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DYNAMICS OF ENERGETIC PARTICLES IN THE MAGNETOSPHERE OF THE EARTH[1]

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Problems of dynamics of magnetospheric charged particles are discussed. Special attention is paid to the particles with rigidities above those for which the Alfvénic approximation is valid, but below the rigidities typical for cosmic rays. A variety of interesting problems for the "intermediate rigidity particles" is shown. The dynamics of the parameter of nonadiabaticity as well as the magnetic moment are discussed for the regimes of the strong, the weak and the Arnold diffusion, respectively. Consequences of the asymmetry of the field are assumed. Applications of the above considerations for the albedo particles high energy particles trapped in the radiation belt and low energy particles in the assymmetric magnetosphere are shown. The consequences of the nonadiabaticity of the particle motion are shown for solar cosmic rays penetrating into the polar caps and on the boundary position of the trapped protons during magnetic storms.

ДИНАМИКА ЭНЕРГИЧНЫХ ЧАСТИЦ В МАГНИТОСФЕРЕ ЗЕМЛИ

В работе обсуждаются вопросы динамики магнитосферных заряженных частиц высоких энергий. Особое внимание уделено частицам с жесткостями свыше тех, к которым применимо альвеновское приближение, но ниже тех, которые типичны для космических лучей. Показано, что существует ряд интересных физических проблем для частиц этих «промежуточных» жестокостей. Кроме того, обсуждаются изменения параметра неадиабатичности и магнитного момента для режима сильной и слабой диффузии, а также диффузии Арнольда. При этом здесь учтены следствия асимметрии поля. Показано, что аналогичное рассмотрение имеет место для частиц альбедо, для высокоэнергетических частиц, захваченных в радиационном поясе, и для низкоэнергетических частиц в асимметрической магнитосфере. Отмечаются также последствия неадиабатичности для движения частиц от солнечных космических лучей, проникающих в полярные шапки, и для положения границы протонов, захваченных во время геомагнитных бурь.

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I. INTRODUCTION

The particles registered in the magnetosphere are of various rigidities starting from electrons with energy dozens of eV up to cosmic rays penetrating it. The large range of rigidities of the particles causes different approaches to the description of their motion.

Two groups of particles with a greatly differing description of motion can be distinguished.

The problem of the penetration of cosmic rays into the geomagnetic dipole field was solved by Störmer [1], then this question was solved including the screening of the Earth's body [2].

After the discovery of deformation of the magnetosphere by the solar wind it become clear that the computation of the penetration of cosmic rays into the Earth's magnetosphere is a serious problem for an analytical solution, and the problem was solved by numerical methods on computers [3, 4].

The second important task is the investigation of low rigidity particle motion in the magnetosphere. The analysis of the motion of such particles is obviously made in Alfvén's approximation [5]. The motion of the particle is supposed to be a superposition of three independent motions: the rotation of the particle around the field line, around its guiding centre, oscillation of the guiding centre along the field line and the drift of the guiding centre around the Earth. To each of these motions there corresponds its own integral (adiabatic invariant). The conservation of the magnetic moment of the particle $\mu = p^2/2mB$ plays the determining role in the validity of such a description of the particle motion.

The magnetic moment of the particle is conserved when

$$\varrho(\nabla B/B) < \varepsilon \ll 1 \ [6],$$

where ϱ is the Larmor radius of the particle. Experimentally it is found to be $\varepsilon \simeq 0.1$.

The breaking of the invariant of motion is caused by the existence of electromagnetic fluctuations interacting with particles, the Coulomb scattering on the residual atmosphere. The dynamics of the motion of these low energy particles in the magnetosphere will be discussed in what follows.

II. FLUCTUATIONS OF MAGNETIC MOMENT

To begin with we shall consider the motion of particles for which μ is not an integral of motion due to large rigidity, and from the other hand the rigidity is lower than that of cosmic rays. According to [7]

$$2/L^2 \leqslant p/z < 14.9/L^2$$

p is in GeV/c, z is charge of the particle.

In fact the problem was in the fifties formulated for laboratory magnetic traps [8] and at that time the non-conservation of μ was already supposed to play a great role in the formation of the Earth's radiation belt [9].

In 1969 paper [10] was published, where the precise formula for the rate of the magnetic moment change was derived for the case of a non-uniform magnetic field

$$\dot{\mu} = \frac{mv_\perp}{BR_L}\left(v^2 - \frac{v_\perp^2}{2}\right)\sin\Phi - \frac{mv_\parallel v_\perp^2}{2B^2}\frac{\partial B}{\partial l}\sin 2\Phi \tag{1}$$

$v_\perp = v \sin\alpha$, $v_{/\!/} = v\cos\alpha$, α-pitch angle, R_L the radius of the field line curvature, Φ the phase of the particle rotation around the field line.

This formula gives the possibility to compute the change of the magnetic moment during the period of one oscillation along the field line [11—13] for the field of a different configuration. For the field of dipolar configuration the analytical expression for $\Delta\mu/\mu$ was obtained in [14, 15]. It should be noted that in these computations they neglected the second term, because its value fluctuates twice as frequently as that of the first. For the dipolar field in [14, 15] the formula is given by

$$\frac{\Delta\mu}{\mu} = \frac{0.74(14 - \sin^2\alpha)}{\sin 2\alpha}\exp\left(-\frac{3\Psi}{\chi_\perp}\right). \tag{2}$$

The analytical approximation of $\Psi(\alpha)$ [14] is

$$\Psi(\alpha) = \frac{1}{3\sqrt{2}\sin\alpha}\left[\left(\frac{1}{\sin^2\alpha} + 1\right)\operatorname{arcsh}\frac{\sin\alpha}{\cos\alpha} - \frac{1}{\sin\alpha}\right];$$

in [15] the tabulated values of $\Psi(\alpha)$ are given, based on numerical computations. $\chi_\perp = \varrho_\perp/R_L = 5.04 \times 10^{-5}\, pcL^2$ is the ratio of the Lamour radius of the particle to the curvature radius of the field line at the equator with $\alpha = 90°$, pc is measured in MeV.

III. REGIMES OF THE PITCH ANGLE DIFFUSION

In Fig. 1 the curve 1 shows the dependence of $\chi_\perp$ on the pitch-angle of the particle under conditions of a strong pitch-angle diffusion, when during one half of the bounce along the field line the change of the magnetic moment is such that $\Delta\alpha = \alpha$.

It should be noted that for the cut-off of the cosmic rays

$$p_{crit}(GV) = 14.9/L^2, \ \chi_\perp \simeq 0.7.$$

From the profile of curve 1 it can be seen that already at $\chi_\perp = 0.7$ the fluctuations of α may be arbitrary. This is confirmed by (2).

At $\chi_\perp$ less than that corresponding to the strong diffusion the weak pitch-angle diffusion occurs which is strongly decreased with decreasing $\chi_\perp$.

In [12] in analogy with [16] the authors supposed that two types of the magnetic moment fluctuations existed: the first is stochastic in character, occurring when the ratio of the half-period of oscillation along the field line to the average of the rotation period is not equal to an integer; to the second case (the ratio described above is an integer number) there corresponds the pitch-angle together with the radial diffusion and a real asymmetric field. When the ratio of the half-period of the oscillation along the field line to the average period along the field line is equal to n ($n = 1, 2, 3, \ldots$), the first type passes into the second. This idea is developed for the motion magnetospheric particles in [15].

This second type of diffusion for the system with many degrees of freedom and with a weak disturbance of the adiabatic invariants was proposed in [17], analysed in more detail in [18] and called the diffusion of Arnold.

In Fig. 1 the dotted lines correspond to integer numbers (n) of the ratio described above. The value n in agreement with [15] is found from formula

$$n = \frac{0.96\, F(\alpha)}{\chi_\perp}.$$

The graph of the $F(\alpha)$ function in [15] is given for the interval of α between 21° and 90°, the supposed analytical approximation is very rough at low angles. According to our opinion it is better to use the formula

$$F(\alpha) = \sin^{-1.28}\alpha - 0.26.$$

Now we can present the pitch-angle diffusion, caused by the break-up of the magnetic moment, in the following way. At a non-integer n the fluctuations of μ lead to the pitch-angle change, until the value of n become integer. Then the diffusion of Arnold takes place with a quicker change of L, which corresponds to the enhancement of $\chi_\perp$ (Fig. 1), i.e. to the increase of the fluctuation of μ.

It is interesting to compare the formula for

$$\mu = EL^3 \sin^2\alpha / 0.31 \quad \text{and} \quad n = \frac{0.96(\sin^{1.28}\alpha - 0.26)}{5.04 \times 10^{-5}\, pcL^2}$$

for α sufficiently low

$$n \sim \frac{1}{\sin^{1.28}\alpha \,.\, L^2} \quad \text{and} \quad 1/n^{3/2} \sim L^3 \sin^{1.92}\alpha,$$

i.e. near the expression for μ that leads to the strong change of L for $\Delta\mu$, which follows from expression 2. Finally the fluctuations of μ are so strong that the particle may change the value of n to 1, then again the stochastic mechanism of the pitch-angle diffusion is switched on with weak changes of L, till the particle passes into the loss cone.

The dependence between $\chi_\perp$ and α for such a boundary is given in Fig. 1, curve II.

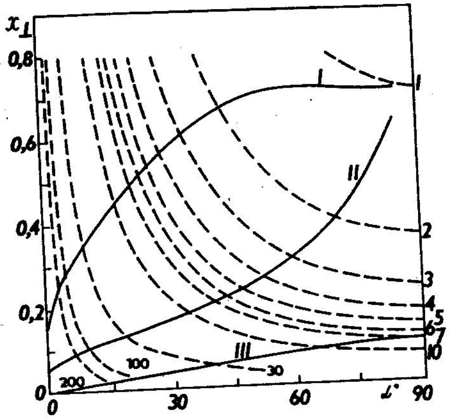

Fig. 1. I — the boundary of a strong pitch-angle diffusion due to the break-up of μ in the dipolar field, II — the boundary of the stochastic pitch-angle diffusion in the dipolar field, III — the boundary of the Arnold diffusion according to [14]; the dotted lines — lines of the integer n.

The azimuthal asymmetry of the field leads to interesting results. Every level n is split into the series of sublevels m. The overlapping of these sublevels begins earlier than in the case of the azimuthally symmetric field. According to some opinions an Arnold diffusion develops in the case of the azimuthal asymmetry of the field. In such a case $n = const$ to the right of line II must be the region of the stable motion of the particle [15]. However, in [14] by the same author, the experimental boundary of the stable motion of the particle in the dipolar field for $\alpha \gtrsim 35°$ is given as $\chi_\perp = 0.1 \sin^{4/3}\alpha$.

In Fig. 1 it is presented by curve III. Practically, it is the boundary of the Arnold diffusion. At lower $\chi_\perp$ the motion of the particles is presented practically with the conservation of μ.

The above presented considerations regarding the motion of particles with high μ can find the following applications: in the analysis of the albedo particle motions, in the analysis of motion of high energy trapped particles in the radiation belt, in the analysis of the low energy cosmic ray motion under the conditions of the asymmetrical magnetosphere.

IV. ALBEDO PARTICLES

The analysis of the albedo particle motion with help of the way described above shows that quasitrapping and the storage of albedo particles is possible in the case when fluctuations of the pitch-angle of the particle occur in the stochastic regime. Curve II describing the beginning of such a regime of the pitch-angle fluctuations of the particles in the interval $0.1 < \sin\alpha < 0.6$ is approximated by the formula $\chi_\perp = 0.7 \sin\alpha + 0.23$, and because

$$\sin\alpha \simeq \frac{1+\dfrac{3}{16L}}{\sqrt{2}L^{3/2}},$$

χ of the particles undergoing the quasitrapping will be in the interval

$$\frac{0.7\left(1+\dfrac{3}{16L}\right)}{\sqrt{2}L^{3/2}}+0.23<\chi<0.7$$

or

$$\left(\frac{1+\dfrac{3}{16L}}{\sqrt{2}L^{3/2}}+0.33\right)\frac{14.9}{L^2}<pc<\frac{14.9}{L^2}.$$

It means that the interval of the rigidities where the quasitrapping of particles is possible increases with L. Qualitatively such a result is obtained also in computer modelling [19].

V. RADIATION BELT PARTICLES

The motion of the radiation belt particles differing from that of the albedo particles takes place in the regime of a low $\Delta\mu$.

The analysis of the data on the structure of the proton belt shows that in the energy interval of $1 < E < 100$ MeV the boundary of the belts is registered at $\chi_\perp \simeq 0.1$ [7]. The estimation shows that in the region $\alpha \sim 60°$ $\Delta\alpha \sim 10^{-50}$, while for $\alpha \sim 20°$ there is $\Delta\alpha \sim 10^{-2o}$. At the fluctuations of the pitch-angle near the equator their short lifetime of particles may be investigated in the case when such pitch-angle diffusion, connected with the fluctuations of μ does not proceed to the loss cone but to the nearest integer n. Then the faster diffusion of Arnold is switched on, which transforms the particles into a higher L, where $\chi_\perp$ as well the disturbance of the magnetic moment are greater.

During the magnetic storm due to the depression of the magnetic field the $\chi_\perp$ of the particles is enhanced, and the lifetime of the particles decreases, after the storm the boundary of the energetic protons is registered at lower L. The example of such a variation is given in Fig. 2 taken from [7]. In that paper the summary of other investigations of the shift of the belt boundary to a lower L is given.

The change of $\chi_\perp$ in the case of $D_{st} \ll B_{eq} = 0.31/L^3$ can be estimed by the formulas:

$$\chi_{\perp 2} = \chi_{\perp 1}\left(1+\frac{3}{4}\frac{D_{st}L^3}{0.31}\right)$$

for the near-equatorial particles, and

$$\chi_{\perp 2} = \chi_{\perp 1}\left(1+\frac{3}{2}\frac{D_{st}L^3}{0.31}\right)$$

for particles with $\alpha \ll 90°$. The difference is caused by the fact that for particles $\alpha \ll 90°$ the adiabatic lowering of the particle energy during the effect of the D_{st} variation can be neglected.

The decrease of the lifetime of particles with high rigidity must manifest itself especially in the distribution of heavy ions in the belts. If they are created due to solar particle trapping, then the original z for o is about 6 [20] for particles with $E_p \sim 1$ MeV/nucl. Further, in the motion of particles in the plasmasphere the z of particles is quickly lowered to ~ 1, which leads to the limiting of the maximum energy of trapped particles in comparison with protons.

VI. SOLAR COSMIC RAYS

Particles of low energy (protons with $E \sim 1$ MeV and lower and electrons of the same energies) penetrate to minimal latitudes from the nightside of the Earth $\Lambda \gtrsim 68°$ ($L \sim 7 \div 9$). They are drifting and at the first passing to the dayside their drift shells are splitted, the particles with a pitch-angle $\sim 90°$ impinge practically upon the magnetospheric boundary, particles with low pitch-angle come to the latitude $\Lambda \gtrsim 70°$.

In the analysis of the experimental data by the cosmic rays the isotropic particle fluxes at high latitudes are called. In such a way on those field lines, where the breaking-up of μ is weak ($\chi_\perp < 0.2$—0.3 (as it follows from Fig. 1)), the particles behave as trapped, although during the following drift onto the night-side they can appear again in the population of particles called cosmic rays.

During the fluctuation of the magnetic field with the characteristic period near to the period of particle drift around the Earth these particles may fill the radiation belts.

On the field lines, coming at higher latitudes from the dayside, where for particles the value of $\chi_\perp > 0.2$—0.3 the isotropic flux is registered. This is explained by the deeper penetration of low energy particles into the magnetosphere from the dayside. The important task in the study of penetration of protons and ions into the magnetosphere is the analysis of their penetration through the magnetopause.

Several works have been devoted to the solution of this question [21—23]. In these papers the boundary of the magnetosphere is assumed as a tangential discontinuity. The coefficient of transparency through the discontinuity is dependent on the normal component in this discontinuity, on the value of the tangential component on both sides of discontinuity, on the angle of the field deflection at the discontinuity.

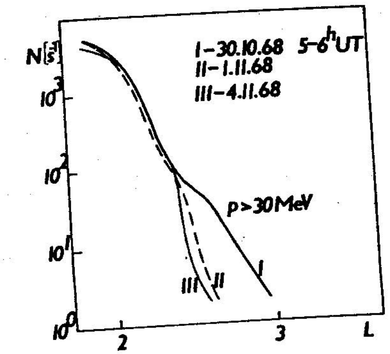

Fig. 2. The proton flux variations ($E_p > 30$ MeV) during the severe magnetic storm in October 30—31, 1968.

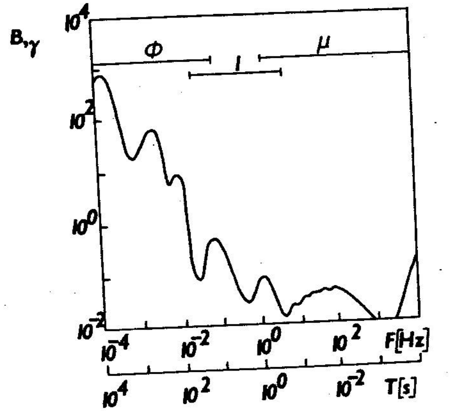

Fig. 3. The amplitude spectra of the magnetic variations with various periods leading to the breaking-up of adiabatic invariants of motion [28].

Assuming these facts the structure of polar caps is determined, i.e. the polar cap regions connected with the magnetopause by the neutral sheet in the tail are determined [24, 25]. It has been tried to obtain the experimental separation of the different regions of polar caps [26, 27]. The question, however, needs further investigations.

VI. PARTICLES WITH $\chi_\perp \ll 0.1$

We shall assume the motion of low rigidity particles with $\chi_\perp \ll 0.1$. They are moved adiabatically. However, in the Earth's magnetosphere, together with the trapped particle fluxes, electromagnetic waves of different periods of 10^{-4} to 10^5 Hz are present and the interaction with them determines the breaking-up of the adiabatic invariants.

In Fig. 3 taken from [28], there is given the average amplitude of the magnetic disturbance in a wide frequency interval. Analysing the picture we see that among

the magnetic disturbances there are such that can break up all the three basic invariants of the particle motion.

The periods $T > 20$ s cause the violation of the 3rd invariant, the radial diffusion. This process is the basic one for the radiation belt formation, because the source of the main part of the particle population of the radiation belts is caused by the effects originating on the most distant close drift shells. The disturbances of such periods are of two types:

Those connected with changes of the magnetic field inside the magnetosphere, for instance si and ssc. The changes of magnetic field are caused by the whirl electric field, which in consequence causes the violation of the third invariant of motion and the radial diffusion. The coefficient of radial diffusion is maximal for particles with $\alpha \sim 90°$ and decreases with the decrease of the pitch-angle.

The change of quasistationary electric field responsible for the plasma convection inside the magnetosphere also leads to the radial diffusion of energetic particles. The coefficient of radial diffusion in this case does not depend on the pitch-angle.

The redistribution of the belts corresponding to the two types of convection has been investigated experimentally [29—32]. Theoretically, the radial diffusion process has been considered in many papers [33—35].

There have been also experimental works, on the basis of which the coefficient of radial diffusion [36, 37] may be computed.

An interesting phenomenological approach to the radial structure of the belts has been developed in [38].

The second process playing an important role in the dynamics of the belts, especially for electron fluxes — is the pitch-angle diffusion. Inside the plasmasphere it is driven by the cyclotron interaction of the waves and particles [39], which lead to the violation of the first invariant. The waves with frequency 1 — 10^5 Hz are responsible for the interaction of particles with various energies and types. The important role here plays the development of the cyclotron instability. The most detailed consideration of this problem is given in review [40]. Experimental investigation of the existing low frequency electromagnetic fields is discussed in [41, 42] and on this basis estimations of the pitch-angle diffusion coefficient were made [42, 43].

The pitch-angle diffusion of electrons was investigated also by comparison of quasitrapped and precipitating fluxes of electrons [44] or the structure of fluxes in the loss cone [45]. At present there exists experimental evidence of the connection of the VLF power and the rate of precipitation of the electrons [46] during the development of the cyclotron instability [47]. Besides the interaction outside the plasmasphere there may occur the Čerenkov interaction of electromagnetic or electrostatic waves with particles outside the plasmapause. Besides the pitch-angle diffusion, an effective diffusion in energies exist in connection with this. This interaction can cause the acceleration of electrons both during the "magnetoquiet" time and the magnetic storms [48, 49]. This process, however, has not been investigated satisfactorily theoretically.

At present we have experimental evidence of the fact that man's activity is an important source of the VLF emission in space and causes the enhancement of the pitch-angle diffusion [50, 51].

In principle, oscillations with periods of 1—20 s can also lead to the pitch-angle diffusion. The effect is accompanied by the violation of the second invariant (the 1st is here violated also). This process can be effective for particles with a pitch-angle of $\alpha \sim 90°$, for particles with a low pitch-angle this process may be important for the region of the midlatitude trough [52], where the plasma density is low. Unlike the Fermi acceleration in the interplanetary space where $\Delta B \sim B$ (ΔB — the amplitude of magnetic inhomogeneity) and $\Delta E \sim 4E \frac{v_l}{v_\tau}$, v_l — the velocity of magnetic inhomogeneity motion, v_τ — the velocity of the particle motion in the magnetosphere [53]

$$\Delta E \sim 4E \frac{v_l}{v_\tau} \frac{\Delta B}{(B - B_{eq}) + \Delta B},$$

where B is the magnetic field at the mirroring point, B_{eq} the magnetic field at the equator, $v_l = B/\sqrt{4\pi\varrho}$ is the Alfvénic velocity, ΔE is the increase of energy, connected with the velocity parallel to the magnetic field. In [54] an analogous process was analysed concerning the high harmonics of the period of oscillation of the particle along the field line. However, the Čerenkov interaction of the wave and particle is in concurrence with this mechanism. For protons and ions of the radiation belts besides the processes considered above the ionization losses in the residual atmosphere and charge-exchange play a great role. For the electrons in the inner belt the Rutherford scattering plays a certain role.

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