel dielectric plate, which serves as a model of the F_2 region of ionosphere (as it was done in the paper of TEPLEY and LANDSHOFF, 1966). To obtain more precise results, MANCHESTER (1966) divided the ionosphere in several plane layers and numerically solved the corresponding equation for poles. The main results of these calculations are given below.

For the ionospheric waveguide as for any other, there exists a critical frequency ω_c: the normal waves with frequencies less than ω_c cannot propagate. During the day, the value of this low-frequency cut off is ~ 0.3 Hz, during the night ~ 0.6 Hz. Therefore, the ionosphere canalize the hydromagnetic waves in the range of Pc 1.

The effective velocity of the propagation in the waveguide due to calculations is, at night, of the order of 400–700 km/sec. This value is quite near to the value of the velocity revealed in experiment for the velocity of Pc-1 propagation along the earth's surface (WENTWORTH *et al.*, 1966; BARANSKY *et al.*, 1966). The waveguide damping on the frequency 3 Hz, at night, is of the order of 1 Db, and during the day of the order of 70 Db for 1000 km of the path in the waveguide (MANCHESTER, 1966).

The problems of the theory of micropulsations have many other, not mentioned above, unsolved questions. For instance, we have not at all considered the question of the influence of the finite earth conductivity on micropulsations, that is, we have not considered the surface impedance of the earth. The connection of the surface impedance with the electrical conductivity of the earth's crust is very interesting because it allows one to utilize the micropulsations properties for the investigations of the earth's structure (TIKHONOV and SHAKHSUVAROV, 1956). However, in the problems of the diagnostics of the magnetosphere utilizing micropulsations, one can consider in most cases the earth as ideally conducting. More important from the positions of this survey are the questions of generation of some types of micropulsations directly into the ionospheric layers. Some authors (CAMPBELL, 1961; (CAMPBELL and MATSUSHITA, 1962; LOGINOV *et al.*, 1963) suggest that micropulsations may be due to the magnetostatic variations arising as a result of pulsations of the polar electrojet. The pulsations of the electrojet may arise due to the chaotic modulation of the electric conductivity of polar ionosphere under the influence of the fluctuating streams of electrons with energies of several keV. These problems will not be discussed here.

The theory of geomagnetic micropulsations is far from being completed and several properties of micropulsations must be investigated experimentally in detail. Nevertheless the results obtained up to date are a sound base for the first endeavours of the diagnostics of the magnetosphere, utilizing the surface observations of micropulsations.

3.0. Determining the Location of the Boundary of the Magnetosphere

3.1. Position of the boundary on the sunlit side

Interaction of the streams of solar plasma with the geomagnetic field leads to the formation of a large cavity of a complicated form – of the magnetosphere of the earth. From the sunlit side, the regular magnetic field is restricted at a distance equal to approximately 10 earth radii by the quasi-spherical surface. On the opposite side it is shaped in a long, so-called magnetic tail.

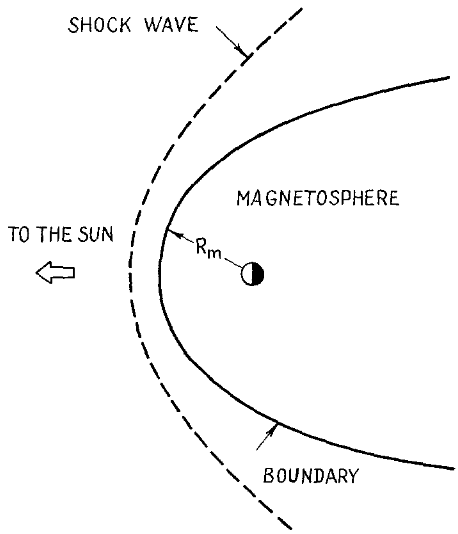

Fig. 11. Equatorial section of the magnetosphere.

The direct measurements of the magnetic field and particle fluxes on rockets and satellites have shown that the boundary of the magnetosphere is in constant movement. It draws nearer to the earth's surface when the solar wind gets stronger and moves farther from the earth's surface when the wind weakens and the normal pressure on the surface of the cavity becomes smaller. The location of the boundary (R_m) on the line sun-earth changes in the average approximately from ~ 8 to ~ 12 earth radii. It would be very tempting to have a simple indirect surface indicator, which would allow to trace continuously and uninterruptedly the position of the boundary of the magnetosphere. In the papers of Saito (1964), Troitskaya and Bolshakova (1964), and Bolshakova (1965a, b, c) it was shown that the oscillations of Pc 2 – Pc 4 can serve as such an indicator.

Due to existing conceptions the Pc-2 – Pc-4 pulsations are poloidal oscillations generated in the turbulent layer on the periphery of the sunlit magnetosphere. The frequency of oscillations naturally augments when the dimensions R_m of the resonator R_m diminish. Indirectly this connection is revealed in the experimentally discovered inverse correlative dependence of the period of oscillations T from the K_p index, of the magnetic activity. From Figure 12, on which the distribution of different groups of Pc relative to K_p are shown it is seen, that the occurrence of: Pc 4 (T=45–150 sec) is most probable when K_p=0–1, Pc 3 (T=10–45 sec) is most probable when K_p=2–3, and Pc 2 (T=5–10 sec) is most probable when K_p=3–5.

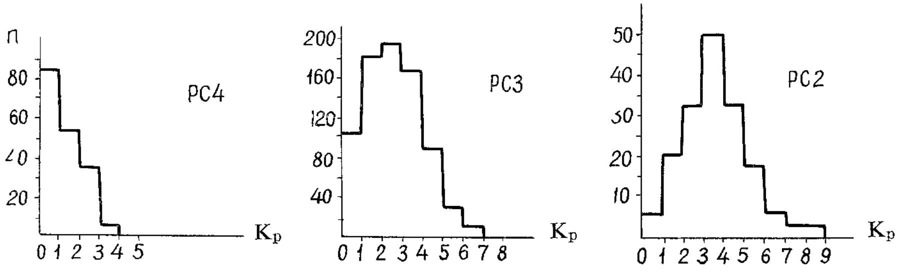

Fig. 12. The dependence of the frequency of occurrence of micropulsations of Pc-2–4 types on the level of magnetic activity.

The direct evidence of the dependence of the periods of these pulsations from R_m give the results of their comparisons with satellite data on the position of the boundary of the magnetosphere.

The first measurements of the location of the boundary of the magnetosphere from the sunlit side in the equatorial plane were made by the Explorer-XII (CAHILL and AMAZEEN, 1963). The apogee of the satellite was 77000 km, that is around 12 Earth radii. The data on the location of the boundary obtained by this satellite embraces the period from August 16th to December 6th, 1961. All these data were compared with the mean periods of continuous pulsations registered on the middle latitude observatory Borok and on some other stations (for definite intervals). It was found that the change of location of the boundary of the magnetosphere almost always was accompanied by the corresponding change of the pulsations periods. A typical example of such a correlation is shown in Figure 13.

It was revealed also, that the periods of Pc reflect more precisely the location of the boundary than the K_p indexes. For instance, the 21st, 22nd and 23rd of September 1961, the mean K_p for the day was correspondingly 0+, 1+ and 1−, but the boundary of the magnetosphere was located at this time at distances significantly smaller than those corresponding to the quiet state of the magnetosphere. This situation was reflected in the diminished period of Pc. These facts have stimulated the further investigations, which have led to the establishment of the empirical relation between the period of continuous pulsations and the location of the boundary of the magnetosphere. If we represent the dependence of R_m and T in the form

$$T = \text{const} \cdot R_m^{\nu} \qquad (4)$$

then the experiment gives for the degree index the value $\nu \approx 4.8$ (Figure 14; BOLSHAKOVA, 1965).

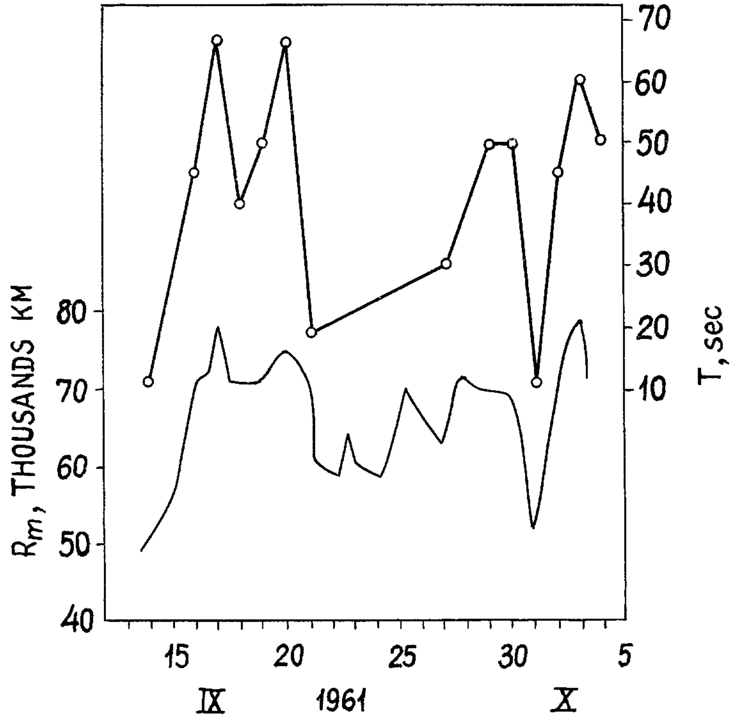

Fig. 13. Comparison of the periods of continuous pulsations with the location of the magnetospheric boundary. The figure shows the periods T of micropulsations registered at the middle-latitude observatory Borok and the corresponding values of R_m determined from the data on intersection of the magnetospheric boundary by the satellite Explorer-12.

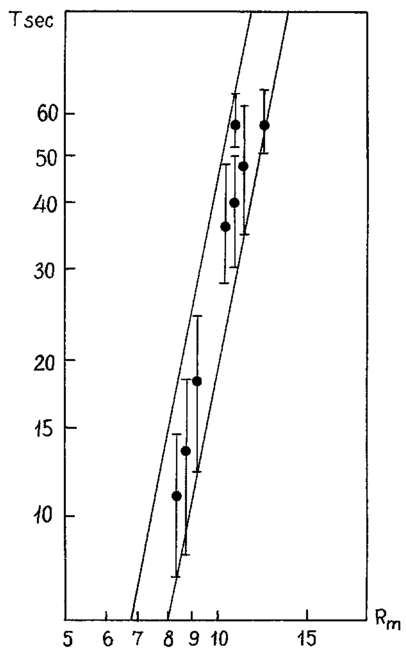

Fig. 14. The dependence of the periods of continuous pulsations from the location of the boundary of the magnetosphere on the sunlit side.

The data of Electron-2 and Electron-4 have confirmed the dependence of the periods of continuous pulsations from the degree of contraction of the magnetosphere. Sputnik Electron-2 did not cross practically the outer boundary of the magnetosphere, but the counters of particles mounted on the Sputnik gave data on the movements of the outer boundary of the radiation belt. It seems that these shiftings occur approximately simultaneously with the shiftings of the boundary of the magnetosphere. Figure 15 shows a high degree of correlation existing between the shiftings of location of the outer boundary of the radiation belt L_b and the corresponding change in the periods of continuous pulsations registered at the observatories Borok and Petropavlovsk. The calculated coefficient of correlation is in this case equal ~0.78.

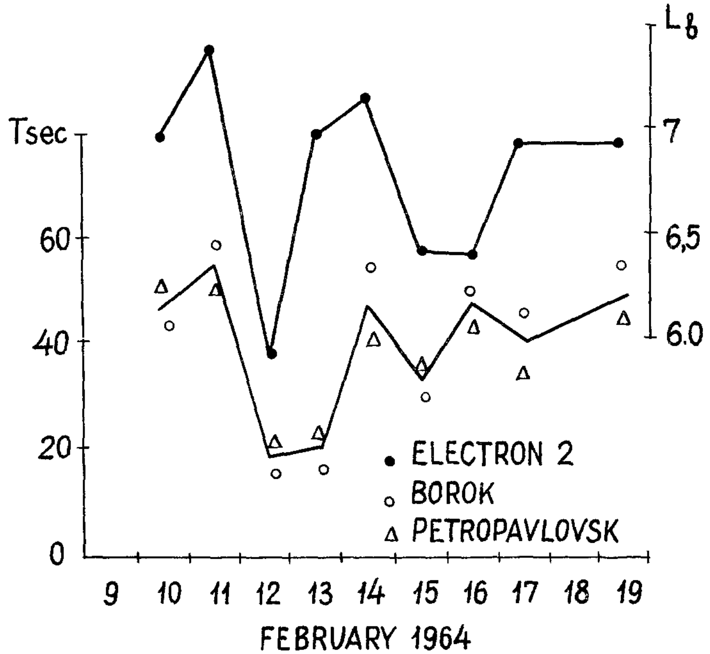

Fig. 15. Comparison of the periods of continuous pulsations with the location of outer boundary of the radiation belt. On the figure are shown the periods of micropulsations registered at the observatory Borok (light circles) and at the observatory Petropavlovsk (triangles). The distance between these two observatories is around 100° in longitude. The boundary of the radiation belt (black circles) was determined from the data of the Sputnik Electron-2.

Another series of comparisons was made utilizing the magnetic measurements on Sputnik Electron-2. Figure 16 shows the variations in time of the location of the region of space, where the measured geomagnetic field coincides with the theoretical one calculated using the first six harmonics of the Gaussian row (Dolginov *et al.*, 1965). The location of this region (the middle curve on Figure 16) changes depending on the level of the magnetic activity, that is, it can serve as a qualitative measure of magnetospheric deformation. The lower curve on Figure 16 shows the changes of micropulsation periods, and the upper one gives the hypothetical location of the boundary of the magnetosphere calculated from the data on micropulsations. In spite of the excellent correspondence of the curves, Figure 16 itself does not allow one to judge with certainty on the precision of the empirical relation between T and R_m, because the location of the above-mentioned region depends not only on the deformation of the magnetospheric boundary but also on the strength of the drift currents flowing in the outer radiation belt. Nonetheless, the combination of the above-

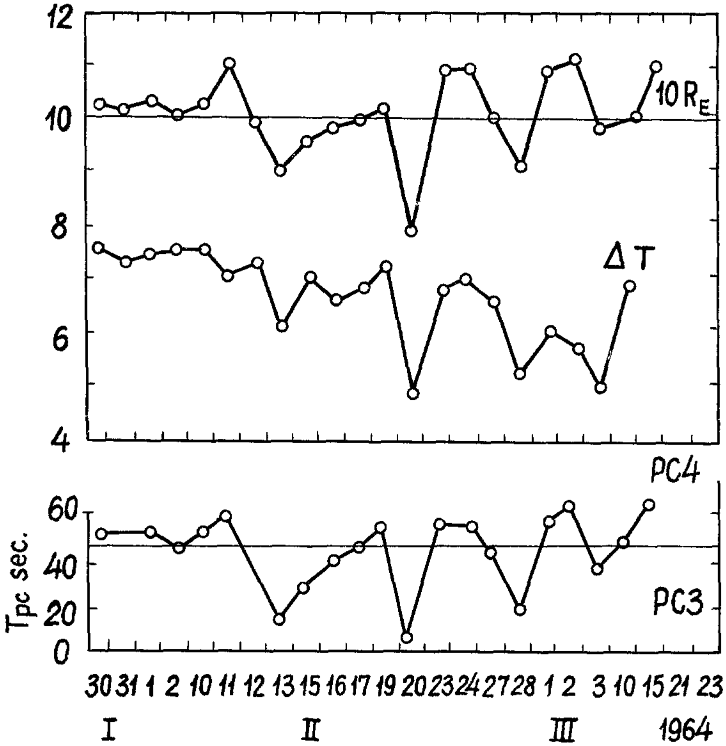

Fig. 16. Comparison of the periods of continuous micropulsations with the results of magnetic measurements inside the magnetosphere. The lower curve shows the changes in time of the periods of micropulsations registered at the observatory Borok. The curve in the middle shows the corresponding locations of the region of space, where the calculated values ΔT of the magnetic field coincide with the experimentally observed (Electron-2) ones. The upper curve shows the location of the magnetospheric boundary determined utilizing data on the periods of micropulsations.

mentioned facts allows one to state that the diagnostics of the location of the magnetospheric boundary based on micropulsation data is an extremely perspective direction of surface service of cosmic space. It is interesting to mention that, using data on micropulsations, the value of R_m was determined during the flight of Sputnik Electron-4 (which crossed the boundary of the magnetosphere) before the data of measurements on board were processed (see Table IV).

TABLE IV

Location of the Boundary of the Magnetosphere for Flight of Sputnik Electron-4

Date	Mean period Pc Borok (sec)	$R_m \sim T^{1/\nu}$ (micropulsations)	*Rm* (Electron-4)
16.VII.64	60	11	–
17.VII.64	18	9	9.6
18.VII.64	13	8.7	9.3
19.VII.64	18	9	–
20.VII.64	38	10.2	10.4
21.VII.64	60	11	10.4

Hirasawa *et al.* (1966) suggested another method of *Rm* estimation using surface data. The idea of the method consists of the following. Due to the small shift of the outer 'wall' of the resonator, a sudden change of the proper oscillations arises, which depends both on the value of the shift dR_m and on the initial value of R_m. The shift dRm is revealed also in the form of positive and negative magnetic impulses *si*. If one compares the values of *si* registered on the earth's surface with the change of the micropulsations periods, one can estimate more or less precisely the value R_m.

In consequence of the results of Mead (1964) the value of a sudden impulse registered at an equatorial observatory depends in the following way from the initial R_{m} and the final R'_{m} 'radii' of the magnetosphere

$$\Delta H \approx \left(\frac{H_1}{R_{\mathrm{m}}^3}\right)\left[\left(\frac{R_{\mathrm{m}}}{R'_{\mathrm{m}}}\right)^3 - 1\right], \tag{5}$$

where $H_1 \approx 25000\gamma$. If the dependence between the T and R_m is of the above-mentioned type (4), then for a small contraction of the magnetosphere $dR_{\mathrm{m}} = R'_{\mathrm{m}} - R_{\mathrm{m}}$ the change of the period $dT = T' - T$ will be

$$dT \approx \nu (T/R_{\mathrm{m}})\, dR, \tag{6}$$

where T and T' are the periods of micropulsations before and after the sudden impulse ($dT \ll T$). Determining dR_{m} from the relation (5)

$$dR_{\mathrm{m}} \approx -(R_{\mathrm{m}}^4/3H_1)\, dH,$$

we find

$$R_{\mathrm{m}}^3 \approx \left(\frac{3H_1}{\nu}\right)\left|\frac{d \ln T}{dH}\right|. \tag{7}$$

In the paper of Hirasawa *et al.* (1966), Equation (7) was used for the estimation of the location of the boundary of the magnetosphere utilizing the gradient of periods for Pc-5 micropulsations before and after a sudden impulse.

The index ν was estimated from the condition of the magnetic field frozen in the plasma: $\nu \approx 3/2$. The results of R_{m} measurements are shown in Figure 17. For com-

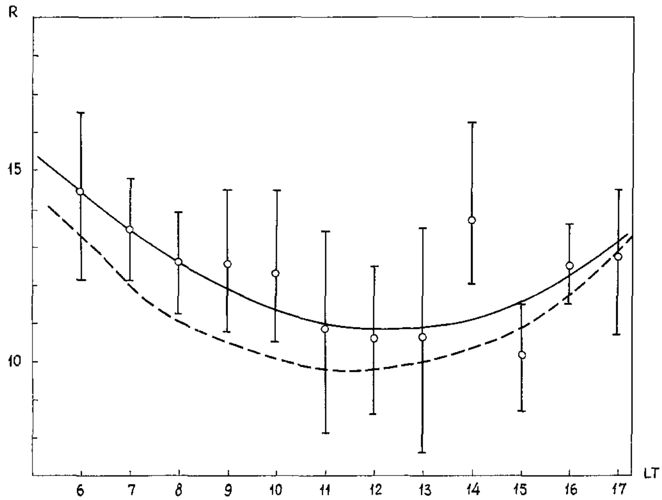

Fig. 17. Determination of the position of the boundary of the magnetosphere from the changes of Pc-5 periods during sudden impulses. The dotted line shows the average position of the boundary of the magnetosphere, determined from the magnetic measurements conducted on the satellite IMP-1.

parison the location of the magnetospheric boundary determined by IMP-1 (NESS *et al.* 1965) is also shown on the figure.

This original method does not allow, however, of conducting a continuous tracing of the boundary of the magnetosphere, because it can be used only if the *si* coincide with the series of Pc 5 which occurs relatively seldom. Moreover, the Pc 5 are observed mainly in conditions of moderate magnetic activity, therefore this method is restricted to some definite position of the boundary. Moreover, the micropulsations Pc 5 represent, most probably, the toroidal oscillations and therefore their period significantly depends not only on the R_m, but also on the latitude of intersection of the oscillating magnetic shell with the earth's surface.

Taking all this into account, it is quite natural to try to apply the idea of HIRASAWA *et al.* (1966) for the diagnostic of the location of the boundary of the magnetosphere to the micropulsations of Pc-2 – Pc-4 type, which are observed on a very large part of the earth's surface, practically every day and at any level of magnetic activity. To apply Equation (7) for this problem one must make some generalization, because the condition $\mathrm{d}T \ll T$ for micropulsations of Pc-2–4-types is as a rule not fulfilled. Excluding from (5) by means of (4) the quantity R'_{m} we get the following formula for the diagnostics:

$$R_{\mathrm{m}} \approx 10\left\{\left[\left(\frac{T}{T'}\right)^{3/\nu} - 1\right]\left(\frac{25}{\Delta H\gamma}\right)\right\}^{1/3}, \qquad (8)$$

where $\nu \approx 4.8$ for Pc-2–4-micropulsations. Using (8) together with (4) one can try to determine the value of the parameter ν exclusively from surface data T, T', and ΔH.

In the paper of TROITSKAYA *et al.* (1967b) the formula (8) is utilized for the cases of change of the Pc-2–4-regime in the moments of sudden impulses. Figure 18 shows the values of R_m obtained in this way and the corresponding values of period T. The inclined line on the plot shows the dependence $T \sim R_m^{4.8}$. It is seen that the experimental points correspond sufficiently well to this dependence.

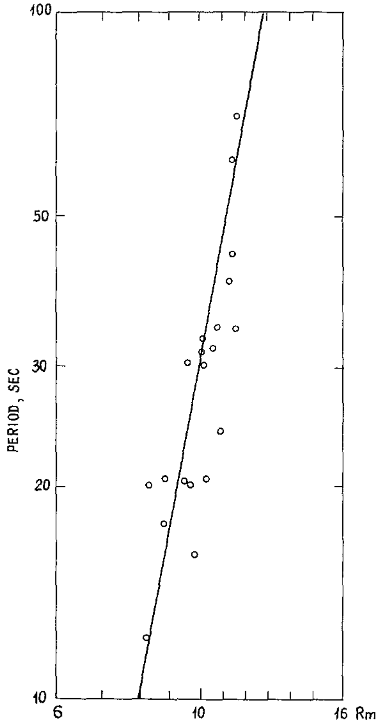

Fig. 18. Dependence of the periods of Pc-2–Pc-4 micropulsations on the location of the boundary of the magnetosphere. The plot is built on data showing the micropulsation period changes during sudden contractions or expansions of the magnetosphere (sudden impulses *si*).

3.2. The boundary of the closed field lines on the night side

The magnetosphere is strongly asymmetrical in respect of the plane of the morning and the evening meridians. The outer field lines are swept by the solar wind into the magnetospheric tail and remain unclosed on distances equal (at least) to several tens of earth radii (Ness, 1967). The axis of the tail evidently does not take part in the daily rotation of the earth. On the other hand the closed inner field lines are rotating with the earth.

The asymmetry of the magnetosphere is revealed not only in the form of its outer surface, but also in the asymmetry of the form of the boundary between the closed and opened field lines. So, if on the sunlit side this boundary intersects the surface of the earth on the geomagnetic latitude $\phi_{day} \approx 78°$, on the night side the boundary of intersection is located much closer to the equator $\phi_{\text{night}} \approx 67.5$ (Figure 19). In other words, on the night side the last closed field lines are located nearer to the earth's surface than on the day side. The question of the location and shifting of the boundary of the closed lines has a principal significance for the theory of the radiation belts and for the general theory of the dynamic of the magnetosphere.

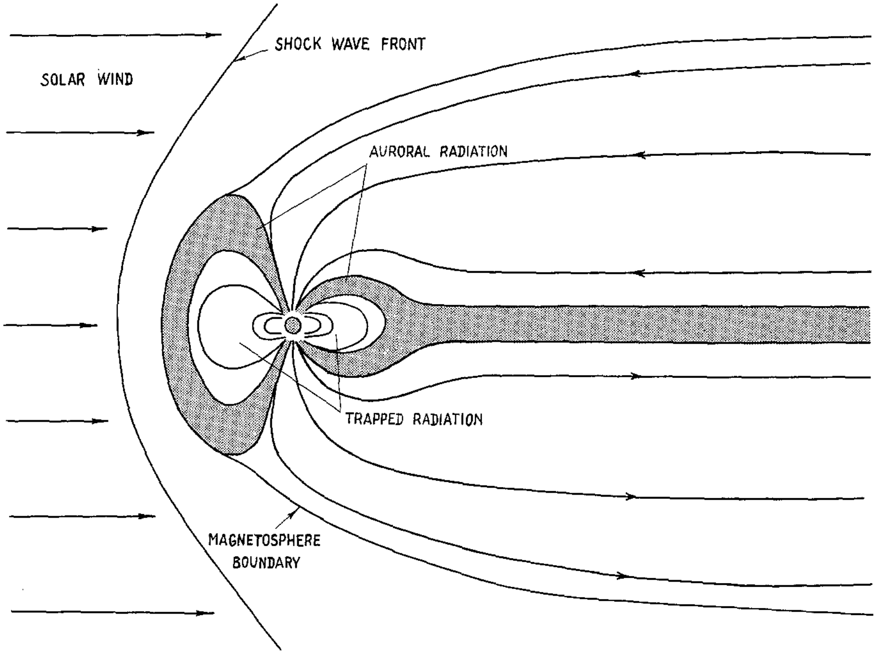

Fig. 19. The scheme of meridional section of the magnetosphere (O'BRIEN, 1967).

On the day side, the boundary of the last closed field lines practically coincides with the boundary of the magnetosphere R_m. The methods of its determination were described in the preceding section. In spite of the definite correlation which exists between the location of the boundary of closed field lines on the night side – ϕ_{night}, and the value R_m, it was felt that some independent source of surface information on this parameter would be desirable. Nature has provided a very effective tool of investigation of this parameter of the magnetosphere – namely the aurora.

The momentary picture of the aurora represents an oval, the shape of which is very close to the line of intersection with the earth's surface of the boundary shell dividing the closed field lines of the magnetosphere from the field lines of the tail (CHOROCHEVA, 1962; FELDSHTEIN, 1966; KRASSOVSKY, 1967). On the night side, the oval zone is located at a distance around 22° from the geomagnetic pole. With the augmentation of the magnetic activity the oval is shifted towards the equator. If, on the other hand, the activity diminishes, the oval is contracted around the pole. The tracing of these movements of the auroral oval require observations on a world wide network of stations equipped with rather complicated devices. Moreover, the processing of the obtained films takes a significant amount of time.

At the same time, many of the general properties of the dynamical shifting of the night boundary of the inner magnetosphere may be quantitatively investigated by the micropulsations method. Most typical for the night hemisphere are the pulsation trains Pi 2 (pt), which occur mainly around the midnight hours. The generation of pulsation trains is due to the processes originating in the tail, but their period is determined by the dimensions of the closed cavity on the night side of the magnetosphere. The fact that the period of pulsation train is connected in some way with the dimensions of the magnetosphere is reflected in Figure 20, where the dependence of $T_{\mathrm{Pi}\ 2}$ from K_p index is shown for different epochs of solar cycle (Troitskaya, 1967).

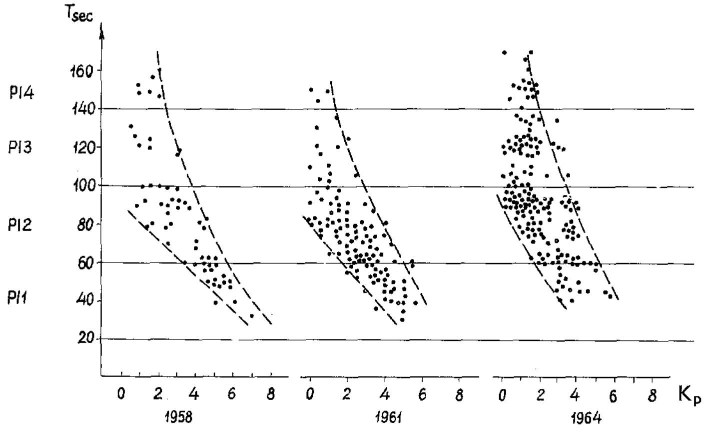

Fig. 20. The dependence of the periods of pulsation trains from the level of the magnetic activity in different years of the solar cycle.

The connection of Pt with the dimensions of the inner magnetosphere on the night side is more clearly illustrated in Figure 21. This figure shows the dependence of periods of pulsation trains from latitude ϕ' of the Southern border of the aurora zone. This curve was plotted using the empirical relationships between ϕ' and K_p, and the dependence of $T_{\mathrm{Pi}\ 2}$ from K_p (Schepetnov, 1967; see also Raspopov, 1967; Rostoker, 1967).

The pulsation trains are observed simultaneously and with the same periods practically on the whole night hemisphere. Therefore, for the diagnostics of the location and the dynamical shifting of the boundary of the closed lines, it is sufficient to have uninterrupted records of micropulsations on two or three widely apart on longitude observatories only. It is necessary to note, that the location of the southern border of the auroral zone does not coincide, generally speaking, with the boundary of closed lines on the night side (O'Brien, 1967). Taking into account, moreover, the manner of obtaining Figure 21, it is necessary to stress that the plot presents only the

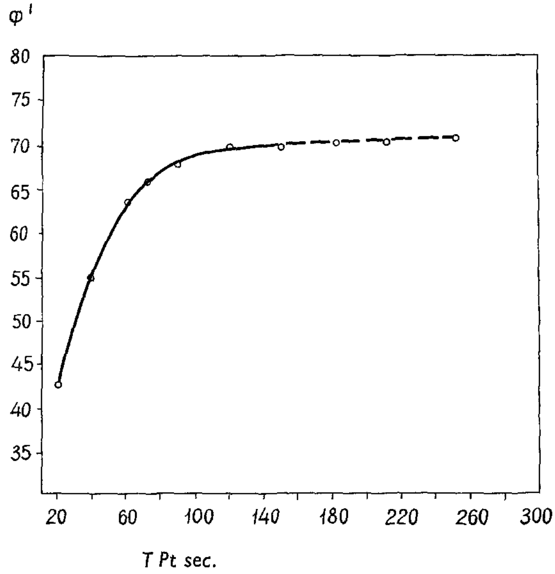

Fig. 21. Comparison of the periods of pulsation trains with the location of the Southern boundary of the auroral zone.

illustration of the possibilities of the diagnostics of the night magnetosphere using micropulsations data. Further investigations are necessary for the solution of the diagnostics, and especially individual comparisons of the location of the oval zone of aurora or of the outer zone of trapped radiation with the periods of pulsation trains.

3.3. Estimation of the properties of the interplanetary space

The boundary of the magnetosphere is formed under the influence of solar corpuscular streams propagating in the interplanetary space. Therefore, the properties of micropulsations used for tracing the location and dynamical shifting of boundary of the magnetosphere comprise also, in some indirect form, information on the properties of interplanetary space surrounding the earth.

This conception was the basic initial point in some interesting statistical comparisons (Bolshakova, 1965d, 1966; Troitskaya *et al.*, 1966; Troitskaya, 1967). It was, for instance, established that the Pc-4 micropulsations are generated by the 'quiet' solar wind sweeping around the magnetosphere. The Pc-3 pulsations are due to the recurrent streams from the disturbed regions of the sun. The Pc-2 pulsations are connected with sporadic streams responsible usually for geomagnetic storms with sudden commencement. The results of comparison of the micropulsation periods with the velocities of corpuscular streams obtained by direct measurements are shown in Figure 22 (Troitskaya, 1967). It is interesting to note the inverse dependence of the period of oscillations from the velocities of the streams. Valuable information on the dynamical changes in the interplanetary space can also be drawn from the relatively quick changes in time of the periods of micropulsations – from the so-called sliding

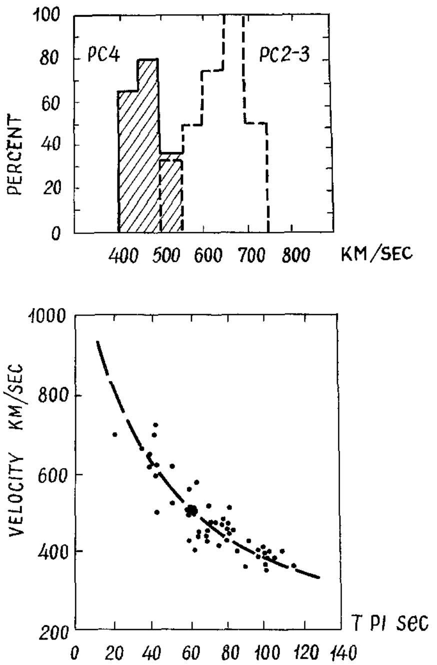

Fig. 22. Comparison of the periods of micropulsations of Pc-2–Pc-4 types with the data on the mean velocities of the solar wind. The figure distinctly shows the inverse dependence of the periods of pulsations from the velocity of the solar wind.

tones (KITAMURA, 1964). Without going into further detail of this direction of research which only recently has begun to develop, let us stress the following circumstances. The location, the form and the velocity of the shifting of the boundaries of the magnetosphere in a given moment of time depend not only on the properties of the interplanetary space at that moment, but also from the preceding history of the interaction of the magnetosphere with the solar wind. For instance, at the end of a strong magnetic disturbance there arise different effects of afteraction – augmented temperature of the magnetosphere, remainders of the ring current, etc., which in principle may determine the character of relaxation of the surface of the magnetosphere to its initial state, and in this way influence the character of micropulsations periods dependence on time.

4.0. Diagnostics of Concentration of Cold Plasma

4.1. INTRODUCTORY REMARKS

The distribution of plasma in the space surrounding the earth is one of the most interesting questions of cosmic geophysics. Its investigation has, first of all, a great scientific interest because the character of development of the magnetic storms, the structure of the radiation belts, etc., depends on the distribution of the plasma and of the magnetic field. It is necessary to know the distribution of the plasma concentration in solving some practical problems, for instance, in projecting the lines of cosmic radiocommunications.

The experimental investigation of plasma concentration above the maximum of F_2 layer was begun practically only in 1953 by means of whistlers (Storey). After that, a number of theoretical calculations were made based on the assumption that a diffusion equilibrium takes place in the exosphere, that is, the distribution of plasma is regulated by the ambipolar diffusion in the gravitational and in the magnetic fields of the rotating planet (ANGERAMI and THOMAS, 1964). Further observations of whistlers and the experiments on satellites showed, however, that the distribution of plasma is formed as a result of complicated processes, which could hardly be taken into account theoretically. It follows, for instance, from such a fact that the discovery of the sharp bend or 'knee' on the vertical profile of concentration in the region of altitudes around 20000 km (CARPENTER, 1966) was quite unexpected.

The observations of whistlers continue to play an important role in these investigations. In recent years some perspectives of utilizing micropulsations of geomagnetic field for the diagnostics of plasma concentration have been discovered ('hydromagnetic sounding'). Most informative in this respect are the micropulsations of Pc-1 and Pc-5 types.

4.2. DIAGNOSTICS OF PLASMA CONCENTRATION FROM THE SPECTRUM OF THE TORSIONAL OSCILLATIONS OF THE MAGNETOSPHERE

The spectrum of proper oscillations of the magnetosphere depends on the distribution in space of plasma density and of the intensity of the magnetic field. Because the structure of the geomagnetic field is known relatively well, the results of observations of the spectrum of the proper frequencies may be used for the estimation of the plasma density at great heights. In this respect the torsional oscillations present great interest. The different parts of its spectrum are formed in different regions of the magnetosphere. This, in principle, opens the possibility to restore to the known spectrum not only the integral but also the local parameters of plasma distribution. As a basic equation that of the torsional oscillations of the magnetosphere (40) will be taken (see Appendices). If the equation of the field line has the form $v = v(r, r_0)$ where r_0 is the distance between the centre of the earth and the summit of the field line (Figure 23), then, by substituting the variables

$$\Psi = h_\varphi r \sin v, \qquad F_1 = (r \sin v)^2 F, \qquad F_2 = (r \sin v)^{-2} F,$$
$$F = H\left[1 + (r\, \mathrm{d}v/\mathrm{d}r)^2\right]^{-1/2},$$

the equation of torsional oscillations is transformed as following:

$$-\frac{F_1}{4\pi}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{F_2}{\varrho}\right)\frac{\mathrm{d}\Psi}{\mathrm{d}r} = \omega^2 \Psi, \tag{9}$$

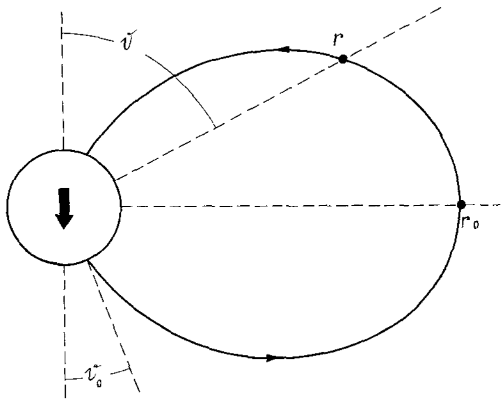

Fig. 23. The line of the geomagnetic field (schematic presentation).

Here $\varrho = Nm_i$ is the density of plasma and represents the chosen harmonic dependence of disturbances on time. The boundary condition is given on the earth's surface, and has the following form:

$$\mathrm{d}\Psi/\mathrm{d}r|_{r=r_e} = 0, \tag{10}$$

where r_e is the earth radius.

Let us consider the inverse problem of Sturm-Liuville for the torsional oscillations: to find ϱ from the experimentally defined spectrum of proper frequencies ω. It is suggested that the magnetic field is known, otherwise the solution of the problem is evidently undetermined.

Let us assume that, in the frames of the magnetosphere the geomagnetic field is potential, and let us conserve in the Gaussian row only two members describing the dipole field and the homogeneous field parallel to the axis of the dipole

$$H_r = \left\{2H_0\left(\frac{r_e}{r}\right)^3 - H_1\right\}\cos v, \qquad H_v = \left\{H_0\left(\frac{r_e}{r}\right)^3 + H_1\right\}\sin v.$$

In this case, the approximate expression for F may be written in the form

$$F^{-1}(r, r_0) = \frac{\sqrt{r_0}}{2H_0}\frac{(r/r_e)^3}{\sqrt{r_0 - r}}\{1 + \Phi(r, r_0)\},$$
$$\Phi(r, r_0) = \left(\frac{r_0}{r_m}\right)^3\left[\left(\frac{r}{r_0}\right)^3 - \frac{r(r_0^3 - r^3)}{2r_0^3(r_0 - r)}\right]. \tag{11}$$

Φ is a small correction, taking into account the non-dipole character of the magnetic field, $r_m = r_e\sqrt[3]{2H_0/H_1}$ is 'radius' of the magnetosphere. In the deduction of (11) it was suggested that the quantity $(r_0/r_m)^3$ is small compared to the unity, and the square members in respect of $(r_0/r_m)^3$ are neglected.

Due to the specification of the posed problem we cannot utilize the strict solutions of Equation (9), which can be built for some of the concrete forms of the function $\varrho(r)$, because the dependence of ϱ from r itself must be found from the known spectrum. Therefore, in the endeavour of the analytical solution of the problem, it is practically inevitable to utilize the approximate methods. In the W.K.B. approximation the proper values ω_n of Equation (9) having the boundary condition (10) are determined by the relation

$$\int_{r_e}^{r_0} \frac{r^3 \sqrt{\varrho(r)}\,\mathrm{d}r}{\sqrt{r_0 - r}} \{1 + \Phi(r, r_0)\} = \frac{r_e^3 H_0 n \sqrt{\pi}}{2 r_0^{1/2} \omega_n(r_0)}, \tag{12}$$

where $n = 1, 2, \ldots$ is the number of the harmonic (GUL'ELMI, 1966a). We are interested in the question how to restore the form of the function $\varrho(r)$ from the dependence $\omega_n(r_0)$, which, it is suggested, is known from the experiment. From the mathematical point of view, the problem consists in solving the integral Equation (12), in which $\varrho(r)$ is considered as the unknown function. Denoting the right part of (12) as $G(r_0)$ and adopting $Q(r) = r^3 \sqrt{\varrho(r)}$ we shall write (12) in a slightly different form

$$G(r_0) = \int_{r_e}^{r_0} \frac{Q(r)\,\mathrm{d}r}{\sqrt{r_0 - r}} \{1 + \Phi(r, r_0)\}. \tag{13}$$

This expression represents the integral equation of Abel. The singularity of its kernel at $r = r_0$ is removed in the following way.

Multiplying the left and the right parts of (13) on $1/\sqrt{\alpha - r_0}$ we shall integrate on $\mathrm{d}r_0$ in the interval from r_e to α and shall change the order of integration in the right part:

$$\int_{r_e}^{\alpha} \frac{G(r_0)\,\mathrm{d}r_0}{\sqrt{\alpha - r_0}} = \int_{r_e}^{\alpha} Q(r)\,\mathrm{d}r \int_{r}^{\alpha} \frac{[1 + \Phi(r, r_0)]\,\mathrm{d}r_0}{\sqrt{(\alpha - r_0)(r_0 - r)}}.$$

Introducing a new variable $z = (r_0 - r)/(\alpha - r)$ we obtain an integral equation

$$\int_{r_e}^{\alpha} K(\alpha, r)\, Q(r)\,\mathrm{d}r = \int_{r_e}^{\alpha} \frac{G(r_0)\,\mathrm{d}r_0}{\sqrt{\alpha - r_0}} \tag{14}$$

with the kernel

$$K(\alpha, r) = \int_0^1 \frac{[1 + \Phi(\alpha, r, z)]}{\sqrt{z(1 - z)}}\,\mathrm{d}z$$

without singularities.

The kernel, the left part of Equation (14) and its derivative are continuous, and the function $Q(r)$ is limited and can be integrated. Therefore, Equation (14) is equivalent to another integral equation, which can be obtained by differentiating both its parts.

$$Q(\alpha) + \int_{r_e}^{\alpha} \frac{K'_\alpha(\alpha, r)}{K(\alpha, \alpha)} Q(r)\, \mathrm{d}r = \frac{1}{K(\alpha, \alpha)} \frac{\mathrm{d}}{\mathrm{d}\alpha} \int_{r_e}^{\alpha} \frac{G(r_0)\, \mathrm{d}r_0}{\sqrt{\alpha - r_0}}.$$

We shall find the solution of the last equation by the method of iterations:

$$Q_1(\alpha) = \frac{1}{K(\alpha, \alpha)} \frac{\mathrm{d}}{\mathrm{d}\alpha} \int_{r_e}^{\alpha} \frac{G(r_0)\, \mathrm{d}r_0}{\sqrt{\alpha - r_0}},$$

$$Q_2(\alpha) = Q_1(\alpha) - \int_{r_e}^{\alpha} \frac{K'_\alpha(\alpha, r)}{K(\alpha, \alpha)} Q_1(r)\, \mathrm{d}r,$$

. . . .

The subintegral function in the solution of the first approximation has a singularity when $r_0 = \alpha$. Therefore, before differentiating the integral, let us make the following:

$$\int_{r_e}^{\alpha} \frac{G(r_0)\, \mathrm{d}r_0}{\sqrt{\alpha - r_0}} = -2 \int_{r_e}^{\alpha} G(r_0)\, \mathrm{d}\sqrt{\alpha - r_0} =$$

$$= 2G(r_e)\sqrt{\alpha - r_e} + 2 \int_{r_e}^{\alpha} \sqrt{\alpha - r_0} \left(\frac{\mathrm{d}G}{\mathrm{d}r_0}\right) \mathrm{d}r_0 .$$

Now, going back to the initial designations, and taking into account the equality $T_n(r_0 = r_e) = 0$ where $T_n = 2\pi/\omega_n$ is the period of the harmonic with the number n, we get the first approximation of the formula of diagnostics of plasma concentration (GUL'ELMI, 1965, 1967c)

$$\sqrt{N(r)} = \frac{H_0 n}{4\pi^{3/2} m_i^{1/2}} \left(\frac{r_e}{r}\right)^3 \left\{1 + \frac{1}{2}\left(\frac{r}{r_m}\right)^3\right\} \int_{r_e}^{r} \left\{\frac{\mathrm{d}T_n}{\mathrm{d}r_0} - \frac{T_n}{2r_0}\right\} \frac{\mathrm{d}r_0}{\sqrt{r - r_0}}. \qquad (15)$$

Because, as it can be easily checked, in the dipole field ($r_m^{-1} = 0$) the first approximation is the correct solution of the problem, and the correction due to the non-dipole character of the field is small, even in the first approximation, it seems meaningless to continue the process of iteration. The fact that in the adopted approximation the problem of diagnostics consists in the solution of the integral equation of Abel is, of course, a coincidence from the physical point of view, but it simplifies greatly the mathematical form of the theory.

For the calculation of the plasma concentration N on a distance r from the centre of the earth, it is necessary to know the form of the function $T_n(r_0)$ in the interval from r_e to r. In consequence, with the distribution of Pc 5 on the earth's surface obtained from the observations on a net of existing stations located in different latitudes, the form of the function $T_{n=1}(r_0)$ is known only in the interval $r_0 \sim (3.5-8) r_e$ (OHL, 1962, 1963, 1964) (in the dipole approximation of the field $r_0 = r_e \cos^2 \phi_0$, where ϕ_0 is the latitude of the point of observation). But, up to the altitudes of ≈ 5000 km the distribution of concentration is well known from the satellite and radar measurements. Therefore, the spectrum $T(r_0)$ in the interval $r_0 \sim (1-2) r_e$ can be calculated theoretically, and in the interval $r_0 \sim (2-3.5)\, r_e$, to draw the interpolating curve. After that Equation (15) allows one to calculate the vertical profile of plasma concentration in the plane of geomagnetic equator.

The described method of diagnostics allows one to find the equatorial profile of concentration $N(r)$ without any a priori suggestions on its form. This aim was obtained due to a number of simplifications the strongest of which consisted in using W.K.B. solutions of Equation (9). One could try to build a sequence of approximations $\Psi_1, \Psi_2, \ldots$ choosing as an initial solution $\Psi_1 = \Psi$(W.K.B.). But, even taking into account the time this procedure would take, the convergence of the lines in this case is doubtful.

The correct numerical calculations of the spectrum of torsional oscillations, fulfilled for some definite models of the exosphere, coincide in general sufficiently well with the calculations in the W.K.B. approximation. Nevertheless, in solving the inverse problem in W.K.B. approximation a summing up of the errors is possible which would deviate the calculated profile of concentration from the true one. Let us try to estimate the sign of this deviation using the extremal properties of the eigenvalues and of the eigenfunctions. It is not difficult to prove that Equation (9) is the Euler–Lagrange equation for the functional

$$I[\Psi] = \int_{r_e}^{r_0} \frac{F_2}{\varrho} \Psi'^2 \, \mathrm{d}r .$$

Therefore, the problem on the spectrum of torsional oscillations is equivalent to the variation problem

$$I[\Psi] = \mathrm{extr},$$

with the additional condition

$$\int_{r_e}^{r_0} \frac{\Psi^2}{F_1} = \mathrm{const}.$$

where the constant is determined by the condition of normalization. If Ψ is chosen as the precise solution of the equation for torsional oscillations, then it leads to the minimal value $I_{\min} = \omega^2$. Any other function, for instance Ψ (W.K.B.) which satisfies the boundary conditions, leads to the greater value of ω^2. In obtaining the formula of the diagnostics (15), the W.K.B. approximation was applied. On the other hand, in its practical use the 'true' values of ω^2 are taken. If we take into account that N is roughly proportional to ω^{-2}, then it becomes evident, that the values of the concentration calculated in this way will be greater than the true ones. In other words, the method of the diagnostics described above allows one to make the higher estimation of the plasma concentration in the exosphere.

Of course, the inverse problem may be solved also by numerical methods. Usually a solution of the corresponding direct problem for a given hypothesis on the structure of the medium is looked for. A suitable approximation of the geomagnetic field is chosen; the distribution of plasma concentration is described by some set of the probing functions, and the calculation of the spectrum of torsional oscillations is carried out. Further on, the parameters of the model are chosen in such a way that the theoretical and the experimental spectra approach each other as close as possible.

Practically, this procedure was realized for the first time by OBAYASHI (1958). The vertical profile of plasma density was found out in the class of functions of the type

$$\varrho(r) = \alpha\, e^{\beta/r},$$

where α and β are the parameters which had to be determined. But the spectrum of torsional oscillations was calculated in the W.K.B. approximation. The numerical calculation of the spectrum for the aims of diagnostics was fulfilled in the works of KITAMURA (1965) and JACOBS and KITAMURA (1966). Some preliminary results of determination of plasma concentration in the exosphere, using the observation of torsional oscillations, are shown in Figure 24.

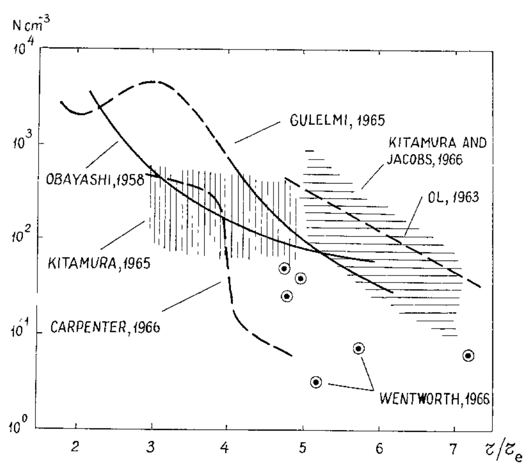

Fig. 24. The preliminary results of the hydromagnetic sounding of the plasma concentration on high altitudes. The vertical profiles of the plasma concentration in the plane of the geomagnetic equator were built by different methods and on the basis of different data referring to different levels of the magnetic activity. KITAMURA (1965) has made the estimates of the concentration on distances $r \approx 3r_e$ and $r \approx 5r_e$, and JACOBS and KITAMURA (1966) on distances $r \approx 5r_e$ and $r \approx 7r_e$. On this plot the regions of intermittent r are hatched arbitrarily. For comparison is shown also the 'knee' obtained from the observations of whistlers.

4.3. Diagnostics of plasma concentration from the dispersion of pearls

The method of diagnostics of plasma concentrations from the dispersion of pearls is quite similar to the method of diagnostics from dispersion of whistlers. In both cases, it is suggested that the electromagnetic signals are propagating along the lines of the geomagnetic field. The dependence of the time of the group delay from the frequency (dispersion) is determined by the expression

$$\tau(\omega) = \frac{1}{c} \int_{(l)} n_g(\omega, l)\, dl, \tag{16}$$

in which $n_g = \partial\omega n/\partial\omega$ is the group index of refraction, dl is the element of arc of the trajectory. The diagnostics of concentration is based on the analysis of the dynamical spectra $\tau(\omega)$ of registered signals. In the diagnostics based on whistlers in (16) the index of refraction for the electron-cyclotron waves (right-hand polarization) is used. If the diagnostics is conducted on the dispersion of pearls, then, in (16) one has to substitute the index of refraction for the iono-cyclotronic waves (left-hand polarization).

In plasma consisting of electrons and ions of one type, for the case of longitudinal propagation we have (see Appendix 2)

$$n = \frac{\omega_{0i}}{[(\Omega_i - \omega)\, \Omega_i]^{1/2}}, \tag{17}$$

$$n_g = \frac{\omega_{0i}(\Omega_i - \omega/2)}{\Omega_i^{1/2}(\Omega_i - \omega)^{3/2}}, \tag{18}$$

where Ω_i is the gyrofrequency of the ions, and $\omega_{0i} = \sqrt{4\pi e^2 N/m_i}$.

Postulating the fact that all the spectral components of pearls propagate along one and the same trajectory, and substituting (18) into (16) one can represent the time of the group delay in the form of a degree row (Watanabe, 1965):

$$\tau(\omega) = \sum_{n=0}^{\infty} \tau_n \omega^n,$$
$$\tau_n = \frac{(4\pi)^{1/2} m_i^{n+1/2}}{(e/c)^n} \frac{(n+1)(2n)!}{(2^n n!)^2} \int_{(l)} \frac{N^{1/2}}{H^{n+1}}\, dl. \tag{19}$$

If we now represent the observed period of pearls repetition in the form of a power series on the degrees of frequency ω, then in principle one can determine the coefficients τ_n, and then, also, the distribution of the plasma concentration $N(l)$ along the trajectory of the ray. Practically, the described procedure cannot be fulfilled in a whole, because this would require the determination of the infinite number of coefficients τ_n. If, however, we take into account that the dominant contribution in the delay $\tau(\omega)$ comes from the parts of the trajectory adjacent to the equator, then we can solve a more modest problem of the determination of the concentration in the apogee of the signals trajectory. To solve this problem in the works of DOWDEN and EMERY (1965); WATANABE (1965); WENTWORTH (1966); LIEMOHN *et al.* (1967) a simple graphical method is suggested, which consists essentially of the following.

Let us use in (16) – (18) dimensionless variables $\tau(\omega)/\tau_0$ and ω/Ω_i; where τ is the time of group delay of Alfvén wave packet ($\omega \to 0$), and Ω_i is the value of gyrofrequency of the protons in the summit of the trajectory of the signal. Then one can conduct the calculations of the time of the group delay $\tau(\omega)$ for a broad class of the models of the magnetosphere and prove, in this way, that the normalized dispersion curve

$$\tau(\omega)/\tau_0 = \Lambda(\omega/\Omega_i) \qquad (20)$$

is 'universal' in that it means that its shape very weakly depends on the latitude of intersection of the trajectory with the earth's surface and on the character of plasma distribution along the trajectory. Figure 25 taken from the paper of WATANABE (1965) represents the function $\Lambda(\omega/\Omega_i)$ for a typical trajectory $\phi_0 = 65°$ of a dipole magnetic field and the so-called gyrofrequency model of plasma concentration distribution $N(l) = \text{Const} \times H^{\nu}(l)$, $\nu = 1$. The curves $\Lambda(\omega/\Omega_i)$ for other values of ϕ_0 and ν do not significantly differ from that given in Figure 25.

The method of determination of τ_0 and Ω_i by means of the normalized dispersion curve from two pairs of experimental values of τ_1, ω_1 and τ_2, ω_2 taken from the spectrogrammes of the pearls is clear from the Figure 25. The value Ω_i gives immedi-

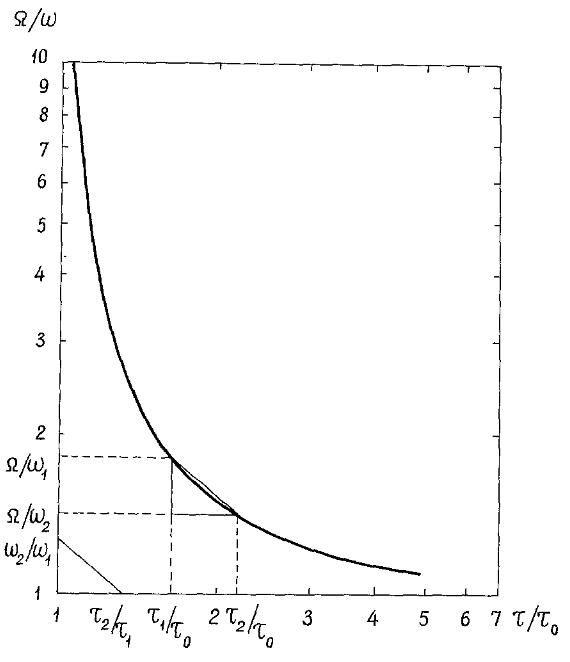

Fig. 25. The normalized dispersion curve. The plot allows from two pairs of measured values τ and ω, the determination of the gyrofrequency of protons Ω_i in the summit of the trajectory, as well as the period of repetition τ_0.

ately the ϕ_0 and the parameter of the trajectory $L = 1/\cos^2\phi_0$. The value τ_0 allows using the formula

$$N = \left[\frac{\tau_0 \Omega_i}{L^4 I(\Phi_0, \nu)}\right]^2 \frac{c^2 m_i}{64\pi e^2 r_e^2}$$

to estimate the plasma concentration on the distance L in the equatorial plane. (The function $I(\phi_0, \nu)$ is tabulated in Table V; WATANABE, 1965.)

TABLE V

The Values of the Function $I(\phi_0, \nu)$

	ν		
ϕ_0 degrees	0.0	1.0	2.0
45°	0.4470	0.5867	0.8568
50°	0.4527	0.6099	0.9524
55°	0.4557	0.6256	1.0426
60°	0.4566	0.6363	1.1255
65°	0.4570	0.6408	1.1993
70°	0.4571	0.6434	1.2623
75°	0.4571	0.6444	1.3129
80°	0.4571	0.6447	1.3500
85°	0.4571	0.6448	1.3627

The inaccuracy of $\tau_{1,2}$ and $\omega_{1,2}$ measurements and the ambiguity of the index ν value lead to the relative inaccuracy of L measurement to the order of 3%. The plasma concentration is determined by this method with precision up to the factor 2 – 4. Taking into account, however, the great scatter of the values of concentration, obtained nowadays by other methods, we can regard this precision as sufficient.

Similarly, but in some other form, the problem of the diagnostics is solved in the paper of WENTWORTH (1966). The basic attention there is given to the account of the real structure of the geomagnetic field.

The results of the diagnostic of plasma concentration from the dispersion of pearls are given in Figure 22 (circles). In spite of the fact that these results correspond rather well with the conception of the existence of the 'knee' on the vertical profile of plasma concentration in the exosphere, they have to be considered as the preliminary ones before clearing out the following important circumstance. In consequence with the results of the diagnostics investigations, the ratio of the proper frequency of pearls to the gyrofrequency of protons in the summit of the trajectory turned out to be close to ≈ 0.5. If so, the frequency ω is higher than the gyrofrequency Ω_{He^+} of the helium ions in the summit of the trajectory. But if the plasma contains some amount of helium ions, then additional pole and zero of the square of the refraction index appear (see Appendix 2). This fact is illustrated in Figure 26 which shows the variation of n^2 along the field line intersecting the earth's surface at the latitude $\phi_0 = 63.5°$ (GUL'ELMI 1966c). The curves are built for the case of small amounts of He^+ ions

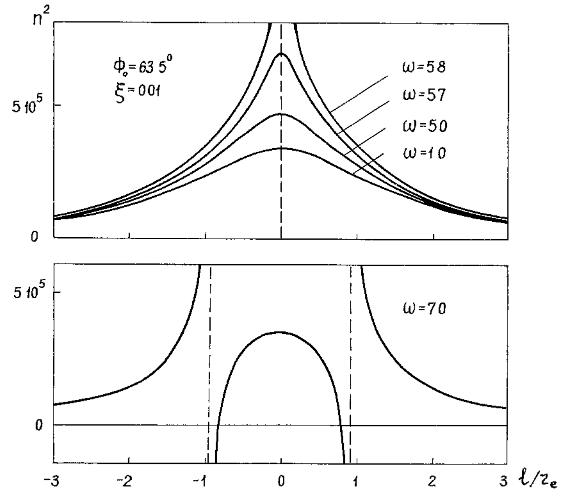

Fig. 26. The square of the refraction index for iono-cyclotronic waves in the magnetosphere. The coordinate l is counted from the plane of the magnetic equator along the field line intersecting the earth's surface on the latitude $\phi_0 = 63.5°$. In the upper figure the frequency of the wave is less than the gyrofrequency of He^+ ions in the summit of the trajectory. In the lower figure the wave frequency is greater than the gyrofrequency of helium ions but less than the gyrofrequency of protons. In the second case the signal propagating from one conjugate point to the other must intersect two opacity bands.

in the exosphere. On the upper figure, the wave frequency is less than the gyrofrequency of helium in the summit of the trajectory ($l=0$). On the lower figure the ratio of frequencies is inverse. In the second case, the signal propagating from one hemisphere to the other must cross two opaque bands located symmetrically in respect to equatorial plane. To estimate the damping of amplitudes which inevitably take place in this case, the tunnel factor of Badden $D=e^{-\pi\beta}$ can be used. Here $\beta=\omega/V_a|l'-l''|$ is the width of the opacity in units of Alfvén wavelengths, l' – the coordinate of the pole of n^2, l'' – the coordinate of the zero of n^2 (see for instance STIX, 1962). If the opaque bands are located far enough from the equatorial plane, and the relative concentration of helium ions $\xi \ll 1$, then the value of damping in decibels is approximately equal*:

$$D_{db} = 20 \log e^{\pi\beta} \approx 5.4 \times 10^{11} [f^{2/3} \xi / V_a] .$$

If $f \approx 1$ Hz, $V_a \approx 10^8$ cm/sec and $\xi \approx 10^{-2}$ (TAYLOR *et al.*, 1965), then the damping is very great: $D \approx 54$ db. Hence, either the frequency of pearls does not exceed the gyrofrequency of helium ions, in the summit of the trajectory, or the value of ξ on great altitudes in the periods of observation of pearls is at least one order of magnitude less than it is given in the paper of TAYLOR *et al.* (1965).

For the solution of this alternative it is necessary to have a more reliable method of determining of parameter L of the pearls trajectory. One of the possible methods of determination of L will be described in the following paragraphs.

* The influence of helium ions on the propagation of pearls was independently analysed in the papers of GUL'ELMI (1966c) and DOWDEN (1966).

Concluding this part we shall say some words on proton whistlers discovered by Injun-3 and Allouette-I at the height of about 1000 km in the range of 500 Hz (GURNETT *et al.*, 1965). Similarly to the atmospheric whistlers, the proton whistlers are generated by lightnings and similarly to pearls, they propagate up the field lines as iono-cyclotron waves. The time of their group delay is described by Equations (16) – (18). But the integration in (16) must be conducted only on a short path ending in the place of satellite location. In the paper of GURNETT and SHAWHAN (1966) a simple asymptotic expression for the group delay of proton whistlers is found for $\omega \to \Omega_i$:

$$\tau(\omega) \sim \frac{\text{const}}{\sqrt{\Delta\omega}},$$

where $\Delta\omega \equiv \Omega_i - \omega$, and Ω_i is the gyrofrequency of protons in the vicinity of the satellite. The coefficient of proportionality depends on the concentration of protons in the plasma surrounding the satellite, and it can be found from character of dispersion of the registered signal (BEGHIN, GENDRIN *et al.*, 1966; GURNETT and SHAWHAN, 1966). This method of diagnostics of plasma concentration has one peculiarity. The proton whistlers propagate along the field lines upwards, but do not reach the opposite end of the line, and consequently can be registered only in cosmic space, that is, on a moving object. However, in the moving relative to the observer, plasma, the character of dispersion of iono-cyclotron waves changes (Appendix 2) and the asymptomic expression for the time of the group delay will have the following form (GUL'ELMI, 1967b)

$$\tau(\omega) \sim \frac{\text{const}}{\sqrt{\Delta\omega}} \left\{1 + \frac{U_z}{2V_a}\left[\frac{\Omega_i}{\Delta\omega}\right]^{3/2}\right\}, \tag{21}$$

where v_z is the projection of velocity of the satellite on the trajectory of the signal.

Due to the Landau damping, the value $\Delta\omega$ is not less than $\Omega_i(V_T/V_a)^{2/3}$, where $V_T = \sqrt{2T/m_i}$ is the thermal velocity of protons. Therefore, the maximal correction to the time of group delay is equal $|\delta\tau/\tau|_{\max} \approx U_z/2V_T$. When $v_z \approx 3 \times 10^5$ cm/sec and $V_T \approx 5 \times 10^5$ cm/sec, we have $|\delta\tau/\tau|_{\max} \approx 0.3$, that is quite an appreciable quantity.

Of course, similar effect may be observed for pearls if they are registered by means of satellites directly in cosmic space.

5.0. Diagnostics of Energetic Particles in the Magnetosphere

5.1. ENERGY OF RESONANCE PROTONS

The magnetospheric plasma consists of low-temperature ('cold') components comprising of almost all particles and of a relatively small amount of high-energetic particles. The distribution of these energetic particles is, as a rule, unbalanced and may get unstable as regards fluctuation of hydromagnetic waves. On the other hand, the growing hydromagnetic waves can influence, through the mechanism of magnetic dissipation, the original distribution function. Therefore, some types of micropulsations are generated due to the existence of high-energetic particles in the magnetosphere. At the same time, some properties of energetic particles distribution are determined by the spectral intensity of micropulsations. This close relationship makes it possible to receive information on energetic particles in the magnetosphere from observations of micropulsations conducted on the earth's surface.

Let us begin with the relatively simple problem of estimation of particle energies responsible for generation of micropulsations. We shall consider pulsations of Pc-1 type which, due to recently developed conceptions, are quite probably generated as a result of cyclotron instability. The method which allows one to connect the observed spectrum of micropulsations with longitudinal energy of resonance particles $\varepsilon_{\rm res} = m_{\rm i}u/2$ is based on the analysis of the following equation (see (3))

$$k_z u = \omega - S\Omega_{\rm i}, \qquad S = 0, \pm 1, \pm 2, \dots \tag{22}$$

Let us, for instance, consider the resonance between protons and transverse waves propagating strictly along the external magnetic-field lines ($k_z = k$). Let us assume that plasma consists of electrons and of one type of ions (protons). Then, in the frequency range $\omega \ll \sqrt{\Omega_{\rm e}\Omega_{\rm i}}$ the dispersion relation between ω and k will have the following form:

$$k = \frac{\omega / V_{\rm a}}{\sqrt{1 \pm \omega/\Omega_{\rm i}}} \tag{23}$$

where the upper sign relates to the waves of right-hand polarization and the lower to the waves of left-hand polarization. Combining (22) and (23) we receive (GINTZBURG, 1961; OBAYASHI, 1965)

$$\frac{U}{V_{\rm a}} = \left(1 \pm \frac{\omega}{\Omega_{\rm i}}\right)^{1/2} \left(1 - S\frac{\Omega_{\rm i}}{\omega}\right). \tag{24}$$

This relation was used to obtain the plot presented on Figure 8. Drawing vertical lines in the frequency range of interest for any problem, one can find the corresponding energies of resonance protons if the parameters of exosphere in the region of generation are known. Let us consider in detail the proton resonance with the waves of left-hand polarization which takes place in the case of normal Doppler effect ($S > 0$). This case is of special interest, because it is understood that this mechanism is responsible for generation of pearls. Choosing in (24) the lower sign and putting $S = +1$ we obtain

$$\varepsilon_{res} = \varepsilon_{\rm m} \left(\frac{\Omega_{\rm i}}{\omega}\right) \left(1 - \frac{\omega}{\Omega_{\rm i}}\right)^3, \tag{25}$$

where $\varepsilon_{\rm m} = H^2/8\pi N$ is the density of magnetic energy on one particle of cold plasma (KENNELL and PETSCHEK, 1966). For the convenience of utilisation of Equation (25) in estimations of energies of resonance protons, the distribution of $\varepsilon_{\rm m}$ in space is shown in Figure 27. The plot is drawn in the plane of geomagnetic equator, because

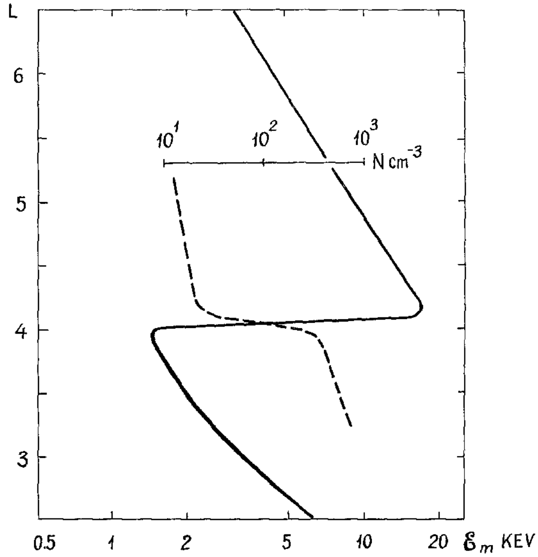

Fig. 27. The density of magnetic energy on one particle of cold plasma in the plane of geomagnetic equator. The dotted line shows the vertical profile of plasma concentration utilized in the plotting of this curve.

it is assumed that the generation of pearls takes place in the vicinity of the summit of their trajectories.

For utilisation of the Equation (25) and of the plot (27) it is necessary, besides the frequency ω of pearls, to know the parameter L of the trajectory (or the relation ω/Ω_i in the top of the trajectory which is practically the same). In the foregoing section it was shown how the relation ω/Ω_i can be found from the characteristics of dispersion of pearls. The results of utilisation of this method give for the relation ω/Ω_i the values of the order $\approx\frac{1}{2}$. If the frequency of the signal is around 1 Hz, then the parameter of the trajectory will be around $L\approx 6.2$, $\varepsilon_m \approx 4$ keV and consequently $\varepsilon_{res} \approx 2$ keV (Jacobs and Watanabe, 1966).

Due to the importance of this problem, we would like to draw attention to the other possibilities of estimating the parameter L which arise in some special cases (Gul'elmi, 1967a).

If the magnetosphere is suddenly contracted the spectrum of emission of fast charged particles (3) must change.* Indeed, due to the contracting of the magnetosphere, the gyrofrequency rises both as a result of the general augmentation of the geomagnetic field and as a result of radial drift of emitters inside the magnetosphere. Moreover, the longitudinal velocity of emitters changes (due to betatron acceleration, changing of pitch angles). Besides, the parameters of surrounding plasma, which influences the value of wave vector, also change. Let us try to estimate the resulting

* Heacock and Hessler (1965) have observed cases of sudden augmentation of pearls frequency at the moment of sudden commencement of the magnetic storms (SSC).

change $\Delta\omega$ of the frequency of emissions for a given value of a sudden contraction of the magnetosphere.

We consider the undisturbed field H as a dipole field. Let us choose the simplest approximation of the disturbance $\mathbf{h}$ of the magnetic field due to SSC. We assume that the disturbance is potential and shall conserve in the Gaussian sequence only the first axially symmetric harmonic

$$\left.\begin{aligned} h_r &= -\, h_0(t)\left(1 - \frac{1}{R^3}\right)\cos v \\ h_v &= h_0(t)\left(1 + \frac{1}{2R^3}\right)\sin v \end{aligned}\right\} \tag{26}$$

Here $R = r/r_e$ is the geocentric distance in earth radii; v – the polar angle measured from the dipole axis.

The induction electric field $\mathbf{E} = -(1/c)\,\partial A/\partial t$ will cause the drift of particles with velocity $\mathbf{V}_E = c[\mathbf{EH}]/H^2$. The vector potential $\mathbf{A}$ of the disturbance field has only the azimuthal component equal on great distances $A_\varphi \approx (R/2)h_0(t)\sin v$. We are interested in the radial displacement of particles $\delta R = \int^t V_E\,dt$ in the plane of geomagnetic equator $(v = \pi/2)$

$$\delta R \approx -\frac{1}{2}\frac{h_0}{H}R. \tag{27}$$

It is easy to see that the gyrofrequency of the displaced emitter will change on the quantity

$$\delta\Omega_i \approx \alpha\frac{eh_0}{m_i c}, \qquad \alpha \approx \frac{5}{2}. \tag{28}$$

The changes of energy and of the angular distribution of particles is found from the relations of conservation of the magnetic moment and of the longitudinal invariant (KRIMOV and TVERSKOI, 1964). In the case of radial drift of particles the equatorial pitch angle does not change significantly, and the energy ε changes in such a way that $\varepsilon R^3 \approx$const. Taking this and (27) into account we obtain

$$\frac{\delta\varepsilon_{res}}{\varepsilon_{res}} \approx \beta\frac{h_0}{H}, \qquad \beta \approx \frac{3}{2}. \tag{29}$$

Estimating the relative change of plasma density from the condition of the frozen in magnetic field and utilising (28) we obtain the change of ε_m

$$\frac{\delta\varepsilon_m}{\varepsilon_m} \approx \gamma\frac{h_0}{H}, \qquad \gamma \approx 3. \tag{30}$$

Combining now (25) with (28) – (30), we find the change of $\Delta\omega$ spectrum due to the sudden contraction of the magnetosphere:

$$\Delta\omega \approx \left(\alpha - \frac{\beta - \gamma}{2}\right)\frac{eh_0}{m_i c}\left(\frac{\omega}{\Omega_i}\right)\left[1 + \frac{\alpha + \beta - \gamma}{2\alpha - \beta + \gamma}\left(\frac{\omega}{\Omega_i}\right)\right]\left[1 + \frac{1}{2}\left(\frac{\omega}{\Omega_i}\right)\right]^{-1}. \tag{31}$$

Here $\alpha \approx 5/2$; $\beta \approx 3/2$; $\gamma \approx 3$; $h_0 \approx (2/3)\,\Delta H$, where ΔH is the value of the sudden impulse of the magnetic field registered at the equatorial observatory. Therefore, if the value of ΔH is fixed, the change of the spectrum $\Delta\omega$ is a function of only one variable quantity – of the ratio of frequency of oscillations to the gyrofrequency of protons at the top of the trajectory.

The above considerations allow one to estimate the ratio ω/Ω_i utilising the measured quantities $\Delta f = \Delta\omega/2\pi$ and ΔH (Figure 28, solid line). The ratio of energy of resonance protons ε_{res} to the density of magnetic energy ε_m in the region of generation is determined simultaneously (the dotted line on the Figure 28).

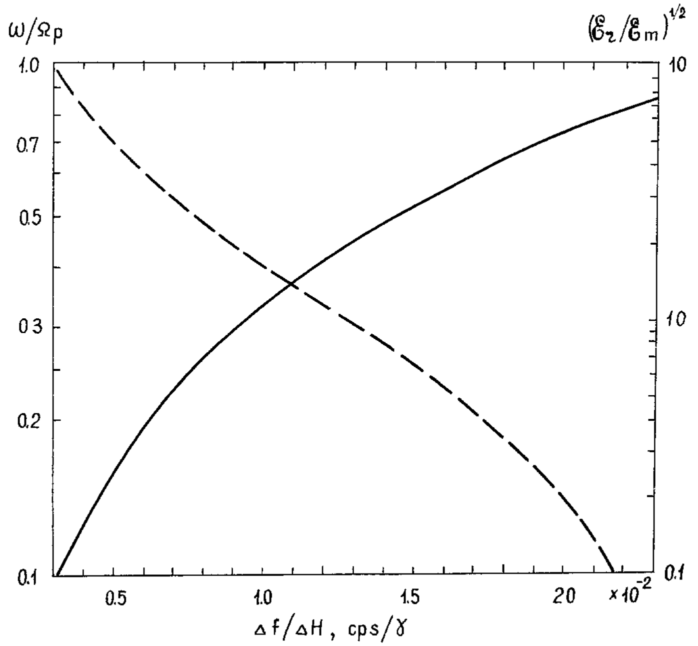

Fig. 28. The change of spectrum of cyclotron emission of protons due to sudden contraction or expansion of the magnetosphere. On the horizontal axis is plotted the ratio of the value of the sudden change Δf of the frequency of emission to the value ΔH of the sudden impulse registered on the equator. The curve makes possible an estimate of the ratio of the frequency of emission to the gyrofrequency of protons in the region of generation (solid curve), and the ratio of the energy of resonance protons to the density of the magnetic energy (dotted curve).

Utilising (31) it is not difficult to obtain a formula to estimate the parameter L of the region of generation

$$L \approx 5.25 \left[\frac{\Delta f}{f} \frac{10^2}{\Delta H_\gamma}\right]^{1/3} \left(1 - 15 \frac{\Delta f}{\Delta H_\gamma}\right)^{-1/3}. \qquad (32)$$

The possibility of application of this method significantly depends on the validity of the indirectly made suggestion that the oscillations both before, as well as after SSC, are generated by the same particles. The generation of the oscillations of the pearl type is due to the anisotropy of distribution of resonance protons on velocities. Due to the fact, that the pitch angle of the separate particle does not change significantly in the course of SSC, one can expect that the degree of anisotropy of the distribution function of particles will probably not change practically. It seems that the SSC leads mainly to the change of energy spectrum and of the distribution of energetic particles in space. As a consequence of these modifications, the spectrum of generated oscillations changes, and this was taken into account by the described above procedure.

Let us consider, as an example, the modification of the mean frequency of Pc 1 during the SSC which occurred on August 12, 1964 at $01^h12'$ GMT. The mean frequency of the pearl series which was observed at this time at Colledge was $f \approx 0.43$ Hz. The sudden change of frequency during the SSC was $\Delta f \approx 0.1$ Hz (See Fig. 2 in HEACOCK and HESSLER, 1965). The value of SSC registered at the observatory Guam was $\Delta H \approx 13\gamma$. Consequently with these data we obtain $\omega/\Omega_i \approx 0.25$; $L \approx 6.5$; $\varepsilon_{res} \approx$ 12 keV.

5.2. Distribution function of resonance protons

If we limit ourselves by the estimation of the energy ε_{res} alone, then our knowledge of the particles responsible for the generation of micropulsations will be quite insufficient.

What, in general, must be known for complete representation of properties of energetic particles in the magnetosphere? The answer is clear but not encouraging.

In stationary conditions the particles in the magnetosphere are fully described by their distribution function $f(\mathbf{r}, \mathbf{v})$ on velocities $\mathbf{v}$ and coordinates $\mathbf{r}$. If we remember that, in the collisionless plasma a very wide class of distributional functions can be imagined, then the reconstructing of $f(\mathbf{r}, \mathbf{v})$ using micropulsations data may seem hopeless. But, if the distribution of the particles is unstable and from some indirect sources the general form of $f(\mathbf{r}, \mathbf{v})$ is known, then one can try to determine the parameters of that distribution, using micropulsations which are generated as a result of instability.

In order to make clear the idea of the applied methods in these cases, it is useful to go back a little and consider the problem of the diagnostics in the whole.

In the approximation of geometrical optic the general scheme of the electromagnetic methods of diagnostics are developed in the following way. First of all, the connection between the complex index of refraction $n = ck/\omega$ with local parameters of the medium is established. Then the relation between the observed parameters of the electromagnetic field and the distribution of n along the paths of propagation is found. At last an endeavour is made to reconstruct in space the distribution of the investigated parameter of the medium utilising the observations of the electromagnetic field. The last problem leads generally to the solution of some integral equation.

The possibility to formulate the problems of the diagnostics as a problem leading to the solution of the integral equation does not mean, of course, that this is the only way which must be followed always. Due to the insufficiency and the low precision of the experimental data the correct solution of the problem is practically impossible in many cases. Therefore, often only the estimates of the investigated parameters are done, based on some simple heuristic conceptions. Namely, this simplified variant of the diagnostics was utilised in estimation of plasma concentration based on analysis of dispersion of pearls and in estimation of the energy of resonance particles based on the analysis of the spectrum of observed emissions.

In the first case, the real part of the index of refraction $\mathrm{Re}\, n(\omega)$ was studied, which is determined by the parameters of cold plasma assuming that the effects of waves damping (or growing) are small.

On the other hand, in the second case the imaginary part of the refraction index $\mathrm{Im}\, n(\omega)$, which depends on the distribution function of the small amounts of energetic resonance particles was studied indirectly. In this problem practically only one suggestion was used, namely, that the generation of pearls is due to the instability which develops in the region of frequencies where $\mathrm{Im}\, n(\omega) \gg 0$ (see Appendix 3).

The next problem is the detailed investigation of the function $\mathrm{Im}\, n(\omega)$ using data on growing waves. Let us assume that a plane wave $e^{i(kz-\omega t)}$ propagates along the external magnetic field. In the analysis of the growing (or damping) waves in the linear approximation, two ways of approach are possible. In the first one it is assumed that the wave number k is known and real and the complex frequency $\omega = \omega' + \omega''$ is determined from the equation of dispersion. If we have to deal with convective instability in a system with definite dimensions, then the second approach would be more adequate. In the latter case the frequency ω is given and the values of real and imaginary parts of wave number $k = k' - ik''$ are determined. In practical calculations one must adopt some parametric model of energetic particles distribution. Let us assume that the differential energetic spectrum of the particles is described by the function $\varepsilon^{-\nu}$ and the pitch angle distribution is determined by the factor $\sin^{\mu}\alpha$. The problem of diagnostics in this case consists in determining, from experimental data on growing waves of the parameters ν, μ and the concentration of energetic particles N'.

If the wave packets responsible for pearls propagate along the field lines, periodically reflecting in the magnetically conjugate regions, then analysing the rate of growing of the amplitude of the signals registered in one of the conjugate points, one can try to estimate the coefficient of amplification during the two-hop propagation of the packet along the field line. The values obtained in such a way are compared with theoretical values of the amplification coefficient $A(\omega) = \int k''(\omega, l)\, \mathrm{d}l$ which were calculated for different suggested values of parameters μ, ν and N' of the function of distribution of resonance particles along the trajectory of the signals.

LIEMOHN (1967) has accomplished detailed calculation of the coefficient of amplification $A(\omega)$ for waves passing through the region of the outer radiation belt. He has given rather convenient tables and plots which allow, in principle, to make comparisons with the experimental data.

The practical solution of this problem encounters different kinds of difficulties. First of all, in the estimation of the parameters of the distribution function arises a significant ambiguity, due to the fact that surface data can give only the value $A_{\text{observ.}} = A - \ln(1/P_1 \times P_2)$, where P_1 and P_2 are the coefficients of reflection of the signal from the ionosphere in the magnetically conjugate points. For obtaining from $A_{\text{observ.}}$ the value of A it is necessary to estimate the coefficients of reflection from some independent data. Secondly, the linear theory of instability is applicable only for the first stages of waves growing. As a sufficient criterion for application of linear approximation may serve, probably, the constant value $A_{\text{observ.}}$ in the beginning of the pearl series. We have tried to determine $A_{\text{observ.}} = \ln[h_{i+1}/h_i]$ using the records of pearls (h_i – amplitude, $i = 1, 2 \ldots$ – the number of a separate pearl in the series). Practically in all processed cases the coefficient of amplification quickly diminishes with time (Figure 29). From this fact we can conclude that, due to the limited sensi-

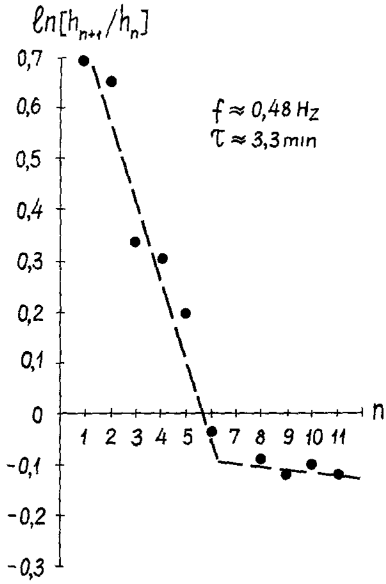

Fig. 29. Amplification and damping of the pearls Pc 1 in an isolated series. The numbers on the horizontal axis give the ordinal number of the signals in the series. On the vertical axis is plotted the logarithm of the amplitudes ratio. This quantity is proportional to the coefficient of amplification (damping) of the signal when it propagates along the field line from one conjugate point to the other and back.

tivity of the equipment, the growing signal is discovered 'too late', when non-linear processes come into play. Another interpretation of this fact is also possible. It is not excluded that pearls are generated by bunches of energetic particles, limited in space, sporadically injected in the magnetosphere from outside. Immediately after injection the bunch begins to disperse due to the natural scatter of particles on velocities. This leads to the diminishing of the coefficient of amplification.

The above considerations show, that the diagnostics of the function of distribution of resonance particles in the magnetosphere, while not a hopeless problem, remains a very complicated and difficult undertaking requiring for its definite solution further experimental and theoretical investigations.

5.3. Non-stationary processes in the geomagnetic trap

During the magnetic storms in the space surrounding the earth a display of complicated electrodynamical and kinetic phenomena in a definite sequence takes place. Some of them are accompanied by specific very low-frequency emissions, which we can compare with winds whirling and whistling in troposphere during weather storms.

In the frequency range of micropulsations during the main phase of the magnetic storm, when a powerful ring current develops inside the magnetosphere, the so-called intervals of pulsations diminishing on periods (IPDP) are observed. At the beginning of the interval the period of pulsations is equal to several to 10 sec. Then the change of oscillatory regimes is observed. In a course of half an hour approximately, the periods of pulsations diminish gradually to a second and less. The spectrum of oscillations is rather broad, as can be seen on the sonogrammes of IPDP (Figure 30a, b). The intervals of IPDP arise most frequently during strong magnetic storms, and during one storm several IPDP may be observed (Troitskaya, 1961, 1964, 1967; Gendrin *et al.*, 1967).

The fact of rising of frequency of oscillations itself shows that these oscillations reflect the non-stability processes occurring in the geomagnetic trap. This point of view is confirmed by a number of results obtained from the comparison of IPDP with data of surface and satellite observations. It was revealed for instance, that the pulsations of diminishing period are accompanied by diminishing of depression of the geomagnetic field due to the ring current and intensive damping of electrons with

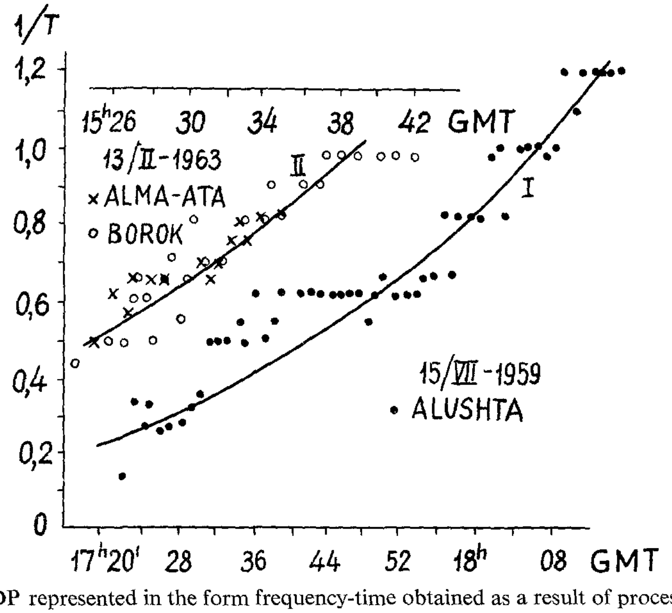

Fig. 30a. IPDP represented in the form frequency-time obtained as a result of processing of records in the form amplitude-time.

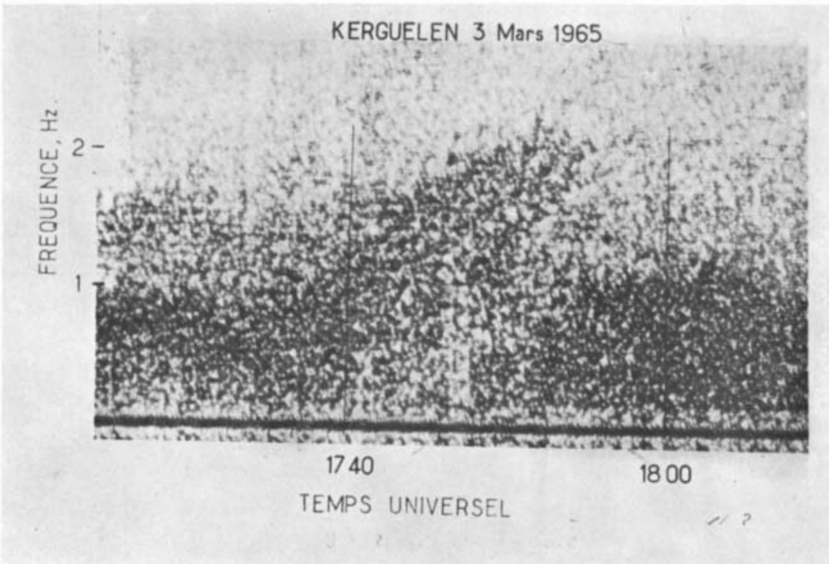

Fig. 30b.

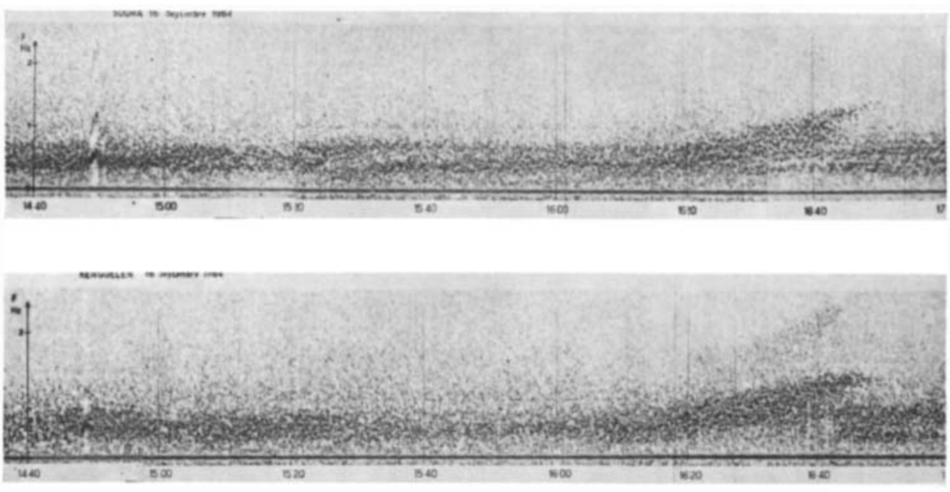

Fig. 30c.

Fig. 30. Interval of pulsations diminishing on periods (IPDP) represented in the form frequency-time (sonogramme).

energies $\varepsilon \gtrsim 100$ keV from the geomagnetic trap (Figure 31 and Table VI). An important result of observations is the established connection between the intensity of the flux of particles damped from the radiation belt into the atmosphere and the gradient of periods in the interval IPDP. This relation allows one to obtain, from observations of micropulsations, qualitative conclusions on the character of non-stationary processes in the geomagnetic trap.

TABLE VI

Comparison of the properties of micropulsations diminishing on periods with data on the radiation belts

Date	Properties of micropulsations			Data on the radiation belt					
				External boundary of the belt			Flux ($\varepsilon_e > 100$ keV) count/sec.		
	Beginning (UT)	Ending (UT)	Frequency at the end of the interval (Hz)	Beginning (Re)	Ending (Re)	ΔR (Re)	Beginning I^1	Ending I^2	ΔI
31.01.64	11.54	12.35	0.8	6.0	5.0	1	$3.5.10^2$	2.10^2	1.10^2
12.02.64	13.59	14.45	0.8	6.5	5.3	1.2	5.10^2	4.10^2	1.10^2
20.02.64	15.52	16.26	0.8	6.0	5.0	1	7.10^2	5.10^2	2.10^2
20.02.64	17.48	19.22	1.55	6.0	4.5	1.5	7.10^2	2.10^2	5.10^2
17.07.64	17.13	18.23	1.55	6.5	5	1.5	6.10^2	2.10^2	4.10^2

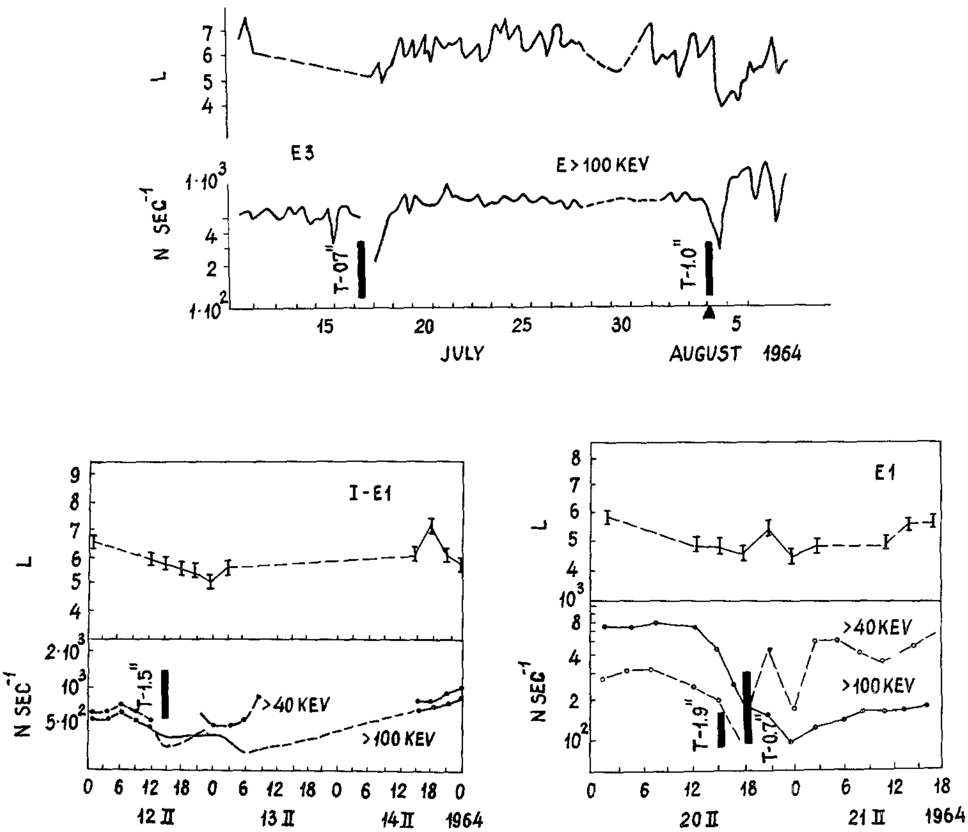

Fig. 31. Connection of IPDP with the variations of particles flux in the radiation belt. ▌ indicates the occurrence of IPDP; the value of T gives the highest observed frequency.

Unfortunately, the origin of the intervals of pulsations diminishing on periods has not yet been explained. But due to the fact that IPDP occur in the period of maximal depression of the magnetic field during the storm it is thought that their origin may be due to the generation of these oscillations by the protons of the ring current (RC).

In the paper by Kozlowski (1963) it is suggested that pulsations of diminishing periods cause the magnetic scattering of protons forming the ring current. It is quite possible that the IPDP may be generated by the same protons which are finally dissipated due to the grown intensity of oscillations. The depression of the geomagnetic field in the region of generation diminishes, and due to the fact that the resonance frequency in the rough approximation has a square dependence on the field – a strong drift of oscillations in frequency arises. A series of consecutive intervals, IPDP, can practically completely destroy the RC and lead to the quick end of the main phase of the storm.

Very interesting investigations of IPDP were made by Knaflich and Kenney (1967). These authors estimated the location of the region of the structured elements generation which occasionally occur on the sonograms of IPDP. These estimates are done using the dispersion measurements. According to the results of this work the structured elements are generated at the periphery of the magnetosphere ($L \sim 6-13$) in the evening quadrant (16 – 22 h LT).

Similar conclusions were reached by GENDRIN *et al.* (1967) from other considerations.

Let us now consider another type of short periodic oscillations, which contain information on the electron streams injected in the high atmosphere. We shall describe the irregular magnetic pulsations Pi 1 ('sip'), which have maximal intensity in the auroral zone.

Oscillations of this type reveal strong correlation with variations of intensity of aurora, bursts of X-rays in the stratosphere and with fluctuations of ionospheric absorption of cosmic radio noise (see for instance BARCUS and ROSENBERG, 1965, 1966). The common source of all these phenomena are the fluctuating streams of electrons, which can be accelerated in the neutral sheet of the magnetospheric tail up to energies of several to tens of keV and injected in the polar atmosphere on the night side of the earth. The bremsstrahlung of electrons generates X-rays which are observed on balloons. The excitation of atoms and molecules of the air leads to the appearance of aurora. The additional ionisation of the upper atmosphere augments the absorption of cosmic radio noise.

The spectra of X-ray pulsations, of aurora and of ionospheric absorption give a rather complete account of the spectra of electron streams fluctuations. A great variety of pulsations was discovered – from slow quasi-periodic variations to short impulse-like bursts. The typical spectrum has a cutoff in the region of high frequencies and small maxima in the range 0.2–0.05 Hz. Pi 1 oscillations have a similar spectrum which occur simultaneously with above-mentioned phenomena.

Several mechanisms were suggested to explain the strong correlation of Pi 1 pulsations and fluctuations of electron streams, but the nature of their relation still remains a mystery. NISHIDA (1964) supposes that, simultaneously with the injection of electron streams in the atmosphere, there develops a beam instability with a spectrum typical for irregular magnetic pulsations. He has considered a model of cold homogeneous plasma and a parallel monoenergetic stream of electrons traversing it. In the hydromagnetic range ($\omega \ll \Omega_i$) the system becomes unstable in respect of generation of transverse oscillations, if the velocity of the stream is greater than the Alfvén velocity. The growing of waves in time occur for wavelengths for which the following relation is fulfilled:

$$1 + \frac{\Omega_i^2}{k^2 V_a^2} \frac{N'}{4N} < \frac{N'}{N} \frac{u\Omega_i}{kV_a^2}. \tag{33}$$

Here N' is the concentration of particles in the stream, N – concentration of plasma, $N' \ll N$.

It is possible to make numerical calculation of the spectrum of unstable oscillations and the increments of waves growing in different parts of the magnetosphere, but it is not difficult to obtain the main results using the strong inequality $u \gg V_a$

which is very well fulfilled in the magnetosphere for electrons with energies $\varepsilon_e \gtrsim 10$ keV. In this case, due to (33) the wave numbers k of unstable oscillations fall in the range practically from zero to

$$k_{\max} \sim \left(\frac{\omega_0'}{c}\right)^2 \frac{u}{\Omega_i}, \quad \text{where} \quad \omega_0'^2 = 4\pi e^2 N'/m_i .$$

Immediately above the ionosphere $N' \approx 1$ cm^{-3}, $u \approx 6 \times 10^9$ cm/sec $\Omega_i \approx 6 \times 10^3$ sec^{-1}. Thus for $K_{\max}$ we obtain $\sim 2 \times 10^{-9}$ cm^{-1}. As the section of the tube of magnetic field lines augments with altitude as Ω_i^{-1}, and N' consequently diminishes, the estimate given above remains valid also on greater distances from the earth's surface. The increment rises to the maximal value in the case of $k \approx k_{\max}/2$ and is equal

$$\mathrm{Im}\omega \approx \frac{u}{c}\left(\frac{N'}{N}\right)^{1/2} \frac{\omega_0'}{2} .$$

In other words, the short periodic disturbances develop most quickly. If $N \approx 10^2$ cm^3 the instability develops in fractions of a second and has essentially an aperiodic character. Therefore, the system is quickly turbulized. It is difficult to say how the spectrum of a developed turbulency will correspond to the observed spectrum of magnetic pulsations. Moreover, the lengths of the growing waves in a homogeneous plasma significantly exceed the characteristic dimensions of inhomogeneity of the magnetosphere, even in the case $k = k_m$. It is quite probable that this circumstance provides the stabilisation of the considered type of instability. In general, it must be acknowledged that the question on the physical nature of Pi-1 bursts still remains open.

For the aims of diagnostics the main practical problem is to establish the coefficients tying the spectra of electron stream pulsations and the spectra of magnetic pulsations observed simultaneously. As the theory of this problem has not yet been elaborated, it is useful to investigate the experimental relation between the steepness of the pulsations spectra, location and intensity of resonance maxima and so on. After that, the observations of Pi 1 may give qualitative information on the character of electron streams injections in the upper atmosphere.

6.0. General Discussion of the Problem of the Diagnostics

Taking into account the high variability of the magnetospheric parameters, it is difficult to underestimate the significance of the surface methods of diagnostics. But the principal possibilities of the diagnostics are still far from their practical realisation. The development of these methods depend on the successful solution of a number of principal theoretical and practical problems.

First of all, the development of the theory of micropulsations has begun only recently and the progress in this direction is rather slow. This can be explained not only by the lack of effort, but first of all by the complicated and very broad character of arising problems. For instance, the experimental facts and theoretical investigations show that the mechanism of micropulsation generation cannot be fully understood in frames of linear approximation. In other words, the interpretation of micropulsations requires solution of difficult non-linear problems.

The development of empirical methods of diagnostics of magnetosphere put new problems before the theory of micropulsations. For instance, the experimentally established fact of dependence of the period of continuous pulsations on the dimensions of the magnetosphere ($T \sim R_{\mathrm{m}}^{\nu}$, $\nu \approx 4.8$) seems, from the theoretical point of view, rather strange. Indeed, if we consider the isotropic contraction of a magnetized cloud of plasma, then $\varrho \sim R_{\mathrm{m}}^{-3}$, and from the 'frozen-in' conditions $H \sim R_m^{-2}$ using the relation $T \sim R_m/V_a$, $V_a = H/\sqrt{4\pi\varrho}$ we obtain an approximate estimate – $T \sim R_{\mathrm{m}}^{3/2}$ that is $\nu \approx 3/2$. This is in serious discrepancy with the experimental result, and it seems difficult to reconcile these two results only by the improvement of the model. Therefore the theory must explain this newly discovered relationship $T(R_m)$.

The successful developments of the methods of diagnostics of the magnetosphere will also depend on the perfection of the methods of micropulsation observations. The precision of the plasma-concentration profiles built using the results of torsional oscillations observations is evidently not high enough, in comparison to the precision of the initial function $T(v_0)$, which was obtained from the network of stations whose location is often not the most appropriate one. To determine the dependence $T(v)$ it is necessary to establish a special meridian profile of observatories equipped with one and the same type of recording devices. The measurements of the periods of torsional oscillations in middle latitudes are especially wanted (Siebert, 1964). Indeed, in high latitudes, the torsional oscillations differ from the poloidal by their greater periods. But with the diminishing of the latitude the periods of both these types of oscillation become comparable and for identification of the type of oscillations some other specific properties must be utilised.

If torsional oscillations really exist in the middle latitudes, then they can be recognised, for instance, by their property to occur locally, and by their strong correlation in the magnetically conjugate points.

Many important properties of micropulsations have to be cleared out as a result of coordinated investigations on a worldwide network of surface observatories and of observations of hydromagnetic waves directly in cosmic space.

It should be noted that the question of typical parameters L of pearls in the exosphere still remains rather obscure. As in the case of whistlers, the latitude of the point of observation does not contain information about the parameter L. Indeed, when the reflection from the ionosphere takes place, a part of the energy of the signal diffuses into the ionospheric waveguide and propagates parallel to the earth's surface on significant distances from the place of the real arrival of the signal. The determining of L is made using indirect methods, the reliability of which is rather difficult to estimate. But the observations of pearls on the satellite would allow one to solve this question definitely. Indeed, from the fact of the quasi-monochromatic character of pearls, it follows that the dimensions of the signals in the transverse to the magnetic field direction are relatively small. Therefore, in the case of the registration of pearls above the ionosphere, the position of the satellite in the moment of registration would definitely determine the parameters of the signals trajectory.

When slow waves are registered on the satellite, one can expect in principle to observe specific effects of waves dispersion in the moving plasma. Especially notable effects are expected in the vicinity of gyrofrequencies of ions (see Appendix 2).

The development of the methods of diagnostics will be undoubtedly connected with the wide use of electronic computers both in the processing of micropulsation records and in the solution of the appropriate indirect problems. This in turn will require the transition to the methods of micropulsations registrations in the form making it possible to introduce these records directly to the input of the electronic computers.

It is necessary to stress that the micropulsations have not only an informative value. They are themselves an interesting natural phenomenon and a convenient object by which it is possible to study the conditions of generation and propagation of electromagnetic waves in plasma. The problems arising in the course of interpretation of micropulsations have a definite stimulating influence on the development of the theory of plasmic waves. We can note, for instance, the paper of WATANABE (1966), in which the non-linear effects of propagation of iono-cyclotronic waves are discussed in order to explain the peculiarities of pearls dispersion. Moreover the observation of pearls on a wide network of stations put forward the problem of hydromagnetic waveguide centered at the level of the maximum of ionisation of the F_2 region of the ionosphere. It is interesting to note that the measurements of the critical frequency of the waveguide, of the phase velocity of different modes, of the waveguide damping, etc., will quite probably allow in the future, determination of some of the effective parameters of ionosphere and lower exosphere. Formally, the methods of such measurements are similar to that used in the investigations of atmospheric propagation in the waveguide earth-ionosphere. But the technical difficulties of precision measurements in the range around 1 Hz are rather great. To overcome these difficulties one requires the elaborating of special methods of analysis (see for instance the description of the procedure of 'pearls cultivation' in the paper of WENTWORTH *et al.*, 1966). The theory of hydromagnetic ionospheric waveguide is also more complicated than the theory of the waveguide earth-ionosphere. The future will show how informative such measurements are. But already the fact itself of the existence of the hydromagnetic waveguide, discovered by means of observations of micropulsations, is of principal significance.

Systematic observations of micropulsations on the worldwide network of observatories were begun in 1957. During the last 10 years a vast amount of experimental materials was gathered allowing definite conclusions to be made on the regularities of micropulsations behaviour in the course of solar activity (TROITSKAYA *et al.*, 1967a). Some preliminary results of this analysis are given on Figures 32–35. In building these plots, the systematic records of the magnetic-field and earth currents at the observatories Borok, Petropavlovsk and Lovozero were used. Also, for the analysis of separate cases records of the Arctic, Antarctic and conjugate points, stations Sogra–Kerguelen were utilized. On Figure 32, results of the analysis of the frequency

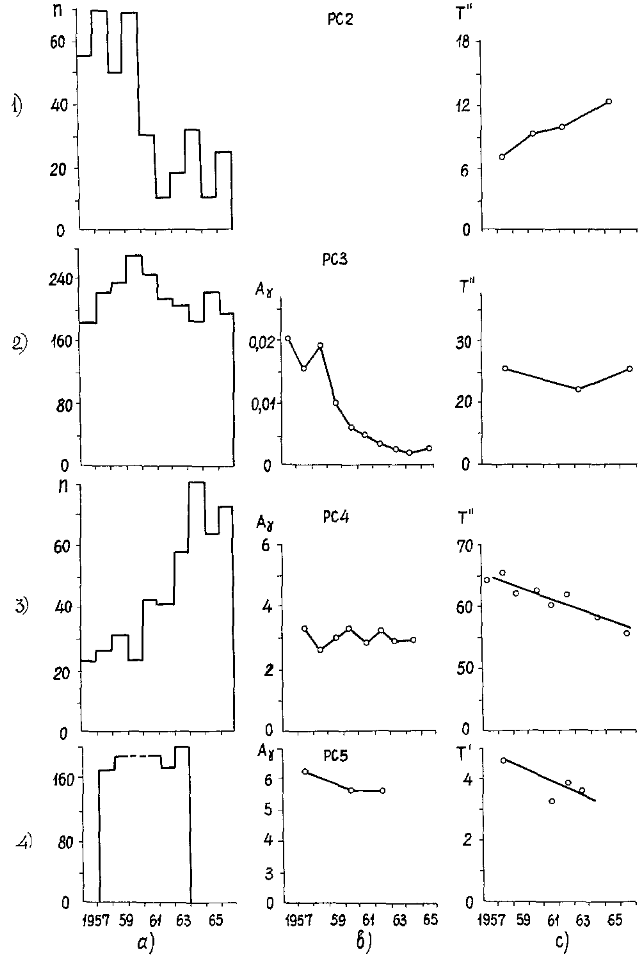

Fig. 32. The behaviour of Pc-2–Pc-5 micropulsations in the course of the solar cycle (frequency of occurrence, mean period and mean amplitude).

of occurrence, of the mean amplitude A (vertical component) and of the mean periods $T_{\rm sec}$ of micropulsations Pc 2 – Pc 5 are given. The changes of these parameters in the cycle reveal some peculiarities which reflect the corresponding variations of the parameters of the magnetosphere and of the solar corpuscular streams in the solar cycle.

Pc 2: Pulsations of this type are usually observed in the first phase of sporadic magnetic storms. Due to the diminishing of the number of sporadic storms in the epoch of minimum of solar activity, the frequency of Pc-2 occurrence also diminishes in this epoch. As regards the mean period of Pc 2 – it augments in the epoch of solar minimum. This may be regarded as evidence of diminishing in average of intensity of corpuscular streams responsible for sporadic storms.

Pc 3: These oscillations often occur during recurrent storms. The frequency of

Pc-3 occurrence practically does not change in the cycle. (Not taking into account the small diminishing of their number to the epoch of minimum.) This result, together with the above-mentioned data on Pc-2 frequency of occurrence evidences that in the epoch of solar minimum the relative number of recurrent storms augments in respect of the number of sporadic storms. The mean amplitude of Pc 3 diminishes from the epoch of minimum to the epoch of maximum almost on an order of magnitude. The meaning of this result is not at all clear. If we adopt the point of view that in the course of solar cycle systematic changes of the dimensions of the magnetospheric resonator take place, then it would seem that the relation of amplitudes in the maximum and the minimum of activity would be opposite to the observed one.

Therefore, the diminishing of Pc-3 amplitudes is quite probably connected with the diminishing of intensity of the pulsations sources. But this point of view also contains some ambiguity. The source of pulsations may be attributed to the turbulency arising due to the instability of flow of corpuscular stream around the magnetosphere. In this case, it is rather difficult to say something about the intensity of pulsations because the transition to the stationary regime is accomplished through the non-linear processes. If we take into account (Figure 32–2c) that the mean Pc-3 periods, and consequently the corresponding velocities of corpuscular streams, practically do not change in the course of the solar cycle, then in any case the increments of the linear theory of instability must be also approximately constant. As one can imagine, in the epoch of solar minimum the streams flow around the magnetosphere more stationary than in the period of maximum. Then the possibilities to break off the instability due to changes of outer conditions are less, and therefore one could expect the occurrence of more intensive pulsations.

From these rather general considerations it follows that quite probably the Pc 3 are generated by inhomogeneities of corpuscular streams, bombarding chaotically the surface of the magnetosphere. In the period of minimum the relative dimensions of inhomogeneities are smaller, and this is revealed in the diminishing of the amplitudes.

Pc 4: The Pc-4 oscillations are generated by the undisturbed solar wind. They are most typical for the epoch of solar minimum (Figure 32–3a). The striking constancy of the Pc-4 mean amplitude (Figure 32–3b) indirectly evidences as to the independence of the properties of the undisturbed solar wind from the phase of the solar cycle.

The period of Pc 4 slightly diminishes in the epoch of solar minimum (Figure 32–3c). This fact can be interpreted in two ways. If the assumption on the constancy of the undisturbed solar wind velocity in the solar cycle is correct and if the relation $T \sim R_m^\nu$ is valid, then the relative augmentation of R_m in quiet days of the epoch of the maximum can be explained by the inflation of the magnetosphere due to the remainders of the ring current after great magnetic storms (OHL, 1963). In the epoch of minimum, when big magnetic storms occur less frequently, the mean dimensions of the magnetosphere will be consequently less.

The other suggestion is, that the small diminishing of Pc-4 periods in the solar cycle is due to the diminishing of the mean density of plasma in the magnetosphere (SAITO, 1964). One cannot exclude also the possibility that the mean velocity of the undisturbed solar wind which determines the dimensions of the magnetosphere augment a little in the epoch of solar minimum.

Pc 5: The frequency of occurrence and the mean amplitude of Pc-5 pulsations practically do not change in the course of the solar cycle (Figure 32–4a, b). On the other hand, the mean period of these pulsations distinctly diminishes to the epoch of solar minimum. This change of Pc-5 period is most naturally explained by the corresponding change of the mean density of plasma in the magnetosphere.

On Figures 33 and 34, the results of Pc-1 analysis in the course of the solar cycle are shown. It is clearly seen that the behaviour of pulsations with periods less than 2 sec in the solar cycle, is different from the behaviour of pulsations with periods greater than 2 sec (see also the paper of MATVEEVA and TROITSKAYA, 1965). The maximal frequency of occurrence for Pc 1 ($T<2$ sec) was observed for the middle-latitude

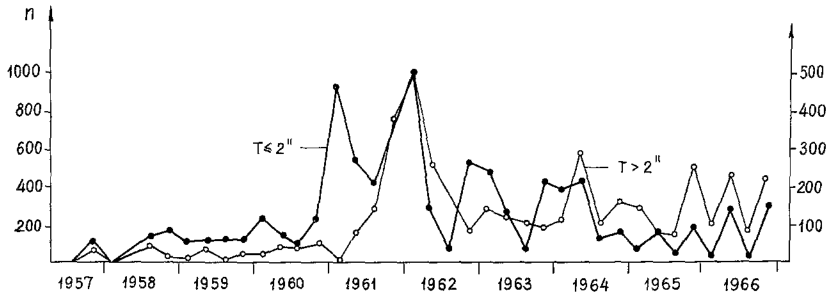

Fig. 33. The frequency of occurrence of Pc-1 micropulsations in the solar cycle for the observatory Borok.

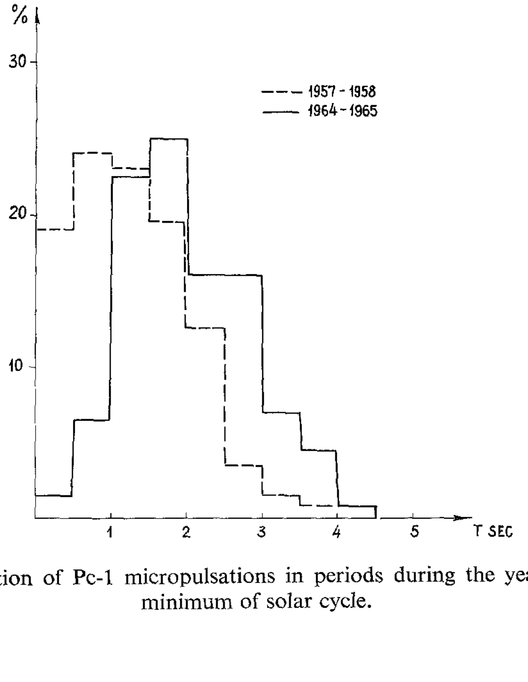

Fig. 34. The distribution of Pc-1 micropulsations in periods during the years of maximum and minimum of solar cycle.

station Borok in 1961, that is in the years of the fall of solar activity cycle. The frequency of occurrence of Pc 1 with periods > 2 sec reveal two maxima in 1961–62 and in 1964 (Figure 33). The spectral distribution of Pc 1 shifts to the greater periods in the epoch of minimum and the maximum becomes a little narrower (Figure 34). As the frequency of pearls represent a definite fraction of the gyrofrequency of the protons in the summit of the field lines, the above-mentioned result shows that the generation of pearls in the epoch of maximum takes place in a larger range of L-shells.

Some peculiarities of Pi-2 behaviour, typical for the nightside of the earth are shown in Figure 35. It is seen that the frequency of Pi-2 occurrence augments to the epoch of solar minimum.

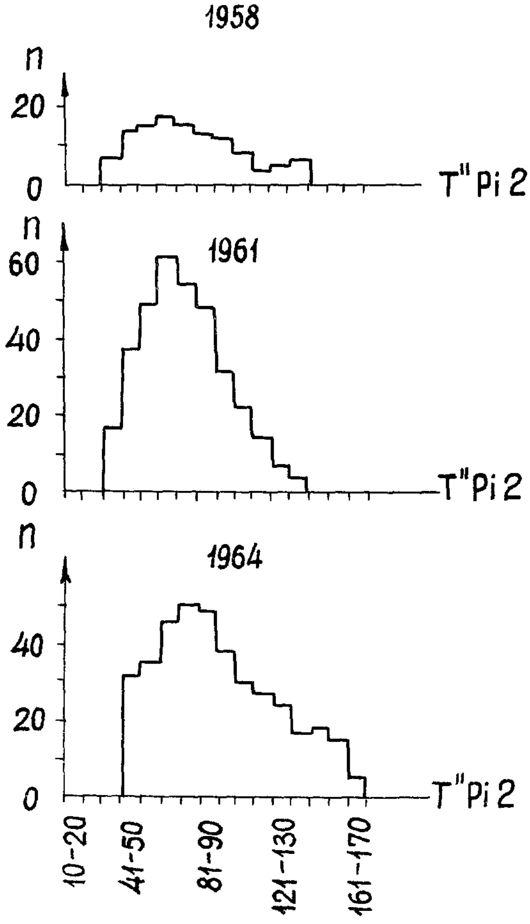

Fig. 35. Distribution of Pi-2 micropulsations on periods in different years of the solar cycle.

The above-mentioned preliminary results do not at all describe the full problem of behaviour of micropulsations in the solar cycle. But they strongly evidence the interest of further investigations in this direction. The more detailed analysis of the already obtained records will allow, in the nearest future, definite conclusions to be made on the changes of the parameters of the magnetosphere of the solar wind and of the general character of solar activity in the course of the solar cycle. For direct investigations of the same parameters by rockets and satellites several years at least are needed only to gather the necessary experimental materials.

In the practice of geomagnetism different types of indexes of activity, characterising the disturbances of the magnetosphere for a given time interval are used. Widely known are the Kp, K, C, U and other indexes deduced from the standard records of the magnetic observations. These indexes of course do not include any characteristics of activity of micropulsations.

Meanwhile, the introduction of a standard unity of activity of micropulsations would be useful from at least two points of view, first of all, as it is clear from the results described above, the micropulsations indirectly reflect the general state of the magnetosphere and the character of processes developing in it. On the other hand the activity of micropulsations is of significant interest by itself, because in a number of cases, the hydromagnetic oscillations and waves significantly influence the parameters of plasma in space surrounding the earth (ROKITYANSKII and SCHEPETNOV, 1964; SAITO, 1964a). In connection with the above-mentioned two types of micropulsations indexes may be useful – the spectral and the energetical one. It is quite clear that the indexes must have a distinct physical meaning and must be sufficiently simple and convenient in their practical utilization. An endeavour to introduce an 'energetical' micropulsations index was undertaken in the paper of ROKITYANSKII and SCHEPETNOV (1964). As a parameter which was used in obtaining the indexes, the amplitude of the most typical day pulsation Pc 3 was chosen. The amplitude was averaged for each 24 hours for 5 middle latitude observatories and was normalised in such a way that the influence of local geological structure on the observations be excluded as far as possible. The tables of these indexes were compiled for 1957–59 and they can be used for different statistical investigations.

The spectral indexes of activity are formed from the average periods of micropulsations for a definite interval of time. The selection of the average interval, of the location of the basic observatories, etc., is a serious practical problem, which must be solved taking into account the experience of long-lasting series of micropulsation observatories on a world-wide network of stations. A suitable selection of spectral and energetical indexes of micropulsations can give a comprehensive characteristic of the general hydromagnetic situation in the outer space surrounding the earth. These indexes would be especially useful in the investigations of micropulsations behaviour in the course of the 11-year cycle of solar activity (SAITO, 1964b).

Conclusion

In conclusion the authors would like to stress the following:

Historically the micropulsations were the first electromagnetic waves, which were registered by man. It seems rather surprising that their high-informative value was revealed only quite recently. A question may arise whether it is worthwhile to spend efforts for working out the methods of utilization of micropulsations for the diagnostics of the magnetosphere in our day, when the outer space cross hundreds of satellites equipped with a variety of recording scientific instruments. "This is a great question", Candide would say, but surely the answer must be definitely negative. It is quite improbable that somebody seriously thinks that the installation on the satellites of magnetometers for measuring regular magnetic field, or the astronomical observations on satellites outside the dense atmosphere will diminish in some measure the significance of the surface observations. The surface and the satellite methods of cosmic-space investigations are by no means concurrent ones but complement each other. From this point of view the value of micropulsations and other low-frequency emissions as an auxiliary tool of investigations is quite evident. The possibility of uninterrupted and long-lasting observations of the state of the magnetosphere by means of relatively simple equipment is an indisputable practical advantage of low-frequency methods of diagnostics.

As in any field of investigations the developing of which has just begun, it may at any moment open unexpected perspectives, meanwhile other possibilities, which seem at present most promising, may prove themselves fruitless. In any way, in spite of the fact that many properties of micropulsations remain a mystery, and the theory of the surface methods of the diagnostics makes only its first steps, the obtained results allow definite affirmation that the observation of micropulsations opens new ways in the investigation of the magnetosphere.

Appendices

The authors thought it useful to give in the Appendices a number of general formulas and equations, as well as two schematic tables (Tables VII and VIII), which help to orientate approximately in the variety of properties of micropulsations, and in the charcater of information they contain.

App. 1: Equations of oscillations of the magnetosphere

The system of linearized equations of ideal magnetic hydrodynamics has the following form (Dungey, 1954)

$$\frac{\partial \mathbf{h}}{\partial t} = - c \operatorname{rot} \mathbf{E}, \tag{34}$$

$$\varrho \frac{\partial \mathbf{v}}{\partial t} = \frac{1}{c} [\mathbf{jH}], \tag{35}$$

$$\mathbf{j} = \frac{c}{4\pi} \operatorname{rot} \mathbf{h}, \tag{36}$$

$$\mathbf{E} = - \frac{1}{c} [\mathbf{vH}], \tag{37}$$

where $\mathbf{H}$ = the external magnetic field, ϱ = the density of plasma; $\mathbf{E}$, $\mathbf{v}$ and $\mathbf{h}$ are small disturbances. In Equation (35) the gradient of pressure is neglected, in (36) the displacement current is omitted, and Equation (37) is written in the assumption that the Hall effect is negligible and the dissipation due to the finite conductivity is small and can be neglected. Moreover, the effects of viscosity, heat conductivity, etc., are not taken into account. The validity of Equations (34) – (37) for the description of the oscillations of the magnetosphere was repeatedly discussed in the literature, and we shall not consider this question.

Differentiating (34) on time, and excluding the field $\mathbf{E}$ by means of (35) – (37) we obtain the wave equation for $\mathbf{h}$:

$$\operatorname{rot}\{(4\pi\varrho)^{-1}[\mathbf{H}[\mathbf{H}\operatorname{rot}\mathbf{h}]]\} - \frac{\partial^2\mathbf{h}}{\partial t^2} = 0. \tag{38}$$

Similarly we obtain the equation for $\mathbf{E}$:

$$(4\pi\varrho)^{-1}[\mathbf{H}[\mathbf{H}\operatorname{rot}\operatorname{rot}\mathbf{E}]] - \frac{\partial^2\mathbf{E}}{\partial t^2} = 0. \tag{39}$$

One can also write down the equation for $\mathbf{v}$ and it will be equivalent to either of Equations (38) – (39).

In some approximation the magnetosphere can be considered axially symmetric, and the solutions of the wave equation depending on φ can be found in the form $e^{im\varphi}$, where φ is the azimuth of spherical system of coordinates (r, v, φ) and m is an integer number. The wave equation is significantly simplified if the oscillations are also symmetrical ($m=0$). For this case we have two differential equations of the second order, non-connected with each other:

$$(r\sin v)(\mathbf{H}\nabla)[(4\pi\varrho)^{-1}(r\sin v)^{-2}(\mathbf{H}\nabla)(h_\varphi r\sin v)] - \frac{\partial^2 h_\varphi}{\partial t^2} = 0 \tag{40}$$

for toroidal oscillations, and

$$\left[\frac{\partial^2}{\partial r^2} + \frac{\sin v}{r^2}\frac{\partial}{\partial v}\frac{1}{\sin v}\frac{\partial}{\partial v}\right]\chi - \frac{1}{V_a^2}\frac{\partial^2\chi}{\partial t^2} = 0 \tag{41}$$

for poloidal oscillations, where $\chi \equiv (r\sin v)\,E_\varphi$ (DUNGEY, 1963).

If $m \neq 0$ or if the asymmetry of the magnetosphere is taken into account the situation is much more complicated. Some simplification arises for very great numbers of m (DUNGEY, 1963), but these cases are still insufficiently investigated. The basic attention is usually given to the Equations (40) – (41), because they can relatively easily be solved by numerical methods (MACDONALD, 1961; WATANABE, 1961; WESTPHAL and JACOBS, 1962; CAROVILLANO and RADOSKI, 1967). If the magnetic field is approximated by the dipole field, then it is sometimes more convenient to write down the wave equation in the so-called dipole coordinates (WATANABE, 1961; RADOSKI, 1967).

The boundary condition for the toroidal oscillations is given on the earth's surface and due to the high conductivity of the earth's crust has the following form

$$\mathbf{E}_t(r = r_e) = 0, \tag{42}$$

where $\mathbf{E}_t$ is the horizontal projection of the electric vector and r_e is the earth radius.

For poloidal oscillations the boundary conditions must be given for the earth's surface, for the outer boundary of the magnetosphere and in general for all other boundaries inside the magnetosphere, for instance on the surface of the 'knee' (VANIAN and ZYBIN, 1967).

APP. 2: THE INDEX OF REFRACTION FOR THE COLD PLASMA

The index of refraction $n = ck/\omega$ for the homogeneous magnetoactive plasma is determined by solution of the dispersion equation (GINSBURG, 1960; STIX, 1962):

$$\mathrm{Det}\{\varepsilon_{\alpha\beta} - n^2(\delta_{\alpha\beta} - k_\alpha k_\beta/k^2)\} = 0, \tag{43}$$

where k_α = the component of the wave vector $\mathbf{k}$, $\delta_{\alpha\beta}$ = the symbol of Kroneker. The tensor of the complex dielectric permeance $\varepsilon_{\alpha\beta}$ is determined by the specific properties of the medium. If we neglect the collisions and the thermal movements of the particles then the tensor $\varepsilon_{\alpha\beta}$ will be of Hermite type: $\varepsilon^*_{\alpha\beta} = \varepsilon_{\beta\alpha}$. In the Cartesian system of coordinates with the axes z directed along the external geomagnetic field it has in this case the following form:

$$\varepsilon_{\alpha\beta} = \begin{Bmatrix} \varepsilon & ig & 0 \\ -ig & \varepsilon & 0 \\ 0 & 0 & \eta \end{Bmatrix} \tag{44}$$

$$\varepsilon = 1 - \Sigma \frac{\omega_{0a}^2}{\omega^2 - \Omega_a^2}, \qquad g = 1 - \Sigma \frac{\omega_{0a}\Omega_a}{\omega(\omega - \Omega_a)},$$

$$\eta = 1 - \Sigma \frac{\omega_{0a}^2}{\omega^2},$$

where $\omega_{0\alpha}^2 = 4\pi e_a^2 N_a/m_a$, $\Omega_a = e_a H/m_a c$, e_a, m_a and N_a are the charge, the mass and the concentration of the particles of the type 'a'. The addition is made on all particles constituting the plasma.

The solution of the dispersion equation (43) with the tensor in form (44) gives a rather complicated dependence of $n^2(\omega, \theta)$ from the frequency of the wave ω and the direction of propagation $\theta = \arccos(k_z/k)$. In the general case, it is impossible to divide the waves on the longitudinal and the transverse ones. But a rather simple situation arises when the waves are propagated strictly along the external magnetic field ($\theta = 0$). The index of refraction is determined in this case by the following expression (STIX, 1962):

$$n_\pm^2(\omega) = 1 - \Sigma \frac{\omega_{0a}^2}{\omega(\omega \pm \Omega_a)}. \tag{45}$$

If the plasma consists only of electrons and ions of one type, then

$$n_{\pm}^2(\omega) = \frac{n_a^2}{1 \pm \omega/\Omega_i} + 1, \tag{46}$$

where $n_a^2 = c^2/V_a^2$. The waves have a circular polarization with right-hand (R-mode) and left-hand (L-mode) direction of rotation of the electric vector (upper and lower signs in the expressions (46) respectively). We shall also give the expression for $n^2(\theta=0)$ in the proton-helium plasma (GINTZBURG, 1962; GURNETT *et al.*, 1965)

$$n_{\pm}^2(\omega) \approx \frac{n_a^2}{1 \pm \omega/\Omega_{\mathrm{H}^+}} \left\{1 + \frac{3\xi}{1 \pm \omega/\Omega_{\mathrm{He}^+}}\right\} + 1, \tag{47}$$

where $\xi \equiv N(\mathrm{He}^+)/N(e^-)$ is the relative concentration of the single-charged helium ions, $\xi \ll 1$. The dispersion curves in the proton-helium plasma are given in Figure 36.

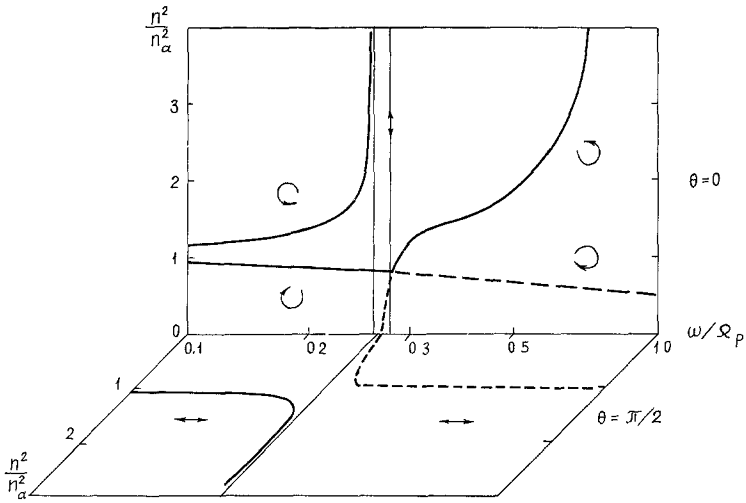

Fig. 36. The dispersion curves for waves in the cold proton-helium plasma. The relative concentration of He^+ ions is 0.01. Cases of transverse ($\theta = \pi/2$) and longitudinal ($\theta = 0$) propagation are shown. The arrows show the character of polarization of waves.

If the waves are propagated under an arbitrary angle to the external geomagnetic field, and $n_a^2 \gg 1$, not very complicated expressions for n^2 can be then written for the frequency range in the vicinity of the gyrofrequencies of ions ($\omega \lesssim \Omega_i$)

$$\begin{aligned} n_+^2 &\approx \frac{n_a^2}{1 + \cos^2\theta}, \\ n_-^2 &\approx \frac{n_a^2}{1 - \omega/\Omega_i} \frac{1 + \cos^2\theta}{2\cos^2\theta}, \end{aligned} \tag{48}$$

and also in the hydromagnetic range of frequencies ($\omega \ll \Omega_i$):

$$n_+^2 \approx n_a^2, \qquad n_-^2 \approx n_a^2/\cos^2\theta. \tag{49}$$

The expression for the refraction index of cold plasma allows analysis of the approximation of geometrical optic, the character of the trajectory of the refraction and the spreading of the wave packets propagating in the magnetosphere of the earth (RAO and BOOKER, 1963; SUGIURA, 1965; DOWDEN, 1965; JACOBS and WATANABE, 1964; OBAYASHI, 1965).

In some cases the necessity arises to know the index of refraction in the moving system of coordinates. If the plasma moves relative to the observer with the velocity **u**, and in the system of coordinates in which plasma is quiescent the index of refraction is $n(\omega, \theta)$, then in the system of the observer the index of refraction is equal (GUL'ELMI, 1963):

$$n' \approx n + \beta_z \left\{ \left(1 - n \frac{\partial \omega n}{\partial \omega} \right) \frac{\cos \gamma}{\cos \alpha} - \frac{1}{n} \frac{\partial n}{\partial \cos \theta} \left(1 - \frac{\cos \gamma \cos \theta}{\cos \alpha} \right) \right\}, \tag{50}$$

where $\beta_z = U_z/c$, $U_z = U \cos \alpha$, $\alpha =$ the angle between the vectors **U** and **H**, and $\gamma =$ the angle between the vectors **U** and **k**.

In the quiescent plasma the projection of the vector of group velocity $\mathbf{V}_g$ on the wave vector is equal (GINSBURG, 1960)

$$V_g = \frac{c}{\partial \omega n / \partial \omega}, \tag{51}$$

and the angle between $\mathbf{V}_g$ and **k** is

$$\Psi = \text{arc tg} \left\{ - \frac{1}{n} \frac{\partial n}{\partial \theta} \right\}. \tag{52}$$

As the rise in the moving plasma, corrections δV_g and $\delta \Psi$ to the quantities V_g and Ψ are usually small, it is convenient to utilize the following approximate expressions

$$\frac{\delta V_g}{V_g} \approx - \frac{\partial \omega \delta n}{\partial \omega} \bigg/ \frac{\partial \omega n}{\partial \omega}, \tag{53}$$

$$\delta \Psi \approx - \frac{\partial}{\partial \theta} \left(\frac{\delta n}{n} \right) \bigg/ \left\{ 1 + \left(\frac{1}{n} \frac{\partial n}{\partial \theta} \right) \right\}. \tag{54}$$

Here δn is the second member in the right part of (50). In the case of the longitudinal propagation of slow waves ($n^2 \gg 1$) the expression determining δn has a simpler form

$$\frac{\delta n}{n} \approx - \frac{U_z}{c} \frac{\partial \omega n}{\partial \omega}. \tag{55}$$

GUL'ELMI (1963, 1966c, 1967b, d) has applied the expressions (53) – (55) practically to the theory of propagation of whistlers, pearls, and proton whistlers.

APP. 3: THE KINETIC INSTABILITY

In the real plasma the tensor of the dielectric permeability is of non-Hermite type, and this is revealed in the growing and damping of oscillations. Non-Hermitian part of the tensor $\varepsilon_{\alpha\beta}$ is determined by the properties of the distribution function

$f(\mathbf{v}, \mathbf{r}, t)$ of particles constituting the plasma. If small disturbances in plasma are growing, it means that the initial function is unstable and the transition into the stable state must take place in time.

In the linear approximation the conditions of instability and the coefficients of waves amplification can be found by the analysis of the roots of the corresponding dispersion equation. The dispersion equation for the transverse waves $e^{i(kz-wt)}$ propagating along the external geomagnetic field in the collisionless plasma has the following form (SAGDEEV and SHAFRANOV, 1961; CORNWALL, 1965; KENNELL and PETSCHEK, 1966)

$$\frac{c^2k^2}{\omega^2} = 1 + \frac{4\pi^2}{\omega} \sum \frac{e_a^2 N_a}{m_a} \int \frac{V_\perp^2 \,\mathrm{d}V_\perp \,\mathrm{d}V_z}{\omega - kV_z \pm \Omega_a} \left[\left(1 - \frac{kV_z}{\omega}\right) \frac{\partial f_a}{\partial V_\perp} + \frac{kV_z}{\omega} \frac{\partial f_a}{\partial V_z} \right], \tag{56}$$

where $f_a(V_\perp V_z)$ is the function of distribution of the particles of the type 'a' on longitudinal V_z and transverse $V_\perp$ velocities. The function is normalized so that $\int f(V_\perp V_z) V_\perp \,\mathrm{d}V_\perp \,\mathrm{d}V_z = 1$. The upper and the lower signs correspond usually to the waves of the right- and left-hand polarizations.

Let us represent the function of particles distribution in the form of a sum consisting of two parts. One of these parts (the Maxwellian) will represent the distribution on velocities of the particles of thermal plasma in the magnetosphere. The other (non-Maxwellian) will describe the energetic particles, which may be considered a small admixture to the thermal plasma. ($N' \ll N$, where N is the whole concentration of plasma, and N' is the concentration of energetic particles.) If the following inequalities take place

$$kV_{T\mathrm{e,i}} \ll |\Omega_{\mathrm{e,i}} - \omega|, \qquad kV_{T\mathrm{e,i}} \ll \omega, \tag{57}$$

where $V_{T\mathrm{e,i}} = \sqrt{2T_{\mathrm{e,i}}/m_{\mathrm{e,i}}}$ is the most probable velocity of the thermal plasma, then, the thermal plasma may be considered as a cold one, and we can write the dispersion Equation (56) in the form (CORNWALL, 1965; LIEMOHN, 1967:

$$k^2 - \frac{\omega^2}{c^2} n_\pm^2(\omega) = i\pi^2 \frac{\Omega_\mathrm{i}\omega_0'^2}{c^2 k} \int\limits_0^\infty V_\perp^2 \,\mathrm{d}V_\perp \left[\frac{kV_\perp}{\Omega_\mathrm{i}} \frac{\partial f}{\partial V_z} \mp \frac{\partial f}{\partial V_\perp} \right]_{v_z = u}, \tag{58}$$

where $n_\pm$ is the refraction index (45), $u = (\omega \pm \Omega_\mathrm{i})/k =$ the resonance velocity, $f(V_\perp V_z)$ = the function of distribution of energetic particles (protons), $\omega_0' = \sqrt{4\pi e^2 N'/m_\mathrm{i}}$.

If we assume different forms of distribution function, we can investigate the roots of the dispersion equation $\omega = \omega' + i\omega''$ for the given and real values of the wave number k. In another setting of the problem, which we shall utilize, the roots $k = k' - ik''$ are investigated for the given real frequency ω. For $|k''| \ll |k'|$ the real part of the wave number is determined by the parameters of the cold plasma: $k'(\omega) = (\omega/c) n_\pm(\omega)$. The imaginary part is equal

$$k'' = \frac{\pi^2}{2} \frac{\Omega_\mathrm{i}}{c^2} \frac{\omega_0'^2}{k'^2} \int\limits_0^\infty V_\perp^2 \,\mathrm{d}V_\perp \left[\frac{kV_\perp}{\Omega_\mathrm{i}} \frac{\partial f}{\partial V_\perp} \mp \frac{\partial f}{\partial V_z} \right]_{V_z = u}. \tag{59}$$

If $k''<0$ the waves are damped; if $k''>0$ the waves are growing and the system is unstable. If the distribution function is isotropic ($f=f(|\mathbf{V}|)$), then the transverse waves are damped on all frequencies. Instability arises if the anisotropy of particle distribution on velocities takes place (CORNWALL, 1965; KENNELL and PETSCHEK, 1966).

Let us utilize the distribution function of the form:

$$f_n(V_\perp, V_z) = \frac{(V_\perp/W_\perp)^{2n}}{\pi^{3/2} W_\| W_\perp^2 n!} \exp(-V_\perp^2/W_\perp^2) \exp[-(V_z - U_\|)^2/W_\|^2], \tag{60}$$

where $n=0, 1, 3\ldots$, $W_\perp$, $W_\|$ and $U_\|$ are some parameters of the distribution. The function (60) sufficiently flexibly describes the different situations. So if $n=0$, $U_\|=0$ we get the two temperature Maxwell distribution ($T_{\perp,\|}=m_i W_{\perp,\|}^2/2$). When $n\geqslant 1$ the function has a maximum when $V_\perp = U_\perp \equiv n^{1/2} W_\perp$ with the relative half width of the other $\langle V_\perp^2\rangle^{1/2}/U_\perp \approx 2/n$.

If, on the other hand, $n\to\infty$, $W_{\perp,\|}\to 0$ and $W_\perp\sqrt{n}=$ const, then (60) transfers in the distribution of the form $\sim\delta(V_\perp - U_\perp)\,\delta(V_z - U_\|)$ (DORY *et al.*, 1965).

Substituting (60) into (59) we obtain (GUL'ELMI, 1966d):

$$k''(\omega) = \frac{\sqrt{\pi}}{2} \frac{\omega_0'^2}{c^2 k^2} \frac{\Omega_i}{W_\|} \left\{ \frac{T_\perp}{T_\|}(n+1) \left[\frac{ku}{\Omega_i} \mp 1 - \frac{\omega}{\Omega_i} \right] \pm 1 \right\} \times$$
$$\times \exp\left\{ -\frac{\Omega_i^2}{k^2 W_\|^2} \left[1 \pm \frac{\omega}{\Omega_i} \mp \frac{ku_\|}{\Omega_i} \right]^2 \right\}, \qquad n = 0, 1, 2, \ldots. \tag{61}$$

Let us consider the growing of the waves of the left-hand polarization. If $n=0$, $U_\|=0$, the instability takes place when $T_\perp > T_\|$ on the frequencies $\omega<\Omega_i(1-T_\perp/T_\|)$. If in addition $W_\| \gg V_a$, then from (61) we obtain

$$k''(\omega) \approx \frac{\sqrt{\pi}}{2} \frac{\Omega_i}{W_\|} \frac{\omega_0'^2}{\omega^2} \frac{\delta}{n_a^2} \exp\left\{ -\left(\frac{V_a}{W_\|} \frac{\Omega_i}{\omega} \right)^2 \right\}, \tag{62}$$

where $\delta \equiv (T_\perp/T_\| - 1)$ is the degree of anisotropy of the temperatures; $n_a \equiv c/V_a$. In this case $k''(\omega)$ has a maximum on the frequency

$$\omega_m \approx \Omega_i \left(\frac{V_a}{W_\|} \right).$$

Let us consider now the waves of left-hand polarization in the Alfvèn region of the frequencies ($\omega \ll \Omega_i$), but when $n \gg 1$, $W_\perp \approx w_\| \ll U_{\perp,\|}$ (almost monoenergetic stream of protons):

$$k''(\omega) \approx \frac{\sqrt{\pi}}{2} \frac{\omega_0'^2}{c^2 k^2} \frac{u_\perp^2}{W^2} \frac{(ku_\| + \Omega_i)}{W} \exp\left\{ -\frac{(\Omega_i + ku_\|)^2}{k^2 W^2} \right\}, \tag{63}$$

where $k \approx \omega/v_a$. The wave will be maximally unstable if it propagates towards ($ku_\| <0$) the stream with a frequency $\omega_m \lesssim \Omega_i |V_a/U_\||$. The relative width of the frequency range in which effective exchange between the energies of waves and particles of the stream takes place is rather narrow: $\Delta\omega/\omega_m \approx W/\sqrt{2}|U_{\|}|$.

In the investigations of some authors the solutions of the dispersion equation (56) are found for other forms of energetic particles distribution functions (NEUFELD and WRIGHT, 1963; HULTQVIST, 1965; CORNWALL, 1965, 1966; HRUŠKA, 1966; KENNELL and PETSCHEK, 1966; TVERSKOY, 1967; LIEMOHN, 1967). The practical application of all these results to the theory of micropulsations generation consists in the calculations of the coefficients of waves amplification having travelled a definite path in the magnetosphere

$$A(\omega) = \int_{(l)} k''(\omega, l)\, \mathrm{d}\ , \tag{64}$$

where the integration is conducted along the trajectory of the wave. These calculations are valid only in cases when the instability of distribution of energetic particles is of convective type (STURROCK, 1958). Meanwhile JACOBS and WATANABE (1966) using the criteria of Sturrock have shown that in the interesting case of interaction of a beam of fast protons with the transverse waves of left-hand polarization the instability has a non-convective character. It was suggested that there is no scatter of longitudinal velocities for the particles of the beam.

The real beams are, of course, in some or other measure dispersed. It was interesting therefore to make clear to what degree the results of JACOBS and WATANABE (1966) depend on the initial suggestion of the absence of the longitudinal velocities scatter. For orientation in this question one can use the approximate criterion of FEIX (1963), which states that the instability will be convective if the group velocity of the growing waves is greater than some critical value (depending on $k''(\omega)$, and on the other hand the instability will be absolute for the inverse inequality of velocities. In case (63) group velocity is equal to the Alfvén one, and the critical velocity U is of the order (GUL'ELMI, 1967a)

$$U \approx V_a \sqrt{\frac{\pi}{e}} \frac{\omega_0'^2}{\Omega_i^2} \left(\frac{U_{\|}}{W}\right)^3 \left(\frac{U_{\perp}}{c}\right)^2 . \tag{65}$$

Comparing (63) and (64) one can conclude that the instability will be convective if the scatter of longitudinal velocities of the particles exceeds some critical value:

$$W > [k''(\omega_m)/k'(\omega_m)]\, |U_{\|}| . \tag{66}$$

APP. 4: THE CYCLOTRON INSTABILITY OF THE OUTER RADIATION BELT PROTONS

The analysis of the cyclotron instability of the outer radiation belt protons present interest from two points of view. First of all, it seems that the hydromagnetic waves growing in the proton belt can be identified with one of the type of micropulsations observed on the earth's surface, namely the Pc-1 pulsations. Due to the absence of the satisfactory theory of Pc-1 generation this aspect of the problem has a serious significance (CORNWALL, 1965; TVERSKOY, 1967; LIEMOHN, 1967). Secondly, no less important is the fact that the instability of the distribution function of the trapped protons leads through the mechanism of magnetic scattering to the leakage of particles from the geomagnetic trap, and therefore plays a definite role in forming the space structure of the radiation belt (CORNWALL, 1966; KENNELL and PETSCHEK, 1966).

Let us make an estimation of the coefficient of the Alfvén waves amplification by the protons of the outer radiation belt. The anisotropy of the angular distribution of protons can in some measure be approximated by the Maxwell function with different temperatures along and across the magnetic field: $T_\| < T_\perp$. If the relation $V_a \ll \sqrt{2T_\|/m_i}$ is fulfilled, then Equation (62) is valid. The amplification will be maximal when $\omega = \omega_m$

$$k''_m \approx \frac{\sqrt{\pi}}{2e} \frac{\omega_0'^2 W_\| \delta}{c^2 \Omega_i}. \tag{67}$$

The trajectories of Alfvén waves are the lines of the geomagnetic field. Let us measure the coordinate l along the trajectory beginning from the plane of the magnetic equator. From the expression (67) it is seen that the greatest amplification takes place at the top of the trajectories. Indeed, when $l=0$, the frequency $\Omega_i(l)$ is minimal and as $T_\perp > T_\|$ the frequency $\omega_0'(l)$ is maximal. Therefore, on a given L shell, the wave with a frequency $\omega = \omega_m(l=0)$ will grow most quickly.

The dependence $k''(l)$ on frequency $\omega = \omega_m(l=0)$ is determined by the factor $\sim \exp\{-[H(l)/H(0)]^4\}$ (as is seen from (62)). Assuming that the geomagnetic field is a dipole field and setting out $H(l)$ into a row in the vicinity of the point $l=0$, we shall find the length of the trajectory on which the effective amplification of the signal takes place: $l_{eff} \approx 2.6 \times 10^8\, L$ cm. This is the doubled distance for which the value $k''(l)$ diminishes in e-times in respect of the value $k''(l=0)$. Utilizing now (67) we find the coefficient of amplification ($A \approx k''_m l_{eff}$) for the one passing of the signal through the region of trapped radiation, from one conjugate point to the other:

$$A(L) \approx 6 \times 10^{-11} L^4 I(L)\, \delta, \tag{68}$$

where $I \equiv N' W_\|$. The supercriticality of the proton belt is relatively small: for $L \approx 4$, $I \approx 5 \times 10^7$ cm^{-2} sec^{-1} and $\delta \approx 1$ the coefficient of amplification is of the order of $A \approx 1$.

The convective character of the instability of the radiation belt is quite evident. In other words, the proton belt works as an amplificator of hydromagnetic signals. But, due to the fact that the amplified signal, after the reflection from the ionosphere returns to the system, the positive feedback arises and the system can be driven into the regime of generation. The condition of self-excitation has a simple form: $A > \ln(1/P)$ where P is the coefficient of reflection from the ionosphere. The transition to the supercritical state is possible both for the augmenting of A and for diminishing of waves-energy loss in the ionosphere. Because the quantity A does not depend practically on the local time, and on the other hand the absorption in the ionosphere during the night is less than during the day – the most favourable hours for the generation are the night hours.

TABLE VII

Type classification of 1963	Period (sec)	Additional characteristics and names	Amplitude (γ) (average)	Characteristic of the spectrum
Pc 1	0.2–5	Pearls. According to recent investigations they consist of two groups: $T \leq 2$ sec and $T \geq 2$ sec	0.05–0.1	Signals in a narrow band frequency range with periodic structure on sonogrammes
Pc 2 Pc 3 Pc 4	5–10 10–45 45–150	Continuous pulsations pc	0.1–1	Relatively regular pulsations with distinct mean period
Pc 5	150–600	pg (giant pulsations)	1–10	Relatively regular pulsations
Pi 1	1–40	Noise bursts	0.01–0.1	Wide band emission. Bursts of wide band emissions
IPDP	1–40 (1–10 for the regular part	Gurglers Pi 1 + Pc 1	0.01–0.1	Wide band emissions with growing average frequency, with separate superimposed structured elements (pearls)
Pi 2	40–150	Pulsation trains (pt), according to recent investigations have periods up to 250 sec	1–5	Separate trains or series of oscillation trains

The growing of the waves takes place until the non-linear processes come into play. Two non-linear mechanisms are known which provide the restriction of the amplitudes of the plasma oscillation (SAGDEEV, GALEEV and ORAEVSKY, 1966).

(1) The decay instability of waves, and

(2) The diffusion of resonance particles in the space of velocities under the influence of growing oscillations.

The relative role of these processes in the condition of the magnetosphere is not yet definitely known. Usually it is suggested that the main non-linear process is the diffusion of the resonance particles into the cone of losses (magnetic scattering). The characteristic time of the magnetic scattering of protons is of the order

$$t_1 \sim \left(\frac{H}{h}\right)^2 \frac{1}{\Omega_i} \tag{69}$$

where h is the amplitude of hydromagnetic noises (KENNELL and PETSCHEK, 1966). Let us compare this quantity with the characteristic time of energy exchange between different components of spectra in dispersed wave packets (GALEEV and ORAEVSKY, 1962).

Geomagnetic Micropulsations

Time of occurrence	Character of planetary distribution	Connection with different types of magnetic activity
Day hours in aurora zone: night and early morning hours in middle latitude	Antiphase relation for the envelope of the series in opposite hemispheres; the global character in one hemisphere depending on period of Pc 1 and state of SMIG	Rising of Pc-1 activity 1–2 hours before, and 4–7 days after the magnetic storm
Day hours	Global on the dayside sometimes global on the whole earth; the modulation of the amplitude – global	Diminishing of the period with augmentation of magnetic activity
Morning and evening hours	Local in latitude and not greatly extended in longitude; strong correlation in conjugate points; dependence of the period from the latitude	Most typical for moderate magnetic activity
Night and early morning hours	Maximum in the aurora zone. Observed also in low and middle latitudes	Close correlation with aurora and connected with phenomena occurring simultaneously with aurora; X-ray burst, etc.
Evening hours	Maximum in subauroral zone. Observed also in middle and low latitudes	Occur in the main phase of the magnetic storms; coincide with aurora in low latitudes, and drastic changes of intensity in radiation belts
Evening and night hours	On the night hemisphere in general, often on the whole globe	Occur on the rising phase of bays. The periods diminish with rising of magnetic activity. The greatest periods correspond to the quiet days with Kp = 0

$$t_2 \sim \frac{1}{\omega}\left(\frac{H}{h}\right)^2\left(\frac{V_s}{V_a}\right), \tag{70}$$

where V_s is the velocity of slowed down magneto-acoustic waves. As $\omega/\Omega_i \approx 0.1$ and $V_s/V_a \approx 10^{-2}$, it seems that the magnetic scattering is a slower process than the decay process.

These estimates show that the processes of interaction of waves with each other may have a determining influence on the formation of the spectrum of hydromagnetic noises in the proton belt. From the condition $t_2\omega'' > 1$, where $\omega'' \approx k''_m V_a$ is the increment of the cyclotron instability, we shall estimate the upper value of the energy density of the hydromagnetic noises in the proton belt

$$\varepsilon < N'\varepsilon\left(\frac{V_s}{V_a}\right)\left(\frac{T_\perp}{T_\parallel} - 1\right), \tag{71}$$

where $\varepsilon = h^2/8\pi$, $\varepsilon_i = m_i W_\parallel^2/2$. In the maximum of the belt $N' = 0.1\ \text{cm}^{-3}$, $\varepsilon_i \approx 100\,\text{keV}$, $(V_s/V_a) \approx 10^{-2}$ and $T_\perp \approx 2T_\parallel$. Therefore we obtain $\varepsilon < 10^{-10}\ \text{erg/cm}^3$.

TABLE VIII

Diagnostics of Magnetosphere on Parameters of Micropulsations

Type of micropulsations	Interpretation		Diagnostics	
	Generation	Propagation	Parameters of magnetosphere	Methods of diagnostic
Pc 1 – Pearls	Cyclotron instability of energetic protons	In the magnetosphere along the field lines (anisotropic mode). In the ionosphere parallel to the earth surface (isotropic-mode)	Plasma density N and energy of resonance protons	Using the data on frequency and dispersion of the signals (see (4.3), (5.1) and (5.2))
Pc 2 Continuous Pc 3 pulsations Pc 4	Turbulent pulsations on the periphery of the magnetosphere	Poloidal oscillations	The location of the boundary of magnetosphere	Using the empirical relation $T \sim R_m^\nu, \quad \nu = 4.8$ (see 3.1)
Pc 5	Interaction of solar wind with magnetosphere on the morning and evening sides	Toroidal oscillations	Plasma density	Using the dependence of the period of oscillations on the latitude (see 4.2)
Pi 1 (sip) Noise bursts	Injections of charged particles in the ionosphere	Magnetostatic variations due to the changes of parameters of auroral electrojet	Spectra of electron streams fluctuations in the auroral zone	Using the spectra of micropulsations (see 5.3)
IPDP	Instability of distribution of charged particles in the ring current	L-mode or R-mode	Intensity changes in the radiation belts during magnetic storms	Using data on the frequency gradient in the IPDP, and the last attained frequency; (empirical relation) (see 5.3)
Pi 2 Pulsation trains	Impulsive processes in the neutral sheet in the tail of magnetosphere	Toroidal oscillations	Location of the last closed lines on the night side of the magnetosphere	Using data on periods of Pi 2 (empirical relation) (see 3.2)

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