

PROBLEMS OF PHYSICS OF Pc1 GEOMAGNETIC PULSATIONS: ON THE 90th ANNIVERSARY OF DISCOVERY OF PEARLS

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Abstract. “Pearl necklaces”, or simply “pearls”, are undoubtedly the true adornment of the rich diversity of ultra-low-frequency electromagnetic waves in Earth’s magnetosphere. They are noted for outstanding beauty of their form and the mystery of their origin. Pearls were first observed by E. Sucksdorff and L. Harang in 1936. This article celebrates the anniversary of their discovery. It briefly outlines the so-called standard model of pearl excitation and propagation. The key importance of the standard model’s fundamental principles in planning research and interpreting the results obtained is emphasized. We point out difficulties with the standard model, particularly the deviation from anti-symmetry in the appearance of pearls at conjugate

points. An alternative model is proposed which is based on the concept of an ion-cyclotron resonator located in the equatorial zone of the outer radiation belt. It is hypothesized that the excitation of a discrete sequence of pearls is caused by ponderomotive self-Q-modulation of the ion-cyclotron resonator.

Keywords: magnetosphere, radiation belt, ion-cyclotron wave, Alfvén wave, ion-cyclotron resonator, ponderomotive force.

INTRODUCTION

In April 2006, a special session “Pc1 Pearl Waves: Discovery, Morphology and Physics” was held in Vienna as part of the General Assembly of the European Geosciences Union (EGU), dedicated to the 70th anniversary of the discovery of ultra-low-frequency electromagnetic waves in the Pc1 (0.2–5 Hz) range [<https://meetings.copernicus.org/egu2006>]. In the session, organized, among others, on the initiative of the authors of this article, reports were presented by premier researchers of one of the most beautiful and mysterious wave phenomena. The reports were published in a special issue of the Journal of Atmospheric and Solar-Terrestrial Physics [Kangas et al., 2007].

Pc1 waves, or pearls as they are commonly referred to, were first recorded by Eyvind Sucksdorff at the Sodankylä Observatory and by Leiv Harang at the Tromsø Observato-

ry [Sucksdorff, 1936; Harang, 1936; Raita, Kultima, 2007].

Figure 1 illustrates a series of pearls recorded by a digital induction magnetometer. Pc1 oscillations lie in the frequency range 1.0–1.4 Hz, their amplitude is as high as 15 pT. The geomagnetic field horizontal *X* component is shown.

After 20 years, the interest in pearls did not wane. The discovery turned out to be meaningful and profound. In this paper, we briefly describe the standard model of pearl excitation and propagation. Particular emphasis is placed on the fact that the model, presented by a number of authors in a simple and clear form, can calculate two important parameters of pearls, namely the carrier frequency of oscillations and the wave packet repetition period. It is, however, difficult to interpret the discreteness of pearls within the framework of the standard model. The standard model is also contradicted by

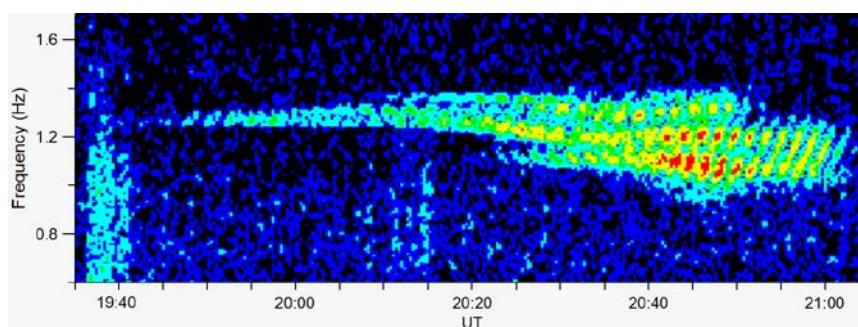


Figure 1. An example of the dynamic spectrum of a series of pearls observed at the mid-latitude Sayan Solar Observatory (Mondy village, Buryatia) on March 23, 2016

the absence of strict antiphase of the oscillation amplitude envelope at conjugate points. In an attempt to go beyond the standard model, we have qualitatively examined the hypothesis about the existence of an ion-cyclotron resonator with Q-modulation in the outer radiation belt, and the modulation occurs under the influence of ponderomotive forces on a small admixture of heavy ions in magnetospheric plasma.

1. ANALYSIS OF THE STANDARD MODEL

In the second half of the last century, the so-called standard model of pearl excitation and propagation was developed (see reviews [Troitskaya, Guglielmi, 1967; Kangas et al., 1998; Demekhov, 2007; Klimushkin et al., 2010; Guglielmi, Potapov, 2019], monographs [Guglielmi, Troitskaya, 1973; Nishida, 1980; Trakhtengerts et al., 1986], and references therein). This model relies on the concept of a wave packet propagating along a geomagnetic field line. The packet is periodically reflected from the ionosphere at magnetically conjugate points and intensifies in the outer radiation belt. When recorded on the Earth surface, the wave packet repetition period

$$\tau(\omega) = \frac{2}{c} \int_{l_N}^{l_S} \frac{d\omega n}{d\omega} dl, \quad (1)$$

where ω is the carrier frequency; $n(\omega, l)$ is the refractive index; integration is performed along the geomagnetic field line from a conjugate point in the Northern Hemisphere l_N to a conjugate point in the Southern Hemisphere l_S . It is assumed that a wave packet is a superposition of waves belonging to the Alfvén branch of dispersion curves. (Recall that waves of this type have left-handed circular polarization during longitudinal propagation and are usually called ion cyclotron waves.)

When reflected from the ionosphere, the wave amplitude decreases, but it restores when the wave packet propagates in the vicinity of the apex of the trajectory. Cornwall [1965] explained the reason for the restoration as follows. The distribution of protons in the radiation belt is nonequilibrium: the average transverse energy is higher than the average longitudinal energy. This leads to the amplification of ion cyclotron waves in the near-equatorial segment of the trajectory. If the amplification compensates for the loss of energy of the wave packet during reflection from the ionosphere, according to the standard model a periodic sequence of discrete signals occurs which is observed on the Earth surface in the form of a pearl necklace (as termed by Sucksdorff).

The wave packet carrier frequency is determined by the ion-cyclotron resonance condition at the trajectory equator [Cornwall, 1965]. Here is an approximate formula for the carrier frequency as reference:

$$\omega = \Omega_p c_A / v_{\parallel p}, \quad (2)$$

where Ω_p is the proton gyrofrequency; c_A is the Alfvén velocity; $v_{\parallel p}$ is the longitudinal velocity of resonant protons of the radiation belt, $\omega \ll \Omega_p$. The combination of

formulas (1) and (2) yields an approximate relation $\tau\omega = \text{const}$ that is valid in practice.

At conjugate points, pearls appear alternately, i.e. envelopes of wave packet amplitudes are shifted by 180° relative to each other. Observations at conjugate points Sogra and Kerguelen confirmed this prediction of the theory with reasonable accuracy [Gendrin, Troitskaya, 1965].

It, however, turned out that pearls are recorded on the Earth surface not only at conjugate points, but also far from them [Tepley, 1966]. A problem arose in the standard model, which was resolved as follows. It was hypothesized that in the ionospheric layers part of the energy of Alfvén waves incident on the ionosphere from above is reflected and propagates upward to the equatorial zone of the radiation belt, and another part of the energy is transformed into the energy of magnetosonic waves, which propagate along the Earth surface over considerable distances in the so-called ionospheric MHD waveguide [Tepley, Landshoff, 1966].

The standard model was criticized, especially in the light of the analysis of satellite data, which showed that the pearl packet repetition period measured on the ground and by a satellite is equal [Mursula et al., 2001]. Alternative hypotheses were put forward about the mechanism of pearl generation and propagation. It was most often supposed that discreteness of emission could result from source modulation by low-frequency (in the Pc4-5 range) ULF oscillations [Plasova-Bakounina et al., 1996; Mursula et al., 2001]. Nonetheless, firstly, no specific modulation mechanisms were proposed. Secondly, although modulation can barely explain the discreteness of emission, it cannot be the reason for alternating observation of pearls at conjugate or quasi-conjugate points anyway [Gendrin, Troitskaya, 1965].

In the standard model, it is really difficult to understand the discreteness of pearls. In particular, it is hard to comprehend the discreteness in combination with the antisymmetry in the appearance of wave packets at conjugate points. There is no doubt that a discrete sequence of wave packets is formed by nonlinear mechanisms of wave excitation and/or propagation. It was suggested that a pearl is a kind of soliton [Guglielmi, 2008], but it did not go beyond that. A model similar to the flow cultivator known in biology was examined [Guglielmi, 1971; Trakhtengerts et al., 1986; Bessalov, Trakhtengerts, 1986]. The model is an open resonator, i.e. a longitudinal waveguide with partially reflecting end faces through the side walls of which, formed by caustics, radiation belt protons flow in and out, drifting in azimuth around Earth. In this case, it is possible to reproduce the discreteness, but the antisymmetry cannot be reproduced. The well-known model of a self-excited oscillator with hard mode was unsuccessfully employed in radio physics [Guglielmi, Troitskaya, 1973]. Much attention was paid to the quasi-linear theory of ion-cyclotron instability of the radiation belt [Feygin, Kurchashov, 1975]. Interpretation of the discreteness failed, but a very important conclusion was

made that the self-excitation of ion cyclotron waves imposes an upper bound to the flux of geomagnetically trapped energetic protons [Kennel, Petschek, 1966].

2. ION-CYCLOTRON RESONATOR

In order to find new approaches to solving the problem of pearl discreteness, we will try to go beyond the standard model. We follow the idea of pearl excitation by protons of the outer radiation belt, but discard the second component of the standard model, namely the periodic oscillation of the wave packet between magnetically conjugate points of the Sogra—Kerguelen type.

The presence of the resonator provides feedback in the self-oscillating dynamic system that excites pearls. Our idea is that the end faces of the open resonator are not ionospheric layers in the Northern and Southern hemispheres, but two reflection points of ion cyclotron waves located in the magnetosphere high above Earth symmetrically relative to the plane of the geomagnetic equator [Guglielmi et al., 2000; Guglielmi, Potapov, 2012].

Figure 2 gives an insight into the ion-cyclotron resonator (ICR) in Earth's magnetosphere. ICR is located between the reflection points z_0 in the northern and southern parts of the magnetosphere. Two poles of n^2 are symmetric relative to the plane of the geomagnetic equator. They occur in those places, where the wave frequency ω is equal to the local gyrofrequency of heavy ions Ω_2 . There is an opaque region between zero and pole of n^2 in which $n^2 < 0$. The opaque region width

$$\Delta z = \left| \frac{1}{B} \frac{\partial B}{\partial z} \right|^{-1} \kappa_2, \quad (3)$$

where B is the magnetic field strength; κ_2 is the clarke of heavy ions, $\kappa_2 \ll 1$. All values on the right side of (3)

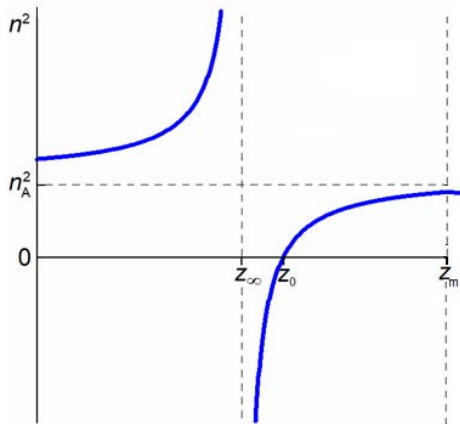


Figure 2. Squared refractive index n^2 along the ion cyclotron wave path in the presence of a small admixture of heavy ions in magnetospheric plasma. The Z -axis is directed along the geomagnetic field line. The field minimum along the path is located at the point z_m . The dependence $n^2(z)$ in the southern part of the magnetosphere is shown. In its northern part, this dependence has the form of a specular reflection $n^2(z)$ from the plane $z=z_m$

refer to the point z_∞ . Cold plasma is assumed to consist of light and heavy ions (indices 1 and 2 respectively), for example, H^+ and O^+ , with $\Omega_2 < \omega \ll \Omega_1$ for simplicity of describing the structure of ICR (for more detail, see [Guglielmi, Potapov, 2021; Guglielmi et al., 2025a]).

The coefficient of wave transmission through the opaque region D and the coefficient of reflection from it R are equal

$$D = \exp\left(-\frac{\pi}{2} \frac{\omega}{c_A} \Delta z\right), \quad (4)$$

$$R = 1 - \exp\left(-\pi \frac{\omega}{c_A} \Delta z\right).$$

Here we have adapted the formulas for D and R , given in the monograph [Ginzburg, 1967], to conditions in ICR.

We can see that with a sufficiently wide opaque region Δz there is a high- Q ICR. Even a small anisotropy of radiation belt protons causes an exponential increase in oscillation amplitude. The bandwidth is proportional to the clarke of heavy ions κ_2 . If, for one reason or another, the density of heavy ions decreases monotonously with time, the coefficient of wave transmission through the opaque region tends to unity; and the reflection coefficient, to zero. The Q -factor of the resonator decreases exponentially, and generation of oscillations stops.

There is a nuance here that should not be overlooked when describing the theory of pearls. Instability of particle distribution in plasma can be absolute or convective [Lifshitz, Pitaevsky, 1979]. Cyclotron instability of the radiation belt is convective [Guglielmi, 1979]. This means that the radiation belt itself functions as an amplifier, not a generator. A high- Q ICR is required to switch the radiation belt to the generation mode.

The existence of the ion cyclotron resonator in the narrow equatorial vicinity of the outer radiation belt follows from theoretical considerations. The authors of the theory [Guglielmi et al., 2000] unsuccessfully tried to obtain direct experimental evidence of the existence of ICR, using the method of spectral analysis of Pc1 waves recorded by ISEE-1 and -2. We have found an unexpected and rather convincing confirmation of the theory in [Loto'aniu et al., 2005], which was apparently carried out without regard to the problem of ICR existence. Let us take a closer look at this point.

The Combined Release and Radiation Effects Satellite (CRRES) measured alternating electromagnetic field components in the Pc1 range in the equatorial vicinity of the outer radiation belt. From the measurement data, the Poynting vector was calculated in order to determine the direction of the electromagnetic energy flux. 248 events with Pc1 oscillations were analyzed [Loto'aniu et al., 2005]. It turned out that in all cases the direction of the Poynting vector is close to the direction of the geomagnetic field line. This suggests that ion cyclotron waves were recorded. The most important conclusion from the measurements and calculations for us is that beyond the narrow band $\pm 11^\circ$ of geomagnetic latitudes in all the events considered the Poynting vector

is directed toward Earth. We consider this result as an indirect experimental evidence of the existence of ICR. Indeed, our resonator, which generates ion cyclotron waves, is located in a narrow equatorial zone. The pearls observed on the Earth surface are wave packets that leave the resonator through its end faces and propagate earthward. It should, however, be emphasized that these arguments do not solve the problem of pearl discreteness and do not answer the question about the mechanism of wave packet escape from the generation region in a narrow equatorial zone. The alternating appearance of pearls at conjugate points on the Earth surface also remains unclear. We discuss these key issues in the next section.

3. DISCRETENESS PROBLEM

We will try to qualitatively understand the discreteness of pearls by taking into account the ponderomotive forces acting in ICR. Recall that a ponderomotive force is a force quadratic in amplitude and averaged over the oscillation period, which acts on a medium from the alternating electromagnetic field. The general expression for ponderomotive force has a rather complex structure [Landau, Lifshitz, 2003]. It is sometimes convenient to single out the individual components of the force that dominate in a particular case. For example, the Abraham force of Pc3 magnetosonic wave leads to a noticeable deceleration of the solar wind ahead of the magnetospheric front [Guglielmi et al., 2025b]. The Alfvén wave ponderomotive force in the polar wind stream accelerates plasma transfer from the high-latitude ionosphere to the geomagnetic tail [Guglielmi, Potapov, 1999]. The action of the Pitaevskii force in the Pc1 range causes effective separation of ions with different charge-to-mass ratios. In particular, it has been theoretically established that the Pitaevskii force leads to an increase in the clark of heavy ions at the equator of the geomagnetic field line along which an ion cyclotron wave propagates [Guglielmi et al., 2024].

Let us imagine a hypothetical scenario in which the action of ponderomotive forces in ICR leads to the formation of discrete wave packets appearing alternately on the Earth surface in the Northern and Southern hemispheres.

For the sake of clarity, let there be a sufficiently low level of start-up oscillations in high-Q ICR at an initial time. The Clarke number is slightly increased at the equator. With time, the oscillation amplitude increases exponentially due to the radiation belt instability. Let us ask ourselves whether the ponderomotive force that is quadratic in amplitude and increases exponentially can limit wave energy pumping into the resonator. Below we present reasonings indicating that the answer may be positive.

Indeed, the Clarke number in the center of the resonator increases rapidly due to the ponderomotive "raking" of heavy ions from the periphery of the resonator toward its center. The partial pressure on the periphery drops, and heavy ions from the opaque region begin to escape equatorward. The opaque regions become thinner. The reflection coefficient R decreases, and the

transmission coefficient D increases. The wave field accumulated in the resonator gets a chance to quickly (with the Alfvén velocity) leave the near-equatorial zone and to begin propagating earthward in the form of a wave packet. It is unlikely that the two opaque regions that served as ICR end faces had the same width. Hence, the wave packet will leave the resonator through a thinner region. At the same time, ICR disappears. The amplitude of ion-cyclotron waves will decrease to the background level. The ponderomotive forces that used to hold a dense layer of heavy ions in the small vicinity of the equator are negligible. The layer begins to spread mainly toward a lower partial pressure, i.e. toward the disappeared end face of the former resonator. Heavy ions begin to fill the empty opaque region. The bandwidth increases, the reflection coefficient goes up, and the resonator is restored. The described pattern is repeated. It is natural to suppose that the opposite opaque region appears to be thinner this time. In other words, we assume that this time the wave packet will leave the resonator in the opposite direction. This will lead to the antisymmetric appearance of pearls at conjugate points.

We are fully aware that without physico-mathematical analysis of the system of nonlinear differential equations describing the dynamics of ICR in view of ponderomotive forces the presented scenario cannot be considered a solution to the discreteness problem. In this regard, it is of some interest to roughly estimate the period of ponderomotive self-Q-switching of ICR, which coincides with the pearl repetition period τ in our scenario. The self-switching period depends on a rather complex sequence of time intervals of varying duration. Among the fast processes, it is necessary to point out, first of all, the exponentially rapid increase in the amplitude of oscillations at high-Q ICR when $\Delta z \geq c_A / \omega$.

The process of motion of heavy ions from the opaque region into the resonator volume under the action of powerful ponderomotive force is also fast. It is, however, natural to assume that the greatest contribution to τ will be made not by fast processes, which are difficult to estimate without detailed numerical calculations, but by slow processes. The slowest process seems to be the filling of a thin opaque region with heavy ions after a wave packet quickly leaves the resonator and propagate rapidly toward Earth with the Alfvén velocity c_A . At this phase of evolution of our dynamic system, ponderomotive forces are inoperative and the relaxation process of the opaque region proceeds at a velocity v_2 of thermal motion of heavy ions. ICR will restore its high Q-factor when the bandwidth Δz increases to the Alfvén wave length c_A / ω . This gives an estimate

$$\tau\omega = 2c_A / v_2. \quad (5)$$

With a quite realistic ratio $c_A / v_2 = 300$, Formula (5) coincides with the empirical dependence $\tau f = 10^2$ (see the next section).

In addition to the above argument in favor of the correctness of the chosen direction for solving the discreteness problem, we point out the possibility of experimental testing of the proposed scenario. Let us tentatively note that the pearl repetition period is now determined not by

Formula (1), but by an unknown combination of key parameters of ICR such as the increment of oscillation growth, the speed of sound, the Alfvén velocity, the relative concentration of heavy ions, and possibly other parameters (of particular interest is the rate of azimuthal drift of radiation belt protons flowing into resonator through its eastern boundary). But here is what is interesting. To be specific, we will talk about the conjugate points Sogra and Kerguelen. Whatever be τ , it can be represented as $\tau = \tau_{SK} + \tau_{KS}$. Here, τ_{SK} is the apparent pearl travel time from Sogra to Kerguelen; and τ_{KS} , the apparent return travel time. The standard model predicts $\tau_{SK} = \tau_{KS}$, which corresponds to a 180° phase shift of envelopes at the conjugate points. Obviously, according to our scenario, $\tau_{SK} \neq \tau_{KS}$. Generally speaking, the difference $\tau_{SK} - \tau_{KS}$ can be measured.

For this purpose, we have used magnetograms of the Sogra—Kerguelen experiment from the archive of Borok Geophysical Observatory of IPE RAS. We have processed and analyzed the recording presented in Figure 3.

Arrival times of central parts of pearls with maximum amplitude of envelope filling were recorded. The carrier frequency of oscillations in all packets is 0.6 Hz. The peak-to-peak amplitude of oscillations varies approximately from 3 to 5 pT. Table lists arrival times of pearl packets at Sogra and Kerguelen and their travel time from one station to another and back.

Arrival times of pearl packets at Sogra (S) and Kerguelen (K) and their travel time from one station to another and back

Packet Number	Arrival time (UT)		Δt , s	
	S	K	S→K	K→S
1	23:17:16	23:18:02	46	53
2	23:18:55	23:19:41	46	61
3	23:20:42	23:21:37	56	
Median			46	57

The main conclusion which can be drawn from our analysis is that in this case there is a clear deviation from antisymmetric appearance of pearls at conjugate points. The phase shift of wave packet amplitude envelopes is close to 200° , and not to 180° , as predicted by the standard model of pearl propagation in the magnetosphere.

4. DISCUSSION

We will not exaggerate the disadvantages of the standard model. The model proved to be an excellent reference point when planning experimental and theoretical studies of wave phenomena in near-Earth space. It provided us with images and language for understanding the results of measurements and calculations for many decades. Let us point out a number of properties and patterns of occurrence and dynamics of Pc1 waves, established due to direct or indirect effect of basic statements of the standard model.

Apparently, the existence of the ionospheric MHD waveguide through which pearls propagate along the Earth surface suggested the existence of the ionospheric Alfvén resonator (IAR) [Polyakov, 1976; Polyakov, Rapoport, 1981] and stimulated relevant observations, which led to the discovery of the amazingly beautiful wave phenomenon in the Pc1 range [Belyaev et al., 1987; Belyaev et al., 1999; Börsinger et al., 2002; Potapov et al., 2014; Potapov et al., 2023].

The standard model prompted directions of searching for empirical patterns for Pc1 waves [Kangas et al., 1998]. Thus, a surprisingly stable statistically significant relation $\tau f \approx 10^2$ has experimentally been established between the repetition period τ and the carrier frequency of pearls $f = \omega/2\pi$. Analysis of (2) led to the prediction and then to the experimental detection of a jump in the carrier frequency of pearls during sudden compression of the magnetosphere by an interplanetary shock. The experimentally found relationship between the frequency jump and the amplitude of the sudden geomagnetic pulse is consistent with the theoretical estimate. Another experimentally confirmed theoretical prediction is that the sudden compression of the magnetosphere by an interplanetary shock causes excitation of a series of pearls in the dayside magnetosphere.

The morphology of Pc1 waves described in the literature based on results of ground-based and satellite experiments is exceptionally rich. It has been established that pearls are most often excited during the decline of the 11-year solar cycle [Matveeva, Troitskaya, 1965]. Seasonal and daily variations in the rate of occurrence of pearls have been thoroughly studied. It has been revealed that during a geomagnetic storm pearls are usually observed in the recovery phase. It has been suggested that during the storm main phase when the geoelectromagnetic field is

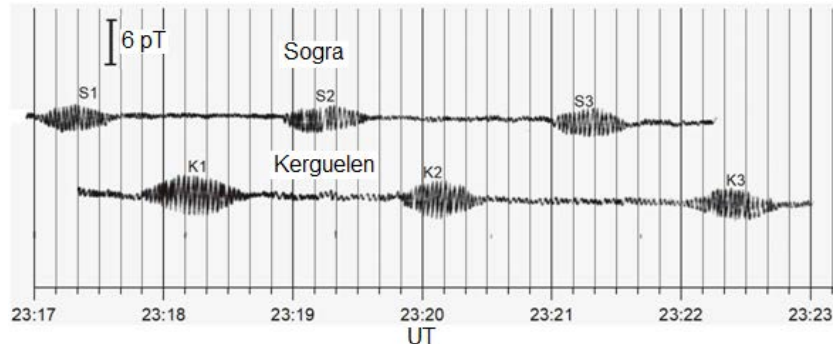


Figure 3. Fragment of simultaneous recording of pearls at magnetically adjacent Sogra and Kerguelen stations on March 5, 1965. Letters S and K with numerals from 1 to 3 denote consecutive pulsation packets detected at Sogra and Kerguelen respectively

globally disturbed in a wide range of frequencies pearls simply cannot be seen in magnetograms. A thorough spectral-temporal analysis of ULF oscillations during the main phase led to a remarkable discovery [Troitskaya, Melnikova, 1959; Troitskaya, 1961]. It turned out that at the peak of the main phase powerful oscillations in the Pc1 range are excited in the dusk sector of the magnetosphere, which are radically different from pearls. The mean frequency of the detected oscillations increases monotonously by several octaves for about half an hour.

The variety of alternative hypotheses that a researcher puts forward during calculations or experiments is of great heuristic importance regardless of the fact that many preliminary considerations will later be changed or completely discarded. Theoretical constructions make it possible to perform thought experiments on the basis of which a strategy for finding new properties and patterns of dynamics of the object under study is chosen. In closing, we would like to express our hope that the hypothesis of ponderomotive self-action of oscillations in the ion-cyclotron resonator will be useful in this sense.

CONCLUSION

We pay tribute and appreciation to Sucksdorff and Harang for the outstanding discovery that enriched magnetospheric physics. The search for the mechanism of pearl excitation drew the general idea of self-excitation of waves in the magnetosphere due to plasma instabilities. Research in this direction led to the discovery of the excitation of Pc3 waves ahead of near-Earth shock front as a result of beam instability of solar wind protons reflected from the wave front [Guglielmi, 1974; Potapov, 1974; Russell, Hoppe, 1983]. The observation of pearls and the development of ideas about wave packets in an active medium have enriched the nonlinear aspects of magnetospheric physics. In particular, the concept of self-limitation of the energetic proton flux in the outer radiation belt arose from the quasi-linear theory of Pc1 waves [Kennel, Petschek, 1966]. The discovery of the ionospheric MHD waveguide through which pearls propagate [Tepley, 1966] suggested the existence of a waveguide under the arch of the plasmasphere in which magnetosonic waves are excited at high harmonics of the gyrofrequency of outer radiation belt ions [Guglielmi et al., 1975]. To this far from complete list we should add that pearls are detected by magnetotelluric sounding during geological exploration.

The study of pearls goes on, and new discoveries await us. We pin our special hopes on searching for pearls in magnetospheres of other planets.

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