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PRINCIPAL HYPOTHESES CONCERNING THE ORIGIN OF THE EARTH'S RADIATION BELTS

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THE number of recently published theoretical and experimental papers devoted to the study of the earth's radiation belts is unusually large. In different stages of the study of the radiation belts, numerous attempts were made to discuss and generalize the obtained experimental material, and also to interpret it theoretically [1-5]. However, most authors attempted to explain the experimental data essentially on the basis of some single hypothesis.

The purpose of the present review is to consider different theoretical and experimental aspects of the origin of the radiation belts.

The earth's radiation belts were discovered early in 1958 with the aid of Soviet and American artificial satellites [6-8]. During the first stages of their study, they were subdivided into the inner and outer radiation belts, which differ from each other both in the region they occupy in the outer space around the earth and in the energy spectra of the main radiation components—protons and electrons.

Figures 1 and 2 show schematically the relative positions of the inner and outer radiation belts, obtained on the basis of the first investigations of outer space near the earth.

Subsequent study has shown that the concept of two individual radiation belts does not reflect the true picture of the distribution of the charge particles in the earth's magnetosphere.* In addition, it was shown with the aid of charged-particle traps installed on the second Soviet space rocket that a new region exists, with intense fluxes of very soft charged particles, not captured by the geomagnetic field. The equatorial cross section of this outermost belt of charged particles extends approximately from 50,000 to 79,000 km from the center of the earth [9].

Figure 3 shows the position of this belt relative to the inner and outer radiation belts of the earth, on the basis of data obtained in 1959. It is presently assumed that the occurrence of the outermost belt is connected with boundary effects of the interaction between the interplanetary plasma and the earth's magnetosphere [10]. According to present-day concepts, the structure of the radiation belt is determined essentially by the character of motion of the charged particles (protons and electrons) in the earth's magnetosphere. The regions in which capture of the charged particles takes place in accordance with their energies, according to the latest data, are shown in Fig. 4 [11]. Thus, the problem of investigating the earth's radiation belt, from the point of view of experiment and theory, is in its present stage a problem of studying the capture and motion of protons

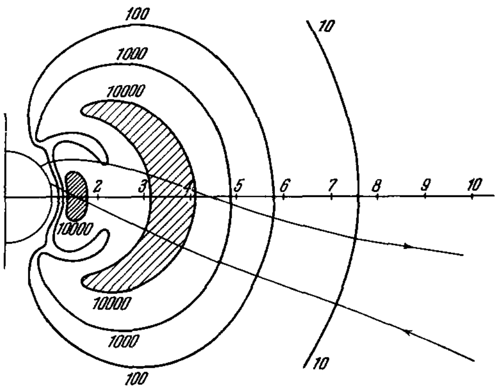

FIG. 1. Original diagram of the structure of the intensity of the captured radiation near the earth. The diagram shows a section in the meridional plane through the three-dimensional figure of revolution around the geomagnetic axis. The lines of constant intensity are marked by the numbers 10, 100, 1000, and 10,000. These numbers give the true counting rates of the Anton-302 Geiger counter, installed on the satellite «Explorer-IV» and on the rocket «Pioneer III». The unit of linear scale is equal to the earth's radius (6371 km). The outgoing and returning trajectories of the «Pioneer-III» rocket are shown by the bent lines with arrows (after Van Allen and Frank).

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*According to the presently available experimental data and theoretical concepts, the geomagnetic field is localized, owing to the external pressure of the stationary solar stream (solar wind), in a limited region in the outer space around the earth. This region is called earth's magnetosphere. We note that both the dimensions of the region of localization of the geomagnetic field and the form of its boundary in the unperturbed state are practically independent of the pressure of the charged particles inside the magnetosphere, in accordance with the initial condition $H^2/8\pi = 2nkT$.

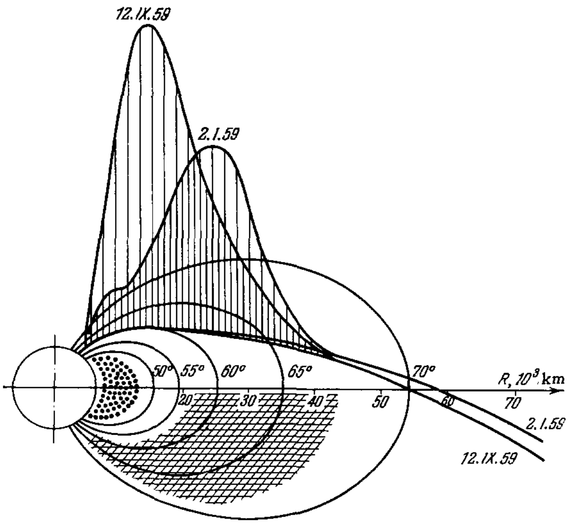


FIG. 2. Structure of the earth's radiation belt from data of Soviet space rockets "Lunnik I" and "Lunnik II". The distance from the earth's center is given in thousands of kilometers.

and electrons in the earth's magnetosphere.

At the same time, the most important problem connected with the origin of the radiation belts is the study of the interaction between the interplanetary plasma (solar wind) and the earth's magnetic field. A solution of this problem is of tremendous significance for a correct understanding of the entire complex of physical phenomena (magnetic storms, auroras, currents in the outer atmosphere of the earth, etc) in the nearest vicinity of the earth.

1. HYPOTHESES PRECEDING THE DISCOVERY OF THE EARTH'S RADIATION BELTS

The purpose of the investigations with the first artificial satellites (and of other experiments) was to measure the intensity of cosmic rays only. It is sufficient to state that the intensity of the particle fluxes in the inner belt, measured with the aid of the instruments of the "Explorer-I", were thousands of times larger than expected[7]. However, even long before the discovery of the radiation belts one could predict their existence on the basis of theoretical investigations made by many authors. It is surprising that although many such studies were made long before the experimental discovery of the radiation belts, in none of them were there any direct indications of the possibility of very large intensity of the particles captured in the geomagnetic trap.

Even from the early papers of Stoermer it was known that the earth's field can behave like a magnetic trap with respect to particles of definite energy. Stoermer[12] has shown that in the vicinities of the magnetic dipole there exist two regions which are allowed for the motion of charged particles, one of which could be cut off from infinity. The position of the forbidden and allowed regions of the dipole magnetic field is determined for each particle not only by the magnitude of the magnetic moment of the dipole and by the particle energy, but also by the value of the constant of integration γ of the equations of motion, which is proportional to the angular momentum of the particle relative to the dipole axis at infinity. The case of an allowed region of dipole field which is completely detached from infinity corresponds to values $\gamma < -1$. Charged particles that fall into this region in some manner cannot leave it and will execute periodic motion in the vicinity of the dipole.

In one of Stoermer's papers, devoted to orbits of particles in the field of the dipole[13], he considered in detail the periodic orbits corresponding to the inner allowed region (Fig. 5). This analysis, however, pertains to the theory of the solar corona and to the theory of laboratory experiments with a "miniature earth," and does not concern the inner allowed region of the geomagnetic field, which Stoermer apparently regarded as empty of particles.

The idea that the magnetic field can capture charged particles is contained implicitly in the first hypothesis concerning annular currents which cause changes in the earth's field during the time of a magnetic storm. The first to point out the possibility of

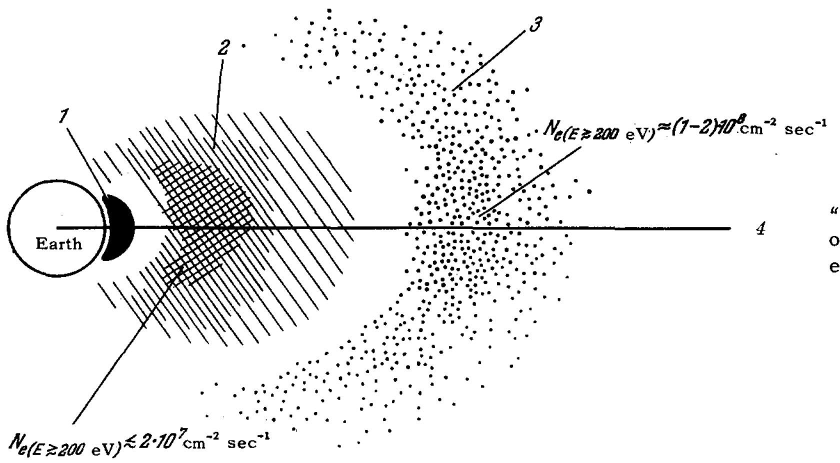
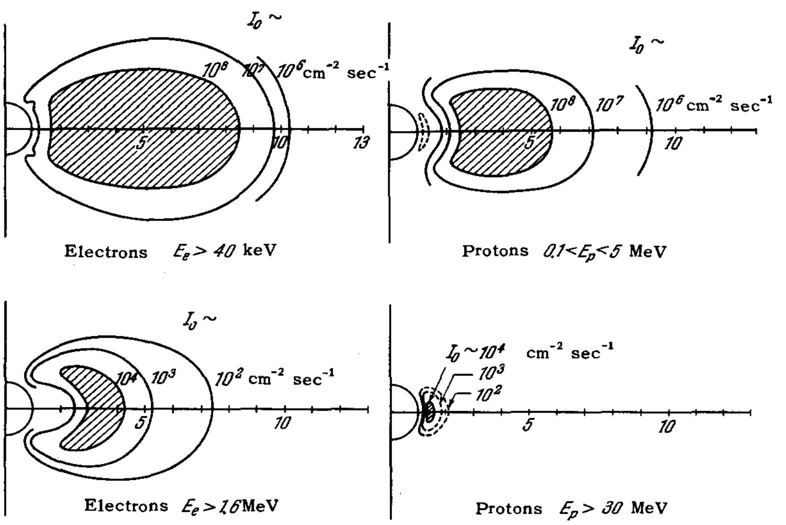


FIG. 3. Schematic diagram of the earth's belts. 1 – "Inner" radiation belt; 2 – "outer" radiation belt; 3 – outermost belt of charged particles; 4 – geomagnetic equator.



Electrons $E_e > 40$ keV

Protons $0.1 < E_p < 5$ MeV

Electrons $E_e > 1.6$ MeV

Protons $E_p > 30$ MeV

FIG. 4. Distribution of intensities of protons and electrons in the radiation belts. The distances are expressed in earth's radii.

existence of currents near the earth was Stoermer [14], who used them to explain the shift of the zone of the auroras to lower latitudes during the time of the storm. However, as follows from Stoermer's own papers concerning the character of the motion of the charged particles in the equatorial plane of the earth, the current proposed by him could not surround the earth and therefore was not annular [15].

The hypothesis of a truly annular current was considered by Schmidt [16]. From this hypothesis one could draw certain conclusions concerning the capture of solar plasma by the earth's magnetic field. Direct indications of the possibility of such a capture are contained in the paper by Chapman and Ferraro [17], devoted to the theory of the principal phase of a magnetic storm. However, they did not develop the concrete mechanism of capture of the solar-plasma particles by the geomagnetic field. Moreover, according to [17], the annular current causing a decrease in the earth's magnetic field during the time of the principal phase of the storm, is a boundary current and is localized in the inner regions of the geomagnetic field. It owes its origin not to drift of charged particles captured in an inhomogeneous geomagnetic field, but to a charge distribution of particles of the neutral solar flux on the boundary of the magnetosphere (called at that time the Chapman-Ferraro cavity) (Fig. 6).

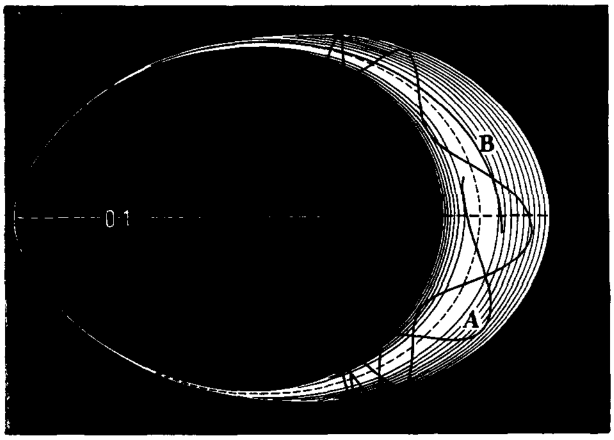


FIG. 5. Motion of a charged particle in a magnetic force tube, after Stoermer (periodic trajectory).

In 1947, in considering the question of the cutoff of the low energy part of the cosmic-ray spectrum, Alfven [18] advanced the hypothesis that the sun's dipole magnetic field can prevent the penetration of low-energy particles into the earth's atmosphere. He proposed simultaneously that the solar dipole field produces magnetic traps of charged particles, which can be scattered in the earth's magnetic field. In 1950, applying perturbation theory to the motion of a particle in a magnetic field, Alfven has shown [19] that analogous magnetic traps can exist also in the earth's dipole field, and that such a trap corresponds to Stoermer's inner allowed region.

The perturbation method has made it possible to investigate in detail the trajectories of the captured particles over a wide range of energies. However, this method became actively applied to the study of the motion of particles in the geomagnetic field only after the experimental discovery of the earth's radiation belts. Even before the discovery of the radiation belts, Stoermer's results were used for estimates of the contribution of the secondary cosmic radiation to data obtained by rocket measurements of primary radiation. This was the topic of the works of Treiman and Griem and of Singer [20,21], with [21] devoted to the capture of charged particles produced during the neutron decay—secondary products of interaction between cosmic rays and the earth's atmosphere—by the geomagnetic field (the neutron albedo effect).

Griem and Singer have shown that particles can trace many loops in a low-density atmosphere before they become absorbed by collisions, and estimated the contribution made to the intensity of cosmic radi-

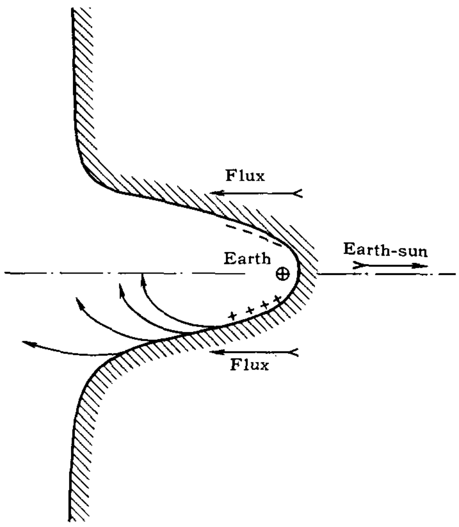


FIG. 6. Flow of the solar stream around the Chapman-Ferraro cavity during the time of a magnetic storm. The cross denotes the earth. The figure shows the charge separation of the flux particles on the "walls" of the cavity and the direction of the annular current resulting from this separation in the equatorial plane.

ation from these particles as a function of the energy and altitude[22]. No special investigation of the mechanism of injection into the geomagnetic trap was made in these papers. The only exception in this respect were the calculations of Christofilos, which were not published until the discovery of the radiation belts.[23]

Finally, in 1956-1957, in connection with the already mentioned current theory of magnetic storms, Singer[24,25] made several suggestions concerning the possibility of the solar-stream plasma piercing into the inner allowed region of Stoermer. It was assumed there that in the case of an intense flux from the sun the collective action of the incoming particles can distort the magnetic field to such an extent that the charged particles can penetrate into the geomagnetic trap. After passage of the solar stream, some of the particles may remain in the trap and produce the annular current responsible for the principal phase of the magnetic storm.

Naturally, immediately after the discovery of the radiation belts they were correctly explained from the point of view of capture of charged particles by the earth's geomagnetic field. It is not surprising that one of the first hypotheses concerning the origin of the belts were the hypotheses of neutron albedo and of the piercing of the geomagnetic field by the solar-stream particles and their capture.

2. CHARGED PARTICLES IN THE GEOMAGNETIC TRAP AND THE ADIABATIC INVARIANTS OF THEIR MOTION

Let us consider in most general form the existing notions concerning the kinematics and dynamics of the earth's radiation belts.* The subdivision of the theory of the radiation belts into kinematic and dynamic has the same meaning as in mechanics. Problems involving purely geometrical properties of the motion of charged particles are kinematic. The analysis of these properties is based on the conservation of adiabatic invariants of motion of the charged particle in the magnetic field. From the physical point of view, the kinematic description corresponds to consideration of a definite equilibrium state of the radiation belts in an unperturbed magnetic field. Processes which lead to a deviation from this equilibrium state, both in a stationary and in a perturbed geomagnetic field, comprise the dynamics of the radiation belts. We note that a study of the dynamics and kinematics of the radiation belts is impossible without account of the concrete geophysical conditions in the outer space near the earth.

The most convenient method of describing the motion and distribution of charged particles in the earth's magnetic field is the perturbation method. This method makes it possible to describe the motion of charged particles either on the basis of the theory of adiabatic invariants, or with the aid of the corresponding approximate equations of motion of a particle in a magnetic field (for example, the equations of the drift approximation). Experience has shown, however, that calculations of the motion of charged particles of the earth's radiation belts, based on the theory of adiabatic invariants, are much more convenient and more illustrative than the cumbersome equations of drift approximation used for this purpose.†

It is known from the drift-approximation theory[27] that the motion of a charged particle in a magnetic field consists of three independent motions (within the framework of this approximation); fast Larmor rotation around a magnetic force line, relatively fast oscillations along the force line between magnetic mirrors, and slow drift perpendicular to the magnetic field (Fig. 7).‡ A definite adiabatic invariant corresponds to each of these motions.

Thus, for example, for the fast Larmor rotation of the particles in a direction perpendicular to the magnetic force lines, the adiabatic invariant is the magnetic moment of the particle.

$$\mu = \frac{mv_\perp^2}{2H}, \tag{1}$$

where $v_\perp$ is the perpendicular component of the

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*The term "kinematics of radiation belts" is due to B. A. Tverskoĭ, while the term "dynamics of radiation belts" is universal in the physics of the earth's radiation belts[1, 82, 125, 126].

†It must be noted that the theory of adiabatic invariants is an independent theory within the framework of the perturbation method, relative, say, to the theory of the drift approximation[26].

‡The expression for the periods of these motions in a dipole magnetic field can be found, for example, in[1].

particle velocity. The accuracy with which μ is conserved along the trajectory of motion is characterized by the adiabatic-invariance condition

$$T_L \left| \frac{d\mathbf{H}}{dt} \right| \ll H, \tag{2}$$

where T_L is the period of the Larmor rotation of the particle and H the intensity of the magnetic field [19]. For motion in a stationary magnetic field, condition (2) is of the form

$$T_L (\mathbf{v}\nabla) H \ll H, \tag{3}$$

where v is the total velocity of the particle.

Condition (2) is simultaneously the condition for the applicability of the equations of the drift approximation, but for the adiabatic invariance of (1) it is necessary also to satisfy the condition of total independence of all three forms of motion [28]. We note that even if all the necessary conditions of adiabatic invariance are satisfied, μ is not an absolute invariant in the drift approximation. An account of the deviations in the motion of the charged particles from a smooth average trajectory, due to the Larmor rotation of the particle, leads to corresponding deviations of μ from its constant average value. These deviations, according to existing terminology [27], will be called the "jitter" of the particle or of the corresponding adiabatic invariant. As a result of the fact that the "jitters" of μ are approximately the same in amplitude and have opposite signs when averaged over T_L the value of μ remains constant in the drift approximation.

The relatively fast oscillations of the particle between magnetic mirrors corresponds to the adiabatic invariant of longitudinal action (longitudinal invariant)

$$J = \frac{m}{2} \oint v_{\parallel}\, ds, \tag{4}$$

where $v_{\parallel}$ is the component of particle velocity parallel to the field, and ds is an element of the arc of the magnetic force line, along which the particle moves. The condition for the conservation of J is of the form [26]

$$T_{\mathrm{osc}} \left| \frac{d\mathbf{H}}{dt} \right| \ll H, \tag{5}$$

where T_{osc}—period of oscillations between the magnetic mirrors. In a stationary field, Eq. (5) takes the form

$$T_{\mathrm{osc}} (\mathbf{u}_{\mathrm{dr}} \nabla) H \ll H, \tag{6}$$

where u_{dr} is the velocity of the perpendicular drift of the particle in the inhomogeneous magnetic field.

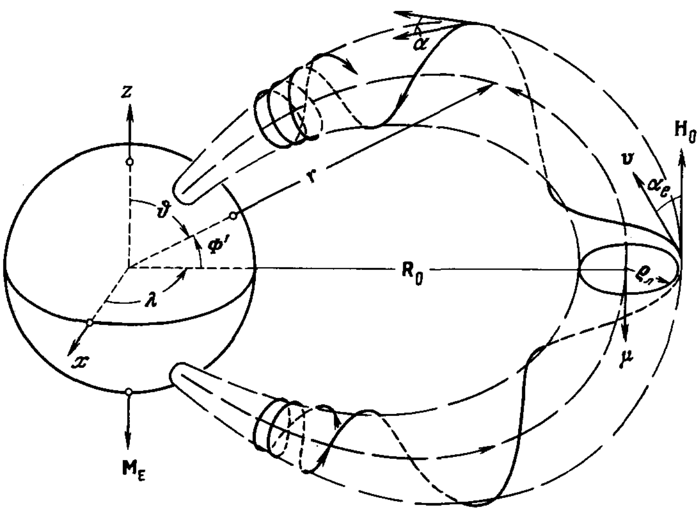

FIG. 7. Motion of a charged particle in a force tube of the earth's dipole field[3]. r, Φ' and λ are respectively the radius vector from the center of the earth, the geomagnetic latitude, and the longitude; R_0 – equatorial value of r; H_0 – intensity of the magnetic field at the equator; v – particle velocity vector; α – angle between v and H; α_0 – equatorial value of α; ρ_L – Larmor radius of rotation of the particle; μ and μ_E – the magnetic moments of the particle and of the earth respectively. The drift of the particle is perpendicular to the plane of the figure.

Finally, the invariant of the slow motion perpendicular to the magnetic field (the drift of the particle due to the magnetic inhomogeneity), is the so-called total flux invariant

$$\Phi = \iint_s \mathbf{H}\, d\mathbf{s}, \tag{7}$$

where ds is the vector element of the cross section area of the drift surface over which the particle moves. The third adiabatic invariant is meaningful only in the case when the drift is in an axially-symmetrical magnetic field or in a field with a small deviation from axial symmetry. The condition for the approximate conservation of Φ is

$$T_{\mathrm{dr}} \left| \frac{\partial \mathbf{H}}{\partial t} \right| \ll H, \tag{8}$$

where T_{dr} is the period of one drift revolution about the symmetry axis.

As can be seen from (2), (5), and (8), the conditions for the adiabatic invariance of J and Φ are stronger (that is, they impose greater limitations on the variation of the magnetic field) than the condition for the invariance of μ. Nonetheless, it is especially convenient to consider the motion of a particle in a geomagnetic field when all three conditions are satisfied. Indeed, if μ is an adiabatic invariant, then the trajectory of the particle is confined to a bounded space, thereby greatly simplifying the calculation of such a trajectory. However, the drift of the charged particle itself can have a complicated form even in this approximation. The drift trajectory of a charged particle becomes much simpler if J and Φ are adiabatically invariant. The approximation of perturbation theory, to which the adiabatic invariance of J corresponds, is called the approximation of the average particle drift. The equations of motion of the particle in this approximation were first derived by B. B. Kadomtsev [29] and by Northrop and Teller[30]. In addition, in [30] we obtain equations of motion corresponding to the adiabatic invariance of Φ.

Let us consider some consequences that follow from the conservation of the adiabatic invariants J and Φ in a stationary geomagnetic field. As is well known[30], in the case of a stationary magnetic field in the absence of electrostatic fields, the position of a charged particle on a given drift invariant surface J = const is completely determined by specifying two quantities

$$I = \frac{J}{p} \quad \text{and} \quad H_{\text{ref}} = \frac{p^2}{2m\mu}, \tag{9}$$

where p is the momentum of the particle and H_{ref} is the intensity of the magnetic field at the point of reflection (or mirror point)^{30}. If we now put p^2 = const, which is correct for particles having the same initial energy in a stationary magnetic field, the values μ = const and J = const define completely the invariant surface.

Thus, the invariance of μ and J makes it possible to obtain a simple system of magnetic surfaces (shells) with a concrete distribution of density and intensity of the fluxes of charged particles, constant for each surface. If we change p^2 in (9) in such a way that p^2/μ and J/p remain constant, then the invariant surface does not change, since, by varying p^2 (or the total particle energy E) in a stationary magnetic field, we change the drift velocity of the particle over the invariant surface, but we do not change the surface itself.*

The calculation of the surfaces of constant

$$I = \frac{J}{p} = \oint \sqrt{1 - \frac{H}{H_{\text{ref}}}}\, ds \tag{10}$$

and H_{ref} for a real geomagnetic field is very useful for the interpretation of the experimental results, since on these surfaces the intensity of the particle flux will also be constant along the lines of constant H. However, owing to the axial asymmetry of the magnetic field of the earth, these surfaces will have a complicated form in ordinary spatial coordinates.

For a dipole magnetic field, the equation of the force line is of the form

$$r = R_0 \cos^2 \Phi', \tag{11}$$

where Φ' is the geomagnetic latitude, r the radius vector from the center of the dipole, and R_0 the equatorial value of r for the given force line. From this and from (10) we can easily show that

$$I = R_0 g(\Phi'_{\text{ref}}), \tag{12}$$

where Φ'_{ref} is the latitude of the mirror point on the given magnetic force line, and g is a function whose form (numerical, but not analytic) is sufficiently well known. If we recognize that in a dipole field the following relation holds true

$$\frac{H_{\text{ref}}}{H_0} = \frac{\sqrt{1 + 3\sin^2\Phi'_{\text{ref}}}}{\cos^6 \Phi'_{\text{ref}}}, \tag{13}$$

where $H_0 = 0.3a^3/R_0^2$ is the equatorial intensity for the given magnetic force line, H_{ref} is the intensity of the field at the mirror point on the same line, and a is the earth's radius, then we get from (12) and (13)

$$R_0^3 = \frac{1}{H_{\text{ref}}} f(I^3 H_{\text{ref}}), \tag{14}$$

where f is a definite function of I and of H_{ref}.

From (11) we see that R_0 is a constant quantity for the dipole magnetic force line, independently of the concrete values of I and H_{ref} of each particle whose mirror point is located on the given line. In an arbitrary non-axially symmetrical field, as follows from (9), R_0 cannot be a constant quantity, that is, the invariant surfaces for particles whose mirror points are situated at the initial instant of time on the same force line may not coincide. However, in a real geomagnetic field with relatively small asymmetry, the effect of "splitting" of the invariant surfaces for such particles is small. This circumstance was noted by McIlwain[62], who showed by calculation that the value of R_0 obtained from (13) over a wide interval of values of H_{ref} and A, on the same magnetic force line of a real geomagnetic field, will be approximately constant (accurate within 3%). Thus, the "curved" invariant surface of the real terrestrial field can be replaced with sufficiently high accuracy by the surface of the symmetrical dipole field corresponding to it, if R_0, which characterizes the surface, is obtained from (14) by calculating the functions f and H_{ref} on a definite force line of the real field. When such a substitution is made, R_0 is designated by L. In order to determine the position of the point on the surface, the second parameter is the intensity of the magnetic field H. It will be shown below that the intensity of radiation along the line of constant H, on a given invariant surface (or shell) characterized by the parameter L does not depend on the longitude. To interpret the experimental data it is therefore sufficient to use the two-parametric system of coordinates L and H.

It is clear from the foregoing that the accuracy with which the distribution of the charged particles of the radiation belt is described in McIlwain's coordinate system depends on the accuracy with which the adiabatic invariants μ and J are conserved. However, it was shown in [26,31] that in a stationary

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*It must be remembered that the considered independence of the invariant surface of the particle energy is formal. In fact, the identity of the invariant surfaces includes in implicit form the condition of constancy of both J and $\mathcal{E}$ for each particle along the surface. The latter becomes clear when we have $\mathcal{E} \neq$ const in the presence of an electrostatic field or temporal variations of the magnetic field, and the invariant surfaces for particles with different initial energies separate.

magnetic field J is not an absolute invariant. The "jitter" in the average-drift approximation can lead to cumulative deviations of J from a constant value, even if the change in the intensity of the magnetic field along the drift trajectory is small during the period of oscillation of the particle between the magnetic mirrors. The reason for the non-averageable slow variation of the invariant of the longitudinal action of the particle lies in the fact that the drift and vibrational motions are not completely independent if these motions take place in a non-axially symmetrical magnetic system. Therefore the McIlwain coordinate system characterizes the position of charged particles in the earth's radiation belts only with a certain degree of approximation. Displacement of the particles from the invariant surfaces should lead to a change in the angular anisotropy of the radiation, and to a different distribution of the fluxes of these particles relative to the magnetic force lines, than in the case of the absolute invariance of J.

Knowing the laws of motion of the charged particles in the geomagnetic field from the theory of adiabatic invariance, we can obtain the distribution of the particles as a function of the energy and of the spatial coordinates.

One of the methods of solving this problem is to solve Boltzmann's equation in the quasi-hydrodynamic approximation (QHDA). The QHDA makes it possible to find the distribution of the charged particles just as accurately as the perturbation theory methods yield the trajectories of individual particles in the earth's radiation belts.

An estimate of the distribution of the particles in the radiation belts in the quasihydrodynamic approximation was made by Pletnev [32]. Pletnev considered various distributions of the particle density and intensity in a stationary field along the magnetic force line, corresponding to definite types of particle-flux anisotropy on the geomagnetic equator. In [33], the QHDA was extended to include the case of adiabatic invariance of the longitudinal action of the charged particle, and it was shown that when J is adiabatically invariant the distribution of the particles does not change along the drift surface and remains constant along the line of constant field intensity H = const. An account of the slow variation of J along the trajectory of motion leads to deviations of the stationary equilibrium distribution of the particles. These deviations are considered in [34].

Thus, changes in the distribution of the charged particles of the radiation belt can be produced to a considerable degree by violation of corresponding adiabatic invariance. We note that even in a nonstationary magnetic field the changes in the distribution are irreversible only if they are accompanied by violation of the invariance of μ, J, or Φ. This explains the close attention which has been paid to violation of the adiabatic invariance of particle motion in radiation belts.

The hypothesis of the nonconservation of the magnetic moment of a charged particle μ in a stationary geomagnetic field was first advanced by Singer[35]. Singer connected the drop of the particle flux intensity in the inner radiation belt with the nonconservation of μ for rigid particles when the field intensity decreases with altitude. It was assumed thereby that the magnetic moment μ is strongly nonconserved if $\alpha_{cr} = \delta H_L/H = 0.076$, where H is the intensity of the magnetic field and δH_L is the change in intensity within the limits of the Larmor circle of the charged particle. The critical value α_{cr} was derived by Singer empirically, on the basis of satellite observations of the decrease in intensity of high-energy protons with increasing altitude.

In 1959 Welch and Whittaker [36], and independently Pletnev [37], proposed that nonconservation of μ can cause scattering of the charged particles of the belts by spatial inhomogeneities produced in the magnetic field by large magnetohydrodynamic waves. If large magnetohydrodynamic waves actually exist in the outer atmosphere of the earth, then they should lead to a sharp increase in the inhomogeneity of the magnetic field, as a result of which the condition of adiabatic invariance $\alpha_{cr} \ll 1$ will not be satisfied. As a result of nonconservation of μ, the belt particles may fall into the lower dense layer of the atmosphere and lose energy. Inasmuch as the Larmor radius of rotation of the particle increases with decreasing geomagnetic field intensity, and the amplitude of the wave also increases with altitude, the nonconservation of μ can cut off the dimension of the inner belt sufficiently sharply and impose an upper bound on the spectrum of the softer particles of the outer radiation belt.

The magnetic-scattering hypothesis was developed further in the papers of Wentzel [38] and Dragt [39]. It was shown in [38] that passage of a charged particle through a transverse magnetohydrodynamic wave can cause resonant disturbance to the magnetic moment of the particle. Wentzel arrives at the conclusion that such a variation of μ can cause the protons of the inner radiation belt to "perish" by falling into the lower dense layers of the atmosphere. Dragt estimated the leakage of protons because of the "jitter" of the magnetic moment μ due to a magnetohydrodynamic wave.

In many recent papers the "jitter" of the magnetic moment of the particle, and the associated change in height of the mirror points of the earth's radiation belt particles, have been estimated with the aid of a rigorous perturbation-theory method. These include the papers by Gall [40], Harris [41], and Hayakawa and Obayashi [42]. At the same time, the question of regular nonconservation of μ has been little investigated. Apparently, μ is conserved with a very high degree

	L	1.2	1.6	3
Protons	10 MeV	2 months	30 years	100 years
	100 MeV	5 years	1000 years	not captured
Electrons	300 keV	10 days	6 years	20 years
	2 MeV	3 months	60 years	200 years

of accuracy for the great part of the spectrum of the radiation-belt particles. More promising are investigations of nonconservation of the second and third adiabatic invariants of motion of a charged particle in either a stationary or a time-varying geomagnetic field.

In estimating the leakage of the charged particles of the radiation belt into the lower denser layer of the atmosphere, due to the ''jitter'' of the mirror points, it is necessary to take into account the effects of elastic scattering and collisions, which lead to particle energy loss. Elastic scattering leads to a change in μ, that is, to diffusion of the particles along the magnetic force lines, and a simultaneous change in J is to be expected. The diffusion to the lower layers of the atmosphere caused by nonconservation of μ and J is particularly large for those particles whose lifetime is determined by the Coulomb scattering in the earth's atmosphere and for which the ratio of the cross section of elastic scattering to the cross section of the energy losses, for example for high-energy electrons, and especially for particles of the artificial radiation belt resulting from high-altitude nuclear explosions.

Another extreme case occurs when the energy losses due to collisions greatly exceed the losses due to elastic scattering. Such a case is realized for protons of high energy and apparently for electrons of moderate energy. This should result in a gradual slowing down of the particles. We present by way of illustration the characteristic times within which the particle energy decreases by a factor of e as a result of Coulomb interactions[3].

In the calculations the authors considered particles whose mirror points are on the equator on the force line, with a fixed McIlwain parameter L (expressed in earth's radii).

The changes in distribution of the charged particles of the radiation belt due to the Coulomb interactions (both scattering and inelastic collisions) are usually estimated by using the Fokker-Planck equation[44].

We have considered above some problems in the dynamics of the radiation belts, connected with irreversible changes in the distribution of the charged particles resulting from nonconservation of certain adiabatic invariants. We note that even theoretically reversible changes in the distribution, brought about by slow variations of the geomagnetic field, can become irreversible as a result of a falling of a considerable part of the particles into the dense lower layers of the atmosphere. This pertains primarily to such relatively slow but large-scale field variations as magnetic storms.

During the time of magnetic storms the magnetosphere of the earth is appreciably deformed, and this can lead both to the penetration of particles of relatively low energy from the outside into the inner allowed region, and to the spilling out of "old" particles. The question of the behavior of the magnetosphere as a whole during the time of a storm has so far been little investigated, although recently a considerable number of theoretical and experimental papers have been published, aimed at relating the observed variations of the geomagnetic field during the time of a storm with definite processes both inside the magnetosphere and on its boundary.*

The first theory of magnetic storm was the Chapman-Ferraro current theory[17] referred to above (Sec. 1). However, after Alfven[45] demonstrated the instability of the current system, to which Chapman and Ferraro attributed the principal phase of the magnetic storm, attempts were made[25-46] to examine the current system due to the drift of individual charged particles captured by the geomagnetic field. A rigorous formulation of such a problem became possible only after experimental investigations of the outer space near the earth have demonstrated the presence of a plasma in both interplanetary space and in the earth's nearest vicinity (beyond the ionosphere)[9,43]. Owing to the large conductivity of the plasma near the earth, the geomagnetic force lines are entrapped in this plasma and form the earth's magnetic field. Thus, the theory of magnetic storms, based on processes of interaction of solar corpuscular streams with the earth's mag-

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*These questions will be discussed by the authors in greater detail in a second review, "The Magnetosphere of the Earth." In the present section we dwell only on processes involving interaction with captured particles.

netosphere, became a problem in magnetohydrodynamics. The magnetohydrodynamic theory of the principal phase of the storm is based on an estimate of collective effects of the motion of charged particles of the radiation belts. The influence on the currents that result from this motion on the geomagnetic field has been considered in [43,46].

The first to consider the question of the connection between the density of the macroscopic current with the motion of the individual current particles in a nonuniform magnetic field were Schluter and Spitzer [47,48]. Spitzer has shown [48] that the motion of the leading centers of the charged particle cannot always produce a macroscopic current, defined as the average velocity of all the particles situated in a volume element, regardless of where their leading centers are located.

In 1957 the question was examine by Parker [49], who obtained the expression for the density of the macroscopic current on the basis of averaging the motion of the leading centers of individual particles:

$$\mathbf{I}=\frac{c}{8\pi p_m eN}\left[\mathbf{H},\ \left\{\nabla p_\perp+[(p_\parallel-p_\perp)/p_m](\mathbf{H}\nabla)\frac{\mathbf{H}}{8\pi}\right\}\right]. \tag{15}$$

In (15) **I** is the density of the macroscopic current, N the density of the particles, p_m the magnetic pressure, and $p_\parallel$ and $p_\perp$ the components of the particle pressure parallel and perpendicular to the field. It follows from (15) that in an isotropic distribution of the charged particles at the initial instant of motion the pressure will also be isotropic ($p_\parallel = p_\perp$ and $\nabla p_\perp = 0$), and the macroscopic current is $I = 0$. At the same time, the drift velocity of each particle taken separately is not equal to zero in the given inhomogeneous field. This becomes understandable if account is taken of the fact that the isotropic distribution is not changed when the particles move either along the magnetic force line or perpendicular to it, in the direction of the particle drift. Therefore the average charge transported in these directions is equal to zero. At the same time, the density of the anisotropically distributed charged particles is changed by motion along the force lines. Consequently, the macroscopic transport of charge as a result of the drift is not equal to zero, since the drift occurs simultaneously with the motion of the particle along the magnetic force line [48].

We note that expression (15) is obtained in a most natural and correct manner on the basis of the quasihydrodynamic approximation [50]. For the particular case of a closed stationary system of particles in a dipole magnetic field, Eq. (9) assumes the form [46]

$$\mathbf{I}=\left[\frac{c(1+3\sin^2\Phi)^{1/2}}{H\cos^3\Phi}\frac{\partial p_\perp}{\partial R_0}-\frac{cQ_1}{H}(p_\parallel-p_\perp)\right]\mathbf{e}_3, \tag{16}$$

where ρ_1 is the curvature of the magnetic force lines, R_0 the equatorial distance from the given force line to the center of the dipole, and $\mathbf{e}_3$ a unit vector binormal to the force line and directed in a western direction in the earth's dipole field.

It follows from (16) that in the presence of strong anisotropy of the corpuscular radiation, of the form

$$j=j_0\sin^x\theta_0, \tag{17}$$

(where θ_0 is the angle between the particle-velocity vector and the tangent to the force line from the equator, and j is the differential radiation intensity) the condition $p_{0\parallel} \ll p_{0\perp}$ will be satisfied if x is sufficiently large [32,51], and therefore the current flows in an eastern direction (under the condition that $\partial p_\perp/\partial R_0 < 0$, that is, the particle density decreases with increasing distance from the earth). In this case the current is localized in the equatorial region and should increase the intensity of the magnetic field on the earth. A similar situation can correspond to the initial phase of a magnetic storm, when a sudden compression of the earth's magnetosphere by the solar wind leads to a sharp anisotropy, such as (17), of the particle fluxes of the radiation belt.

If the anisotropy of the corpuscular radiation is of the form

$$j=j_0\cos^x\theta_0, \tag{18}$$

then $p_\parallel \gg p_\perp$ in the region close to the equator and $p_\parallel \ll p_\perp$ in the region close to the magnetic mirrors. In this case the equatorial current flows in a western direction and decreases the field intensity at the earth, while the current at high latitudes has an opposite direction and increases the intensity. The sign of $\partial p_\perp/\partial R$ will obviously be negative in the region of the largest accumulation of particles, that is, near the magnetic "mirrors," and positive in the equatorial region. If we attribute the occurrence of the principal phase of a magnetic storm to a similar current system, then it is necessary to assume the presence of a large anisotropy of the type of (18) in the currents of the radiation-belt particles during this phase of the storm.

Along with the problem of the change in the geomagnetic field by the particles trapped by this field, magnetohydrodynamic theory solves the problem of the squeezing of the earth's field by the incoming solar stream.

We note that the first papers devoted to the magnetohydrodynamic solution of the problem of flow around the earth's magnetosphere were the papers of Obayashi (1959) [52] and of Zhigulev and Romishevskiĭ (1959) [53]. The latter, for example, considered the interaction of a free-molecular ionized current with the earth's magnetic field, and it showed that if no account is taken at all of particle collision even in a stream moving away from the sun, then the picture of the magnetohydrodynamic squeezing of the field by the stream will hold true (Fig. 8). Zhigulev also noted that the points of the boundary between the stream and the "squeezed out"

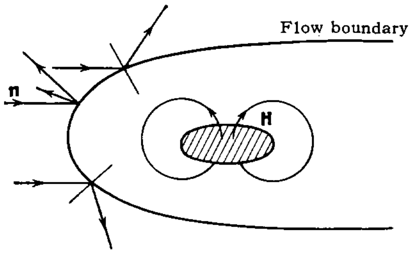

FIG. 8. Flow of the solar corpuscular stream around the magnetic dipole at large distances from the center of the dipole.

magnetic field, in which the magnetic field component perpendicular to the stream velocities vanishes, are singular points through which particles can break through towards the earth.

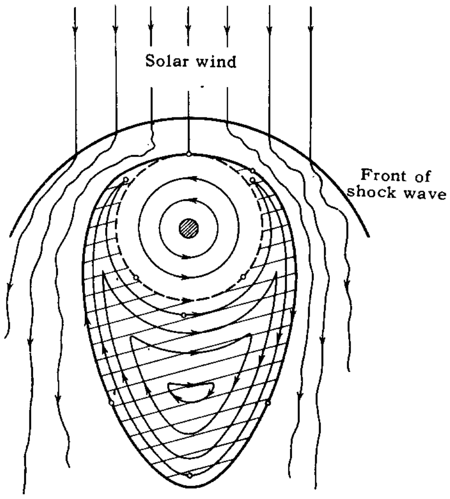

FIG. 9. Model of closed magnetosphere (equatorial section). The wavy lines correspond to flow of the solar wind around the magnetosphere. The "tail" of the magnetosphere (shaded area) encloses completely the region of low-latitude magnetic lines (unshaded region of the figure).

In this review we are unable to consider in detail the numerous papers devoted to the magnetohydrodynamic theory of storms. We note only that the main problems which this theory is called upon to solve are, first, an estimate of the influence of the internal current both on the shape and on the dimensions of the magnetosphere as a whole and on the field inside the magnetosphere, and, second, an account of the external disturbing influence of the solar wind from the same point of view. A solution of the latter problem depends essentially on the concrete model of the magnetosphere. Some writers [54,57] suggest that the magnetosphere has a sharp boundary connected with the expulsion of the geomagnetic field by the solar wind (the model of the closed magnetosphere). Others [58] believe that there will be no such boundary, since the solar plasma with the interplanetary magnetic field frozen in it can penetrate inside the magnetosphere (model of open magnetosphere). Figure 9 shows the form of the boundary of the closed magnetosphere, after [56]. For comparison we show the schematic representation (equatorial section) of the earth's magnetosphere in accordance with data obtained with space rockets crossing the boundary of the magnetosphere (Fig. 10)[58]. It is interesting that an examination of different models of the magnetosphere has started to employ recently the single-particle approximation, which actually corresponds to the already mentioned quasihydrodynamic approximation [59].

3. SOME EXPERIMENTAL DATA OBTAINED BY INVESTIGATION OF THE RADIATION BELT

A full comparison of the existing theoretical notions concerning the origin, dynamics, and kinematics of the earth's radiation belts and the experimental data available on these questions is still impossible. This is connected, on the one hand, with the incompleteness of the obtained experimental data on the kinematics and dynamics of the belts. The

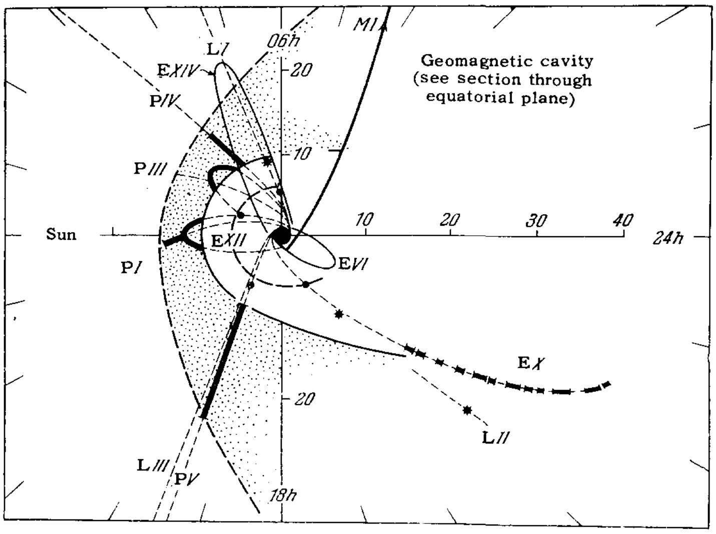

FIG. 10. Boundary of magnetosphere from data obtained by observations with artificial satellites and space ships. E – Explorer, P – Pioneer, L – Lunnik, M – Mars.

effects that are the most subtle and the most interesting from the point of view of theory have so far been investigated only by accident. On the other hand, the existing hypotheses concerning the origin of the radiation belts have a one-sided character and do not include all the geophysical phenomena connected with the dynamics of the belts.

In this section the authors have attempted to focus attention only on those questions which in their opinion are of greatest interest for the theory of the radiation belts.

a) Geometrical Structure of the Radiation Belts in the Stationary State

We have already mentioned that the distinction between the earth's two radiation belts is highly arbitrary. The main argument in favor of such a differentiation was the presence of a zone of minimum (slot) between the belts. However, subsequent investigations have shown that the slot is in fact filled with particles having energies which could not be registered by the counters installed on the first space rockets. Nonetheless, the ideas concerning the geometrical structure of the radiation belts obtained as a result of the first investigations, give a correct general picture of the distribution of the bulk of the high-energy particles captured by the geomagnetic field. We therefore base our exposition of the experimental data on these ideas. The subsequent refinement of the spatial distribution of the trapped corpuscular radiation (principally due to measurements of particle fluxes of particles of relatively low energy) are shown in Fig. 4.

The "inner" radiation belt begins at a height of approximately 600 km in the western hemisphere, around 1600 km in the eastern hemisphere, and reaches a height of approximately 9000 km in the plane of the equator. In its lower part, this belt extends approximately from −40° to +40° geomagnetic latitude. The distance between the lower boundary of the "inner" belt and the earth's surface varies, depending on the geographical position. The difference in the altitude of the lower boundary in the western and eastern hemispheres of the earth is connected with the shift of the center of uniform magnetization relative to the earth's center towards the east by approximately 440 km.

The geometrical structure of the "inner" radiation belt of the earth is determined essentially by the dipole magnetic field, that is, the position of the lines of equal intensity of radiation is determined by the force lines of the magnetic dipole. A diagram showing the dependence of the intensity in the radiation belts on the altitude and on the geomagnetic latitude was first obtained by Van Allen and Frank on the basis of observations with the aid of Explorer-IV and Pioneer-III, and was subsequently refined by the results of the satellites Explorer-VI and Explorer-VII. (See Fig. 1).

The "outer" radiation belt, discovered by the third Soviet satellite, is located at appreciably larger altitudes in the equatorial plane than the "inner" belt, and its lower part extends from ±50° to ±65° geomagnetic latitude. The first investigations with the aid of space rockets (the first and second Soviet space rockets and the American rockets Pioneer-III and Pioneer-IV) have shown that in the plane of the equator the "outer" and "inner" radiation belts are separated by a region of a relative minimum of particle flux intensity, extending from 2.5 earth's radii (from the earth's center) to 3.5 earth's radii. By now it has been made clear that this slot is also filled with particle streams with energies larger than in the outer belt but smaller than in the inner one.

We recall that measurements with the aid of the first Soviet space rocket and the American rocket Pioneer-III disclosed a maximum of the "outer" belt at a distance 4.5 earth's radii in the plane of the equator. However, a comparison of the flight data of the first and second Soviet space rockets through the outer radiation belt (2 January 1959 and 12 September 1959) has disclosed a shift of the zone of the maximum of the outer belt in the equatorial plane in a direction towards the earth by 900 km (see Fig. 2). During the time of flight of the second space rocket, the intensity of radiation in the outer belt was much higher than during the flight of the first Soviet space rocket[60].

An analogous phenomenon was observed by comparing the results of flight of the American space rockets Pioneer-III and Pioneer-IV, which crossed the earth's radiation belts on 6 December 1958 and 3 March 1959, and also by comparing the results of measurements made with these rockets and with the satellite Explorer-VI. During the flight of Pioneer-IV, the total intensity of radiation increased in the belts, while during the flight of Explorer-VI the intensity decreased. Figure 11 shows a diagram of the radiation belts of the earth during the flights of Pioneer-III, Pioneer-VI, and Explorer-VI.

The scientists who carried out measurements with both the Soviet and the American space rockets have noted the dependence of these variations of the spatial configuration of the radiation belts and of their over-all intensity on the solar activity. Nonetheless, it still remains unclear whether these changes are the result of temporal variations in the outer belt, connected in particular with a change in the anisotropy of the corpuscular radiation, and consequently with a change of the spatial distribution of this radiation,[51], or whether there is some quasi-stationary picture of a magnetosphere deformed by the solar wind. As a result of such a deformation, the geomagnetic structure of the outer belt, being

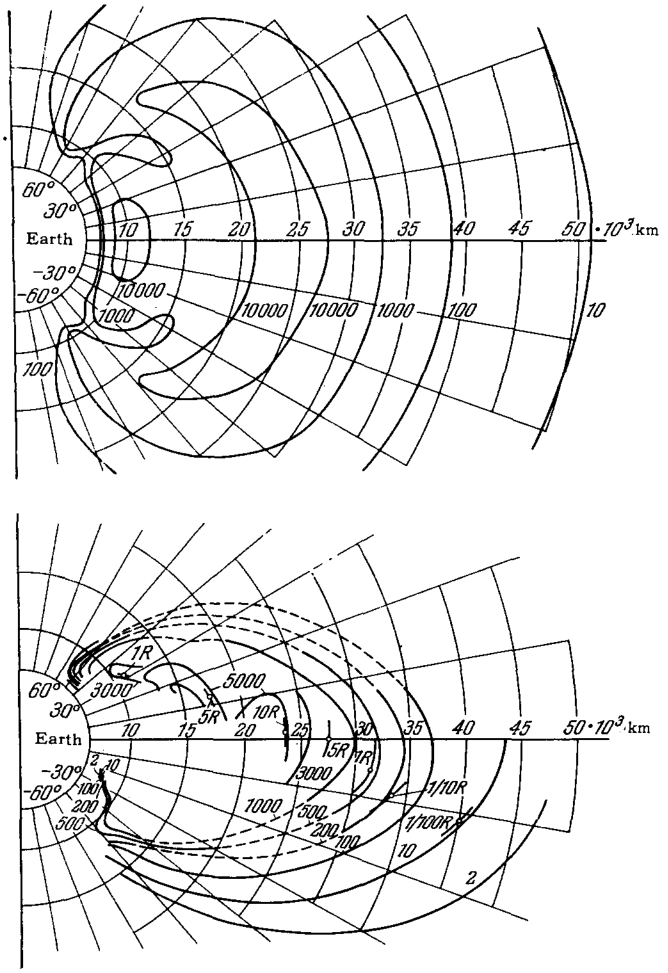

FIG. 11. Comparison of the lines of equal counting rates in the radiation belts (in polar coordinates), obtained by Van Allen (top) and with the Explorer-VI satellite (bottom). It can be seen that since the time of flight of the satellite Explorer-IV and the rockets Pioneer-III and Pioneer-VI until the time of flight of the satellite Explorer-VI the radiation belts have become strongly compressed and changed their shape.

closest to the boundaries of the magnetosphere, can change, depending on the position relative to the sun.*

Finally, it was established during the flight of Explorer-VI that in the region between the outer and inner belts there is still another zone of increased radiation intensity (distance ~17,000 km from the earth center in the plane of the equator). This zone has subsequently been designated E_2, to distinguish it from the zone E_3 of the maximum intensity of the outer radiation belt.

The general qualitative picture of the radiation belts of the earth, considered above, gives an idea of their geometrical structure, that is, of the latitudinal extent of the region of the corpuscular radiation captured by the geomagnetic field, of the distance between the upper and lower boundaries of this region from the earth, and of the localization of the main maxima of the intensity of the corpuscular radiation. Nonetheless, to study the dynamics and kinematics of the radiation belts it is necessary to analyze the altitudinal distribution, the spectral distribution, and the character of the spatial anisotropy of the proton and the electron components of the radiation separately. This necessity is brought about by the fact that the parameters of the trajectories of the electron and of the proton differ greatly from each other in the same magnetic field. The geomagnetic field therefore retains electrons and protons in different manners.

In turn, the reaction of the particle in the magnetic field, together with the interaction between the particles, depends on the mass and charge of the particle. Consequently, both the kinematic and dynamic processes occurring in the radiation belts depend on the spectral and spatial distribution of the proton and electron components and on the quantitative ratio of these components in definite regions of the magnetosphere. We consider below the distribution of the proton and electron components of the corpuscular radiation inside the earth's magnetosphere.

b) Proton Component

The first measurements of charged particles in the region $L \leq 2$ (inner belt) with the aid of Soviet and American satellites have shown the presence of intense fluxes of protons with energies of tens of MeV. According to the data of Explorer-IV, the integral intensity (the intensity in all directions) of the flux of protons with energies larger than 43 MeV in the region $L \sim 1.5$ amounts to 2×10^{12} particles/cm^2 sec. Figures 12 and 13 show the spatial distribution of the intensity of these protons. The second Soviet satellite also measured protons with energies ~100 MeV, while the first Soviet space rocket measured protons with energy ~30 MeV. The results obtained have confirmed the foregoing value of the integral intensity.

At present, the distribution of the integral intensity of the high-energy protons in the earth's magnetosphere ($L < 3$) is believed to be as shown in Fig. 14. Figure 14 is based on data obtained with the satellite Explorer-XV [63], launched in October, 1962. Measurements with Explorer-XV greatly refined and supplemented the previously available data on protons at this energy.

The first investigations of the spectrum of protons of the inner belt were made with high altitude rockets. Thus, according to the experiment of Frieden and White [64] with screened emulsions on a rocket, the

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*It can be regarded as reliably established by now, on the basis of many experimental measurements, that the outer boundary of the radiation belts on the night side of the magnetosphere comes closer to the earth.

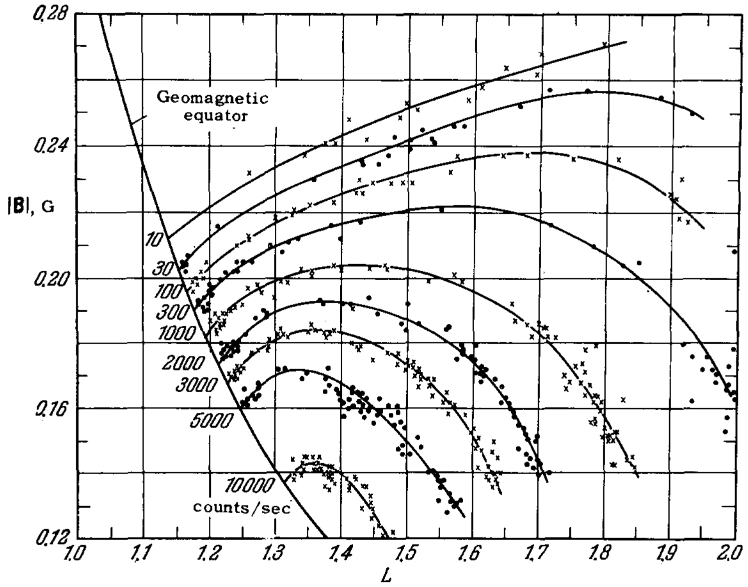

FIG. 12. Intensity contours obtained with the aid of the apparatus of the Explorer-IV (unshielded Geiger counter) in coordinates B and L (after McIlwain). To avoid confusion, the experimental points pertaining to neighboring contours are alternately designated by circles and crosses.

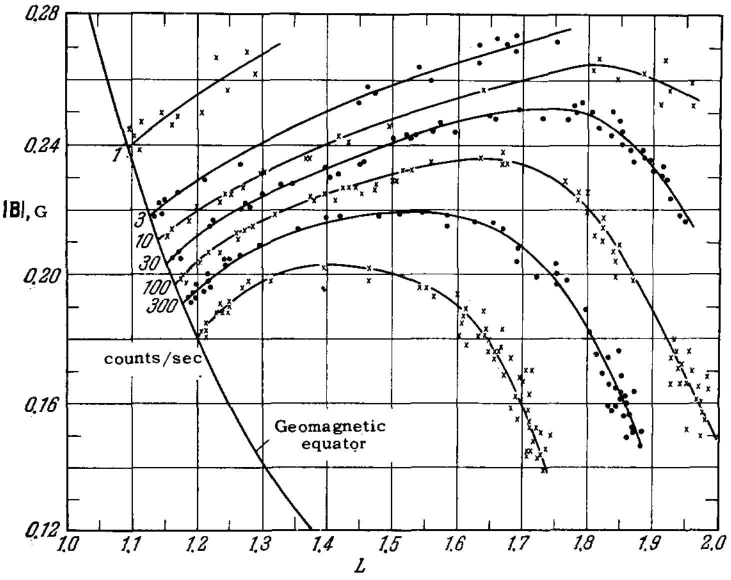

FIG. 13. The same as in Fig. 11, but experimental points were obtained with a shielded counter.

spectrum of the high energy protons in the energy interval from 75 to 700 MeV is of the form

$$N(E)\,dE = kE^{-\gamma}dE, \qquad (19)$$

where $\gamma = -1.84$. These measurements were made at the altitudes 1000—1200 km ($L \approx 1.4$). Subsequent measurements, both with the aid of nuclear photoemulsion and with the aid of counters, did not lead to an essential change in the assumed value of γ. Thus, the measurements of Armstrong et al.[65], made at approximately the same altitude (~ 1200 km), give $\gamma \approx 1.8$ for protons in the energy interval 80—600 MeV. Naugle and Kniffen obtained $\gamma \approx 1.7$ for the interval of energies from 40 to 100 MeV and altitude ~ 1600 km[66].

However, some data offer evidence that deviations from this spectral dependence do occur. These deviations are connected both with the latitudinal distribution of the particles of the inner belt, and with the energy interval of the recorded particles. For example, the measurements of Naugle and Kniffen have shown that for the relatively low-energy proton component from 10 to 50 MeV the spectrum becomes appreciably softer with increasing L. Whereas $\gamma \approx 1.7$ in the region of the geomagnetic equator, γ increases on going farther to the northern boundary of the belt. For example, at geomagnetic latitude $\Phi' = 33°$ and altitude 1600 km ($L \sim 1.79$), measurements have shown that $\gamma = 4.5 \pm 0.5$. The measurements of Armstrong et al. [65] give an anomalously large intensity of protons with energy 80 MeV, which, to be sure, is not confirmed by the measurements of Frieden and White. Thus, one cannot exclude the possibility that the main background of the proton

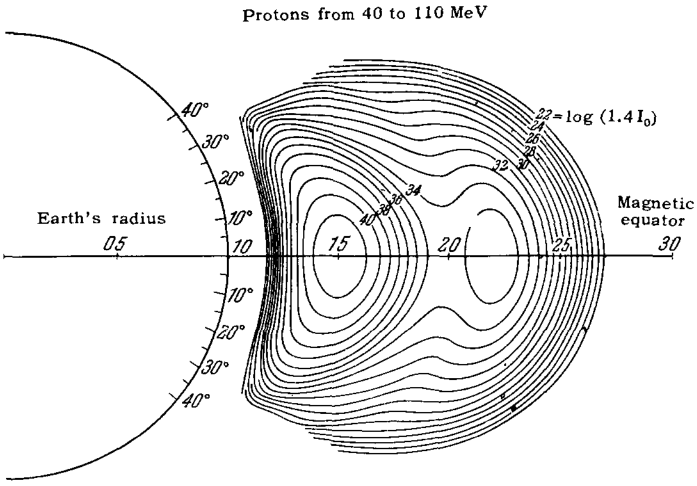

FIG. 14. Contours of constant intensity of high energy protons as obtained with Explorer-XV.

radiation of the inner belt, which satisfies the spectral law (19), is subject to various fluctuations which depend both on the altitude and latitude of the spectral measurement point, and on the energy interval of the protons.

For example, McIlwain and Pizzella[67], analyzing the data of Explorer-VI, observed systematic variations of the spectrum, connected with changes in L. The dependence of the spectrum on L has approximately the form

$$N(E)\,dE = ke^{-\frac{E}{E_0}}dE, \tag{20}$$

where $E_0 = (306 \pm 28)L^{-5.2\pm0.2}$ MeV. On the whole, the question of variation of the proton spectrum in the inner belt with altitude and latitude has not been sufficiently well studied.

With respect to the very low energy proton component of the inner belt (from 400 eV to 500 keV), there are data obtained with the satellite Injun-I at altitude 1000 km[68]. The directional flux of these protons was 60 erg-cm^{-2} sec^{-1} sr^{-1}.

With increasing L, the proton spectrum becomes in general softer, following an exponential law (16) from L = 1.2 to L = 8. The maximum directional density of the protons in the E_2 region ($L \approx 3.5$), according to measurements made by Davis and Williamson with the satellite Explorer-XII[69], is 6×10^7 cm^{-2} sec^{-1} sr^{-1} for energies from 100 keV to 4.5 MeV. As regards the maximum intensity of the integral flux of protons with energies larger than 300 MeV in the E_3 zone, according to measurements made with the second Soviet space rocket it amounts to less than one particle/cm^2 sec[70], and the integral intensity of the flux of protons with energies larger than 75 MeV is 0.1 particle/cm^2 sec[61]. The latter data do not contradict the results of the measurements of the dependence of the spectrum of the protons on E_0 with Explorer-XII. If the spectrum is of the form (20), then E_0 = 400 keV for L = 2.8, E_0 = 120 keV for L = 5.0, and E_0 = 64 keV for L = 6.1[69].

c) Electronic Component

According to the presently available data, the most intense component of the high energy particles in the region $L \leq 2$ is due to the electron flux. For example, the first measurements of Explorer-IV have shown that for $L \sim 1.5$ (the maximum of the inner belt) the integral intensity of the flux of electrons with energy larger than 580 keV is less than 10^8 particles/cm^2 sec, while the intensity of the directional flux of electrons in the same energy band is of the order of 2×10^7 particles/cm^2 sec-sr; the integral intensity of the flux of electrons with energy larger than 20 keV is less than 2×10^9 particles/cm^2 sec, and the intensity of the directional flux of electrons of this energy is of the order of 2×10^8 particles/cm^2 sec-sr.

For electrons with energy larger than 40 keV, the results of measurements made with Explorer-IV and Injun-I give grounds for suggesting that the directional intensity in the region $L \sim 1.5$ is of the order of 3×10^7 particles/cm^2 sec-sr[71].

There are not many data on the spatial distribution of the electrons in the region $L \leq 2$. It can be assumed[72] that the spatial distribution of electrons with energy larger than 600 keV is similar to the distribution of the high-energy protons, but the electron fluxes reach somewhat larger latitudes. According to the data of Injun-I and of Holly et al.[73] the intensity of the electrons with energy larger than 40 keV in the inner belt does not decrease with altitude and latitude as rapidly as the intensity of the protons with energy larger than 40 MeV.

During the flight of the third Soviet satellite it was established that electrons with energies of tens of hundreds of keV are present in the region $L \geq 3.5$[83]. Further investigations have established the presence in this region of electrons with energies from 30 keV to 5 MeV. In the region L ~ 4.5 (maximum of outer belt), according to the data of Explorer-XII, the most probable integral intensity of the fluxes of electrons with energies larger than 40 keV is less than 10^8 particles/cm^2 sec. Measurements of electrons in the region of the outer belt were carried out also with the aid of the second Soviet space rocket. These measurements have shown that for $L \approx 4.5$ the isotropic intensity of the fluxes of electrons with energies above 350 keV is 1.4×10^7 particles/cm^2 sec; for energies larger than 1100 keV the intensity is 5.5×10^5 particles/cm^2 sec, and that for energies larger than 5 MeV is smaller than 10^3 particles/cm^2 sec [70]. Finally, the electron flux registered on the second Soviet space rocket with the aid of charged-particle traps was found to be 2×10^7 particles/cm^2 sec for electrons with energies larger than 200 eV [75].

We recall that the initial interpretation of the results of measurements of fluxes of electrons of high energy in the outer belt was in error. Thus, for example, analyzing the readings of the instruments on the space rockets Pioneer-III and Pioneer-IV, obtained when these rockets passed through the outer radiation belt, Van Allen and his co-workers reached the conclusion that the integral intensity of the fluxes of electrons with energy larger than 20 keV amounts to 10^{11} particles/cm^2 sec in the zone of the maximum of the outer radiation belt (L ~ 4.5). Similar estimates were obtained also in [60]. Subsequent measurements have shown that these estimates are greatly exaggerated and the true density of the electron flux corresponds to the measurement results obtained with the aid of ionic traps on the second Soviet space rocket.

Figure 15 shows a schematic diagram of the distribution of the electrons in the earth's magnetosphere [76]. Only minimal value of the intensities of the registered fluxes are indicated, since according to the available data the electron intensities (especially in the outer belt) are subject to considerable variations (see below).

The first measurements of the spectral distribution of the electrons in the outer radiation belt were made with the aid of American rockets at altitudes of approximately 1000 km in the region of large latitudes [77]. The measurements yielded the spectrum of the electrons in the energy interval from 40 to 500 keV by means of the formula

$$N(E)\,dE \sim e^{-\frac{E}{E_0}}\,dE, \tag{21}$$

where $E_0 = 65$ keV. Investigations of the outer radiation belt with the second Soviet space rocket have shown that the energy spectrum of the electrons has in the energy region from 350 to 650 keV the form

$$N(E) \sim E^{-2}, \tag{22}$$

in the energy interval 650—1100 keV

$$N(E) \sim E^{-3,5} \tag{23}$$

and in the 1100—5000 keV interval

$$N(E) \sim E^{-7}. \tag{24}$$

It is thus assumed that the electron spectrum in the region L > 3.5 is abruptly terminated at energies above 5 MeV [78]. The satellite Explorer-XII was also used to measure the spectrum of the electrons of the outer belt in the energy interval from 40 keV to 5 MeV. The spectrum obtained from these measurements for low electron energies is in good agreement with the spectrum obtained on the basis of the rocket measurements at 1000 km altitude. At higher energies, the results of Explorer-XII agree with the results of the second Soviet space rocket.

d) Some Experimental Data on the Dynamics of the Earth's Radiation Belts

The data given above characterize the stationary state of the earth's radiation belts. At the same time, as already noted, the radiation belts are dynamic formations.

For the dynamics of the radiation belts of the earth, an important factor is the relation between the particle flux density and the energy density of the

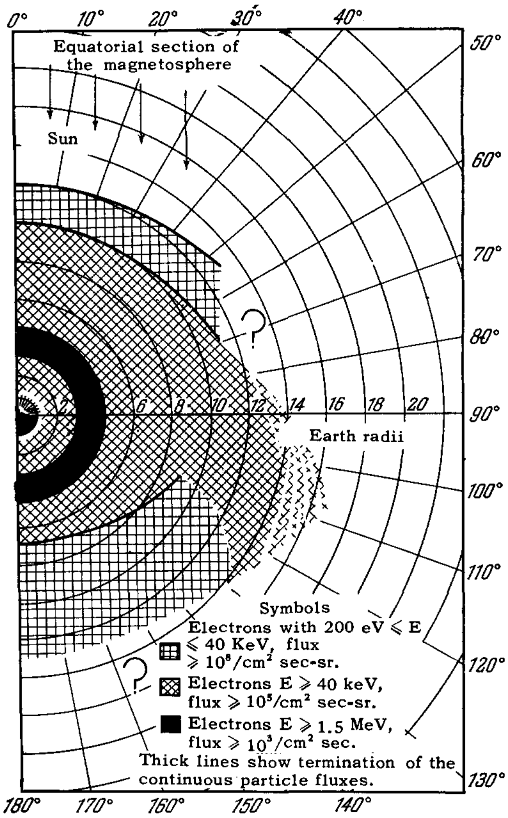

FIG. 15. Diagram showing the distribution of electrons in the earth's magnetosphere from data obtained with Explorer-XII.

magnetic field retaining these particles. After the first measurements in the radiation belts it became universally acknowledged that the flux density of the low-energy electrons in the geomagnetic trap is close to the energy density of the geomagnetic field, that is, the trap is filled almost to the limit. However, the observed errors in the interpretation of the measurements of the particle flux in the outer zone have made it necessary to review these data, after which a more commonly accepted opinion was that the particle energy density is much smaller than the energy density of the magnetic field, although this was established experimentally only with respect to the electron flux. The low-energy protons (< 4.5 MeV) captured in the trap were observed by Davis and Williamson [69] with the Explorer-XII satellite, and it was shown that the trap was filled practically to the limit precisely with such protons (the energy density ratio ≤ 10).

The corresponding effects involving the influence of the proton belts on the geomagnetic field are calculated by Chapman, Akasoufu and Cain [79] and recently confirmed with the satellite Electron-II [80]. Thus, acceleration of the particles in the magnetosphere takes place in a filled trap, something as yet unattainable in the laboratory and insufficiently investigated theoretically. Unfortunately, data on the soft protons in the outer magnetosphere are still very skimpy, owing to the experimental difficulty of their registration. However, the importance of these measurements can hardly be overestimated, since after many refinements (and also following the American high-altitude explosion of 9 July 1962) the experimental data could be summarized as follows: the inner belt consists essentially of high-energy electrons (a considerable fraction of which is of artificial origin), while the outer belt consists essentially of low energy protons (0.1—4.5 MeV). There is a possible connection between these protons and the soft protons which penetrate the aurora zone. During the time of the magnetic storm that occurred during the flight of the first space rocket, auroras were registered by 20 land-based stations. Measurements with Explorer-XII have shown [69] that during that time the intensity of the soft proton flux at the upper boundary of the magnetosphere increases, but there are no analogous measurements within the magnetosphere as yet.

The most important factor in the theory is the sharp asymmetry of the outer magnetosphere, its tremendous extent in the antisolar direction, and the closely associated morphology of the captured radiation at large distances from the earth [81-76]. However, the configuration of the magnetic field and the trajectories of the particles in this region are still quite unclear; we do not even know the distribution of the particles relative to the angles with the magnetic flux line. We can hope that future experiments, particularly with "Electron" satellites, will yield data in this direction.

A detailed connection between the magnetic effects and the radiation captured in the trap was found also on Explorer-VI in a study of simultaneous short-period variations of the field and radiation intensity (of protons with energy > 2 MeV or of electrons with energy > 200 keV). It became clear here that simultaneous oscillations of the field and of radiation are encountered, and these oscillations can be either in phase or in antiphase [82]. Experiments of this kind are apparently of greatest interest for the determination of the mechanisms of particle generation in the belt.

We have considered briefly some results of measurements of low-energy protons. We now proceed to processes of their spilling out of the trap. processes investigated so far only for electrons.

The penetration of low-energy electrons into the dense atmosphere from high altitudes was first observed by Krasovskiĭ and his co-workers with the third Soviet satellite in 1958 [83] and was then investigated in detail by O'Brien for energies larger than 40 keV with the satellites Injun-I and Injun-III and by Mulyarchik et al.[84] with the satellite Kosmos-5. They all found that the isotropy of the radiation increases for lower energies. The electrons with energy ~ 15 keV, which are intense near the aurora zone at altitudes of approximately 1500 km, have a distribution with respect to the angles with the force line such as to evidence their effective spilling into the atmosphere. It is obvious that the lifetime of such electrons allows them to execute only several latitudinal oscillations, and their relative intensity, compared with the captured particles, increases from $\leq 10^{-3}$ at low latitudes to ~ 1 near the aurora zone. This evidently yields information on the properties of the particle generation mechanism, with respect to their distribution over the angles with the force line. Additional information can be obtained by starting from the fact that at all latitudes there is a considerable number of captured electrons whose lifetimes are shorter than one drift revolution around the earth [85]. All these data show that for a considerable number of particles registered in the belt there is no conservation of either the energy or of the first and second invariants of motion during a time on the order of one drift revolution. It is possible that the scattering of these particles can lead to their appreciable diffusion with respect to L.

O'Brien found that the penetration of the particles at medium and high latitudes occurs to a considerable degree via short almost isotropic bursts of particles, lasting several seconds. Equally fast variations were observed earlier with the third satellite (Krasovskiĭ et al.[86]). Apparently these bursts accompanied the "quiet" penetration of particles which is characteristic of high latitudes, since even there individual, almost periodic flashes appear (incidentally, they are characteristic also of certain forms of auroras). It would be very important to clarify the role of hydromagnetic and electromagnetic waves of low frequency in these bursts; however, such data are still missing.

O'Brien believes [87] that the outermost belt of particles (electrons) is populated by such short-duration bursts (that is, by those particles, whose angles to the force line after emergence from the acceleration zone are such as to insure a sufficiently long particle lifetime). It must be stated that the apparatus used to investigate the radiation was frequently not adapted for the registration of such short-duration fluctuations. And particularly surprising is the fact that the burst was observed not on the boundary but within the magnetosphere. Detailed measurements of such effects are obviously essential for the construction of a theory of the particle acceleration mechanisms in the magnetosphere.

An essential factor in the dynamics of radiation belts is also the time variation of the geomagnetic field that retains the corpuscular radiation of the belts. Measurements of the magnetic effects in the earth's magnetosphere during the time of storms were first carried out on the first Soviet space rocket and on the American satellites Explorer-VI and Explorer-XII. They disclosed effects due to annular currents in a western direction, which at that time were tentatively interpreted as being due to the drift of soft protons captured in the trap.

Measurements made with the satellites Explorer-IV, Explorer-VI, Explorer-VII, Explorer-XIV, Explorer-XV, Relay-I, and others also made it possible to estimate directly the fluctuations of the intensity of the corpuscular streams in the radiation belts during the time of magnetic storms. These measurements coincided with large magnetic storms and showed a close connection between the characteristics of both the outer and the inner radiation belts of the earth with the solar activity. For example, in measurement on the satellite Explorer-VII, which moved at lower altitude, it was observed that a concrete connection exists between the solar activity and the intensity of the radiation belts. The strong increase in the solar activity in April, May, and November of 1960, according to the data of this satellite, has led to noticeable increases in the intensity of the radiation from the earth's radiation belts. A particularly interesting result is the increase in the intensity in the region intermediate between the inner and outer radiation belts. At the same time, an increase took place in the outer radiation belt. In the region of the inner belt, the increased intensity of radiation exceeded the unperturbed level by 2—3 times; this can be attributed to the appearance of additional proton fluxes with energies larger than 18 MeV, or to fluxes of electrons with energies larger than 1 MeV.

During the time of motion of the satellite Explorer-IV, at large altitudes (between 270 and 2200 km, several magnetic storms took place, the most intense of which (double storm) was observed on 3-5 September 1958. An analysis of the satellite data shows that in the initial period of the magnetic storm there occurs a large change in the intensity of the registered particles (electrons) in the outer radiation belt, and this change is of opposite nature for large and small altitudes. At low altitudes at the beginning of the storm the intensity increases, while at high altitudes it decreases by a factor of several times. After the end of the storm, the intensity returns to its previous level. An interesting fact is that after the strong storm of 3-5 September the average particle energy turned out to be considerably higher than their average energy prior to the storm. This may be evidence that definite particle-acceleration mechanisms "operate" in the earth's magnetosphere. No changes in the intensity of the fluxes of the protons were observed in the inner belt during the period of the observations, with the exception of changes connected with the nuclear explosions during the Argus experiment.

The flight of the Explorer-VI satellite established the presence of the E_2 zone, with a maximum at 17,000 km from the earth's center in the plane of the equator. During that flight, a change was observed in the characteristic of the radiation zones E_2 and E_3 when the magnetic storms occurred on 16-18 August and 3-5 September 1959. It was found that rapid and simultaneous changes in the distances from the E_2 and E_3 regions to the earth's center occur during the time of the magnetic storms. The change in distances can reach 10% of the total distance from the earth. Both regions move during the first phase of the magnetic storm inside the magnetic field, and the magnitude of the shift in the E_2 region turns out to be much smaller than for E_3. To be sure, a point of view has been advanced that the shift of the E_2 and E_3 zones is connected with variations of the electronic spectrum during the time of the storm[71].

During the time of the principal phase of the storm, an abrupt decrease takes place in the radiation intensity both in the E_3 and in the E_2 zone (but on a smaller scale in E_2 than in E_3). During the reverse phase, a considerable increase takes place in the radiation intensity. After the end of the storm, the intensity gradually again reaches the normal value which was observed prior to the storm. The increase in the intensity during the period of the inverse phase of the storm, according to observations on Explorer-VI can reach dimensions that are ten times the ordinary unperturbed value.

Figure 16 shows a diagram from [88], characterizing the change in the radiation intensity in the radiation zones E_2 and E_3 as read by the instruments of

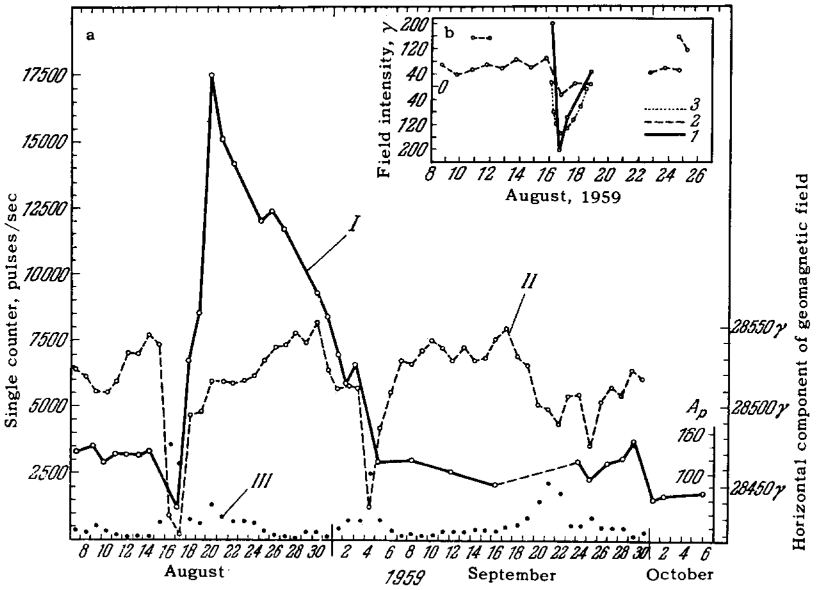

FIG. 16. a) Intensity $E_{3\max}$ in the vicinity of the geomagnetic equator as a function of the time (I), and horizontal component of the equatorial geomagnetic field on the earth's surface (II); b) changes in the magnetic field intensity, registered on Explorer-VI in the outer belt (I).

Explorer-VI during the magnetic storms of 16-18 August and 3-5 September 1959. The authors of the paper relate the change in the intensity of the electron flux during the time of the storm with possible irreversible acceleration of the particles in the alternating magnetic field.

Investigations on Explorer-VI have also shown that during the time of the magnetic storm there can occur a change in the character of the anisotropy of the corpuscular radiation in the outer radiation belt. Thus, for example, if the dependence of the intensity of the particle flux on the position on the given magnetic force line is of the form

$$\frac{I}{I_0}=\left(\frac{B}{B_0}\right)^{\frac{-|x|}{2}}, \qquad (25)$$

where I and B are the radiation intensity and the magnetic field intensity at some point of the force line, while I_0 and B_0 are the intensity and the field strength on the geomagnetic equator, then $|x|$ changes from 1 to 2.4 during the storm.

Large temporal variations of the radiation intensity were observed on Explorer-XII during the storm of 30 September 1961 (the intensity at the maximum of the outer belt dropped by more than three orders of magnitude, after which it was practically completely restored gradually within several days)[89] This case is of interest also because Explorer-XII fixed the motion of the boundary of the magnetosphere, which it crossed and which could be determined from the abrupt decrease in the intensity of medium-energy electrons and from the violation of the regularity of the magnetic field. Figure 17 shows the variation of the intensity within a relatively short time interval, for different flights of this satellite. Since the trajectory shifted insignificantly during that time, the change in intensity registered during the time of the storm can be regarded as a purely temporal variation.

Interesting data on the variations of the electron intensity in the region $L \leq 3.8$ were obtained with the satellite Explorer-XV. As is well known, prior to the explosion of 9 July 1962, the number of electrons in the magnetosphere with energies larger

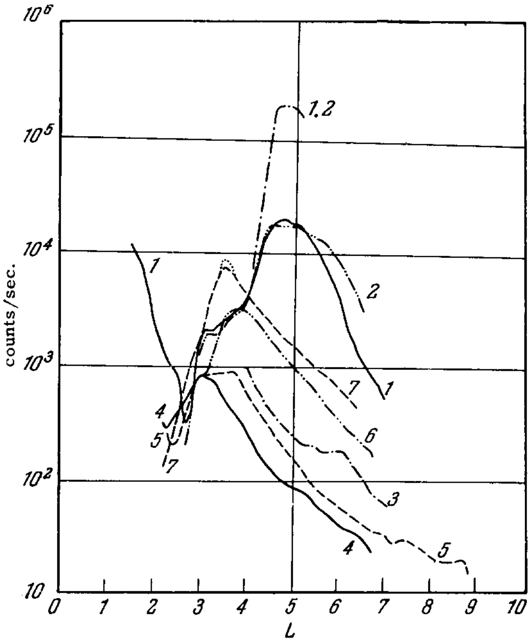

FIG. 17. Change in intensity of particle fluxes during the passage of Explorer-XII through the boundary of the magnetosphere in the time of a storm. The variation in the counting rate during the period from 28 September to 6 October 1961 (the ranges of the satellite inside and outside the atmosphere are shown). 1 – Outside, 28 September; 2 – outside, 30 September; 3 – inside, 1 October, 4 – outside, 1–2 October, 5 – outside, 2–3 October, 6 – inside, 4 October, 7 – inside, 5–6 October, 1961.

than 5 MeV was quite small (one particle/cm^2 sec, Vernov et al.[90]). Therefore all electrons with this energy, which are contained there at present, can be assumed to have been artificially injected. According to the Explorer-XV data [63], the intensity of such electrons decreased almost instantaneously during each small magnetic distrubance in the course of approximately two months, but in a noticeable magnetic storm it increased practically to the initial value. Inasmuch as during the time of the magnetic storm the acceleration of any particles of artificial origin to such large energies is impossible, then the acceptable explanation of the observed variations is as follows: a) deceleration of the electrons under small perturbations with their number remaining the same in the trap, 2) reverse acceleration during the sizable magnetic storm. It is not excluded, to be sure, that this generally speaking unclear mechanism may be effective only for electrons of high energy, that is, it calls for a "primary injector," which is missing in the case of belts of natural origin. Such an injector could be a high altitude nuclear explosion.

According to measurements with the satellite Relay-I, the intensity of the trapped protons with energy larger than 35 MeV in the region of the inner radiation belt ($L < 2$) changed by not more than 10% during the magnetic storm of 22 September 1963. During the same time, the intensity of the protons for $L > 2.5$ decreased by approximately a factor of 10[91]. Figure 18 shows the relative change in the proton intensity during the time of this magnetic storm. Simultaneously, a new external electron zone began to be formed, with a maximum intensity at $L = 3.2$, and a large number of electrons with energies of hundreds of MeV appeared in the region of the outer zone (from $L = 2$ to $L = 4$).

The few experimental data on the dynamics of radiation belts of the earth, which we considered above, lead to the conclusion that the magnetosphere contains without a doubt accelerating mechanisms connected with collective effects in the cosmic plasma in the vicinity of the earth.

However, the question whether these mechanisms have a reversible or irreversible character still remains open, since the influence of the accelerating mechanisms (especially during the time of magnetic storms) can be obscured both by intrusion of external charged particles into the radiation belts, and by the spilling out of "old" particles into the lower dense layers of the atmosphere. A positive role in the clarification of the latter question will undoubtedly be played by further experiments on the study of the dynamics of the belts. It must be noted that the experimental study of the dynamics of the radiation belts has recently become much more systematic.

4. PRINCIPAL HYPOTHESES CONCERNING THE ORIGIN OF THE EARTH'S RADIATION BELTS

The main hypothesis concerning the origin of the radiation belts, which has already received direct experimental confirmation, is that the geomagnetic field captures streams of charged particles. However, the establishment of this fundamental fact is still not a complete solution of the problem of the origin of the radiation belts. It is important to understand the mechanisms by which the particles are produced, to find the energy spectrum and the particle distribution in the earth's magnetosphere corresponding to these mechanisms, and also to determine the intensity of particle injection. The solution of these problems becomes more complicated by dynamic processes which occur in the radiation belts. An important problem is the clarification of the connection between the behavior of the particles inside the magnetosphere and on its boundary. Among the most intensely developed hypotheses devoted to this circle of questions are the "neutron albedo" hypothesis and the hypotheses concerning the capture of solar-plasma particles by the geomagnetic field and their subsequent "local" acceleration.

At the present time the theory of injection of the charged particles produced during the decay of secondary neutrons from cosmic radiation in the geomagnetic trap is the most fully developed. This theory has yielded quantitative estimates which can

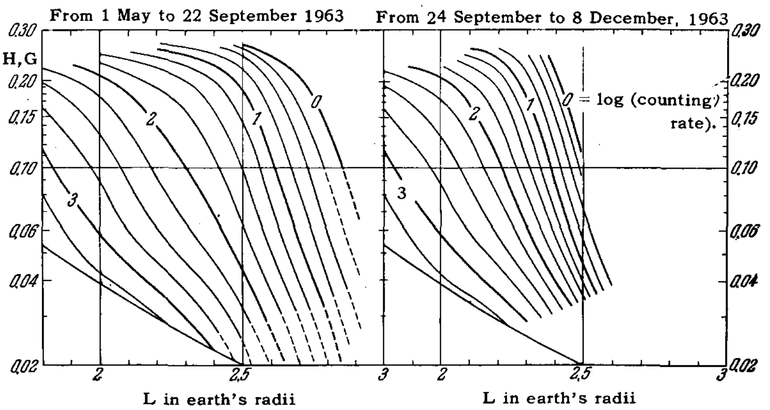

FIG. 18. Contours of constant intensity of trapped protons with energies larger than 35 MeV before and after the magnetic storm of 22 September 1963 (according to the data of the satellite Relay-I).

be compared with the experimental results. A shortcoming of the neutron albedo hypothesis is the lack of a direct connection between the mechanism of particle production and the dynamics of the radiation belts. Indeed, the variations of the geomagnetic field, which give rise to substantial changes in distribution of the trapped-particle flux intensity, can only indirectly influence the injection mechanism connected with the neutron albedo. At the same time, the possibility of separating the estimate of the injection from the estimate of leakage of the trapped particles places the neutron-albedo mechanism in a more favorable position than other hypotheses, and makes it possible to obtain appropriate quantitative estimates relatively simply.

The mechanisms of origin of radiation belts, based on plasma processes, are closely related with concrete conditions in the earth's magnetosphere, for example, with the nonaxial character of the geomagnetic field, with peculiarities in the propagation of the magnetohydrodynamic waves in the magnetosphere, with conditions on the boundary of the magnetosphere, etc. These conditions are not yet sufficiently known from experiment and are far from clear from the point of view of theory. Among the plasma hypotheses of particle generation are different mechanisms involving the breakthrough of solar-wind particles into the geomagnetic trap and mechanisms of "local" acceleration of the particles of the radiation belts. It should be noted that the need for additional acceleration of the particles of the solar wind in order for these particles to have the energy observed in the earth's radiation belt was clear from the very outset. Therefore, the papers devoted to the capture of solar plasma by the geomagnetic trap, consider also several acceleration mechanisms which accompany the capture. At the same time, the local acceleration of particles of the outer atmosphere was related with strong magnetic perturbations during the period of the magnetic storm. Thus, from the point of view of plasma physics, it is difficult to draw a distinct line between the two groups of hypotheses, inasmuch as each attributes the origin of radiation belts to effective interaction between the plasma and the earth's magnetic field.

The resultant impression is that the most promising are from the point of view of further development of the theory of radiation belts the hypotheses based on plasma effects. A serious study of the dynamics and kinematics of the radiation belts of the earth should clarify not only the question of the contribution of the plasma mechanisms of particle production in different regions of the belts, but also the question of the effectiveness of the neutron albedo mechanism.

a) Neutron Albedo Hypothesis

Vernov and Lebedinskiĭ [92] and Singer [93] called attention almost simultaneously to the neutron component of the "albedo" of cosmic rays as a possible source of charged particles in the radiation belts. These assumptions were based on the possibility that the neutrons, produced in nuclear disintegrations in the earth's atmosphere caused by cosmic rays, can break up into protons and electrons during the course of leaking out of the atmosphere. The decay products, protons and electrons, being charged particles, are captured by the earth's magnetic field if the decay occurs within the limits of the trapping region of the field. The neutrons of the "albedo," which go out of the atmosphere, have a broad energy spectrum (from thermal to several hundred MeV). The kinetic energy of the protons produced during neutron decay is comparable with the energy of the latter, and the decay electrons have the well known energy spectrum.

After the first approximate estimates, calculations were published in which account was taken of diffusion, and also the slowing down of the "albedo" neutrons in the atmosphere [94-96].

These calculations and experimental data on the neutrons in the atmosphere have made it possible to obtain a sufficiently well founded quantitative description of the injection of particles for this mechanism.*

Kellog and Hess studied in detail the generation of electrons and protons in the radiation belt by thermal neutrons. Singer investigated the spectrum of hard protons produced in the inner belt during the decay of high energy protons. Lenchek et al.[97] assume that a source of protons of relatively low energy are the polar-cap neutrons generated by solar cosmic rays. These protons can appear only starting with L ~ 1.6. A superposition of the albedo neutrons produced by the solar cosmic rays penetrating into the polar caps on the neutrons produced under the influence of galactic cosmic rays was clearly proved both theoretically and experimentally[3].

Obviously, the leakage processes are more difficult to estimate, since we can never be sure that some new type of leakage (or, to the contrary, acceleration) does not appear on occasion, for example during the time of magnetic storms. However, it can be assumed that at low latitudes Coulomb scattering is indeed the predominating leakage mechanism. In particular, the energy spectrum of the protons and the height of the homogeneous atmosphere, determined under this assumption from the distribution of the high-energy protons, are in good agreement with the direct-measurement data. Until recently the model of the atmosphere was not known to us

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*The neutron albedo hypothesis is detailed in most complete form in the review of Lenchek and Singer[3] and in the paper of Hess[96]. In this article we present only the final results of the corresponding theoretical estimates, on the basis of which one can judge the advantages, shortcomings, and prospects of further development of this hypothesis.

with sufficient accuracy to be able to verify this, but now this difficulty has been overcome [98,99]. However, even now the inaccuracy with which we know the trajectory of the particles in the Brazilian anomaly does not actually make it possible to compare the calculated rate of leakage due to scattering in the atmosphere with the source function calculated by the methods described above. For high-energy protons at small altitudes, where the data obtained prior to the explosion of 9 July 1962 are sufficiently complete [62,100], comparison gives a discrepancy by a factor not larger than 3. In addition, recently there was noticed an increase in the intensity of the protons moving downward with decreasing density of the atmosphere and with increasing cosmic-ray intensity [90,101]. Let us consider the spectrum and the distribution of the hard protons (> 75 MeV), which appear following the decay of the fast neutrons generated in atmospheric interactions of galactic cosmic rays (the so-called "global" neutron component). We denote by $n \equiv n(\mathscr{E}, \theta, L, H)$ the density of the protons directed at an angle θ to the magnetic force line, characterized by a parameter L, in a given point determined by the field intensity H. All the protons have the same energy $\mathscr{E}$. Then the intensity of the directed flux of the trapped radiation, with particle energy in the interval from $\mathscr{E}$ to $\mathscr{E} + d\mathscr{E}$, will be

$$j = 2\pi n v \, d\mathscr{E} \, d\cos\theta_0. \tag{26}$$

Thus the distribution function n is the differential concentration of the flux of particles with a definite direction on the magnetic equator. By the Liouville theorem, n is constant along the trajectory of the particles of the derivative flux and can vary only if L, $\mathscr{E}$, and $\cos\theta_0$ vary. However, because of the anisotropic injection of hard protons, n will depend on the time, with the relation $(\partial n/\partial t)_{\text{inj}} = \bar{q}$ determining the density of the source function of the directed flux of captured protons $\bar{q}$.

On the other hand

$$\bar{q} = \frac{1}{t_n v_n} \oint j_n ds \Big/ \oint ds \, , \tag{27}$$

where t_n is the lifetime of the neutron escaping from the atmosphere, v_n is the neutron velocity, j_n is the intensity of the directed neutron flux, and ds is an element of arc on the particle helical trajectory [3].

A change in n is caused also by the loss of proton energy in inelastic collisions with the atoms of the atmosphere.

The equation describing the equilibrium distribution resulting from both the injection process and particle leakage is called the transport equation. Solving this equation [3], we can find the distribution function n at any point of the magnetosphere and, integrating over θ_0, we obtain the isotropic (integral) intensity of the proton fluxes as a function of E, L, and H. The distribution of the integral intensity of the hard protons as obtained by the theoretical calculations [3] is shown in Fig. 19. This distribution is in good agreement with experiment (Fig. 4).

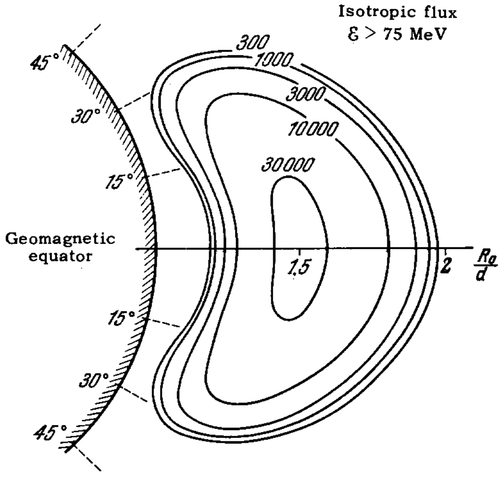

FIG. 19. Distribution of intensity of isotropic flux of captured hard protons (with energy > 75 MeV) obtained on the basis of the theory of neutron albedo (after Singer).

As already mentioned, superposition of a spectrum of softer protons (> 10 MeV) due to the neutrons of the polar cap on the global component begins with L ~ 1.6. This is connected with the inability of the neutrons running away from the polar cap to fall into the trapping region below L ~ 1.6, since the boundary of this region reaches a geomagnetic latitude Φ' ≈ 60°. Figure 20 shows a comparison of the theoretically calculated equilibrium spectrum of the global and polar components with the results of measure-

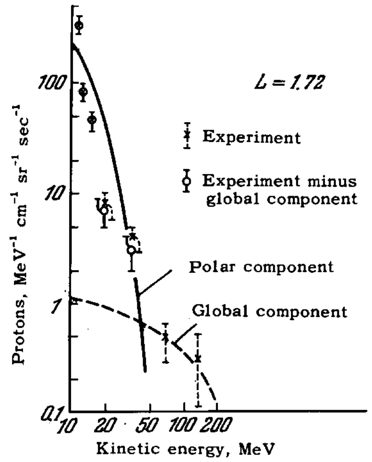

FIG. 20. Comparison of the theoretical calculated spectrum of the protons (Singer and Lenchek) with the experimental data obtained by Naugle and Kniffen.

ments made with nuclear emulsions [66] for L = 1.72. It is seen from Fig. 20 that the theoretical results are in good agreement with the experimental ones. The time variations of the spectrum of the polar component can be explained as being due to the solar cycle.

Thus, the high energy protons actually owe their origin to the albedo-neutron decay mechanism. At the same time, many problems are still insufficiently clear. This pertains first to the low energy protons (≤ 10 MeV). Although qualitatively protons with such energies should be generated by the neutron albedo mechanism with high efficiency, their leakage (essentially by charge exchange with the atmospheric components) should be quite fast. The lack of sufficient knowledge of the intensity distribution of such protons at low altitudes does not make it possible as yet to estimate the rate of their leakage, and so far only an upper estimate can be given for the flux of spilled-out protons with energy > 100 keV from data on the glow of the night sky at low and medium altitudes, namely $J < 10^5$ protons/cm^2 sec [102]. It is not excluded that low-energy protons observed by Davis and Williamson [69] with the satellite Explorer-XII are somehow connected with the soft protons which penetrate irregularly near the aurora zone ($L \sim 5$-7), when their flux can exceed 10^8 particles/cm^2 sec [102]. In light of this, it is little likely that low-energy protons can be due to the neutron albedo mechanism, and one can think that there exists another much more powerful source which supplies captured protons of low energy and possibly the soft aurora protons. The interest in research on low energy protons shown in recent years is therefore not surprising.

Another problem is connected with the variations of the radiation intensity at low latitudes, observed by Pizzella, McIlwain, and Van Allen [67]. Although according to observational data the temporal connection between these variations and the penetration of solar cosmic rays is obvious, however it is impossible to ascribe the observed variation to the decay of albedo neutrons produced by solar cosmic rays, since the relative increase in the intensity is practically independent of L. It may be quite useful here to make use of the notions of the diffusion of particles in the space of natural coordinates, which was already mentioned above. On the other hand, the apparatus employed did not make it possible to distinguish between protons with energies > 18 MeV from electrons with energies > 1.5 MeV. Since it has been clear for a long time that the neutron albedo mechanism cannot explain the observed intensities of the entire energy spectrum of the electrons, there is no doubt of the existence of additional electron generation mechanisms. Such an assumption allows us, at least for the time being to disregard hard-proton (> 18 MeV) generation mechanisms other than neutron albedo, but the uncertainty still remains, obviously, for the softer protons (≤ 10 MeV).

A third problem which in our opinion should be mentioned is the possible refinement of the source function of the albedo neutrons by taking into account high energy particles entering the magnetosphere from the outside on quasiperiodic trajectories (this effect was considered by Gall and Lifschitz [103]). The mechanism proposed in [104] for the capture of such particles in the geomagnetic trap through energy loss to bremsstrahlung may be significant for solar and galactic cosmic rays. In [104] it was proved that these charged particles can be captured by the field of a magnetic dipole (in its equatorial plane), situated in an external stationary magnetic field, and also in the absence of an external field, through the existence of "critical" trajectories for which infinitesimally small losses of kinetic energy of the particle lead to a changeover from the "uncaptured" trajectory to a "captured" one.

It was proved in [105] that the "critical trajectories" and the possibility of capture of charged particles by the field of the magnetic dipole as a result of a loss of their kinetic energy to radiation exist also in the case of three-dimensional motion. This would lead to an apparent increase in the registered intensity of the cosmic rays with increasing altitude, as has indeed been confirmed experimentally. It is not excluded that this effect can make a contribution to the excess intensity of cosmic rays registered by satellites at low altitudes (below the region of the radiation belt)[106]. In addition, the neutron albedo, being a product of this "captured" cosmic radiation, can lead to an essentially different spectrum of protons and electrons than the spectrum of those particles which are due to the neutron albedo of the primary cosmic rays.

It is quite interesting to know whether a change in the distribution of the "natural" high-energy protons occurred during the American high-altitude explosion of 9 July 1962. An indication that such an effect is possible is contained in [107,108]; however, several months later the original distribution was anyway restored, so that the presently observed changes, compared with earlier measurements, can be attributed to variations in the density of the atmosphere and in the intensity of the cosmic rays.

As regards the electrons which are produced also in β decay of the neutrons, the picture is much less clear here. Considerable variations in the intensity and a continuous albeit fluctuating spilling out of the medium-energy electrons at $L \geq 2$ can hardly be due to the weak but constant decay of the albedo neutrons [71]. The discrepancy reaches here several orders of magnitude. For $L < 2$ the lifetimes of the electrons at considerable altitudes are relatively long, and the spilling out is insignificant, so that a detailed examination of the adequacy of the albedo mechanism appears to be useful.

However, the theoretically obtained spectrum of these electrons, under the assumption that they are generated upon decay of thermal neutrons, is in disagreement with the experimental data[94]. It would be interesting to consider this mechanism as a primary "injector" for the mechanisms of particle acceleration in the magnetosphere.

As shown in[109], high energy electrons (> 1.5 MeV) can appear as a result of the mechanism of neutron albedo, but then an abrupt dip in the energy spectrum should occur for an energy ~ 782 keV. In[109] there was also calculated the energy spectrum and the intensity of the electrons produced in this manner, up to ~ 7 MeV.

Unfortunately, a check on these conclusions can not be realized for a long time, since the appearance of a tremendous number of captured hard electrons of artificial origin after the high-altitude explosion of 9 July 1962 has contaminated the radiation belts for dozens of years to come, and will hardly allow us to separate in foreseeable future the weak natural source, which calls for a long lifetime. Moreover, even comparison with theory, of the measured hard electrons of 1959-1960, can also be made complicated by registration of radiation which appeared in the atmosphere during the high-altitude explosions "Argus," "Tick", and "Orange" in 1958, since it is now clear that the lifetime of electrons with energy of several MeV is sufficiently long.

b) Hypotheses Based on Effective Interaction of a Plasma with the Magnetic Field

Simultaneously with a hypothesis of neutron albedo, there were advanced hypotheses explaining the origin of the radiation belts of the earth both as due to local acceleration of charged particles of the outer atmosphere (Krasovskiĭ[110]) and as due to the abrupt intrusion of particles from the solar wind into the geomagnetic trap, accompanied by capture and acceleration of these particles (Van Allen[111]). The hypothesis of local acceleration was developed in the papers of Dessler[112], Crawford[113], Parker[114], Alfven[115], and others. The idea of abrupt intrusion and subsequent capture of charged particles by the geomagnetic field was supported by Gold[116], Kellog[117], Obayashi[118,119], Dorman[120], and others.

Krasovskiĭ has shown recently[121] that intrusion of particles from the corpuscular stream through the boundary of the magnetosphere, down to sufficiently great depths, is apparently quite unavoidable, since according to the available data on the density of the "cold" plasma at large distances in the earth's magnetosphere, not only the energy, but even the number of plasma electrons (for any acceleration mechanism) are insufficient to maintain the average rate at which they spill out in the dense atmosphere. It is obvious, in light of this conclusion, that it is necessary to reanalyze carefully the available data on the density of the "cold" plasma in the magnetosphere and to carry out new detailed experiments. It is necessary to clarify, in particular, the mechanisms by which this plasma is replenished at the upper ionosphere of the earth. For example, the ejection of ions and electrons from the regions of heating in the auroras can turn out to be a rather important method of replenishing the plasma in the magnetosphere. At any rate, it is now obvious that the dumping processes affect not some small fraction of the most energetic particles of the magnetosphere (some "tail" of the distribution), but are fundamental in the plasma of outer space near earth. The solution of this problem can be significant also for a laboratory investigation of plasma heating.

The main principle of acceleration of charged particles to the observed energies consists in transferring the energy of the solar wind or of the shock wave propagating from the sun, to the earth's magnetosphere. The earth's magnetosphere can in turn transfer this energy to the rarefied plasma of the radiation belts both via the variations of the magnetic field, in which the non-interacting particles move, and with the aid of collective effects of "heating" the plasma which is frozen in the magnetic field. The most natural is the assumption that both effects play a role in the formation of the belts. Particles having a low energy (on the order of the energy of the particles of the solar winds, that is, several electron volts for electrons and several keV for protons), are first "heated" by interacting with each other and with the electromagnetic fields, and then drift in the alternating field, acquiring additional energy.

Examples of acceleration hypotheses based on collective effects are those of Dessler and Obayashi. In[96] it was proposed that magnetohydrodynamic waves with large amplitude can propagate in the outer atmosphere of the earth. Starting with altitudes of the order of 1000 km and above, these waves will have a narrow front with a large magnetic-field gradient. Such a situation is very favorable for the Fermi acceleration mechanism. In[118,119] Obayashi carried out calculations corresponding to Dessler's model. Two active regions (in the sense of particle acceleration) were found at altitudes 1000—3000 and 10,000—20,000 km (Fig. 21).

The energy spectrum of the particles accelerated by the nonrelativistic Fermi mechanism was given by Parker[122] in the form

$$j\ (W)=\frac{1}{2N_0mv^2}\exp\left(-\frac{W-W_0}{2mW_0v^2}\right), \tag{28}$$

(where W_0 is the energy of the thermal ions in the outer atmosphere, N_0 the number of collisions between the particle and the magnetohydrodynamic wave, the length of which is λ) prior to the instant when this particle goes out from the accelerating region with characteristic dimension $\mathscr{L}$. If the particles execute random motion in the region $\mathscr{L}$, then $N_0 = (\mathscr{L}/\lambda)^2$, and $v = (2kT/m)^{1/2}$ is the speed of sound. For $\mathscr{L} = 10{,}000$ km and $\lambda = 5000$ km, the

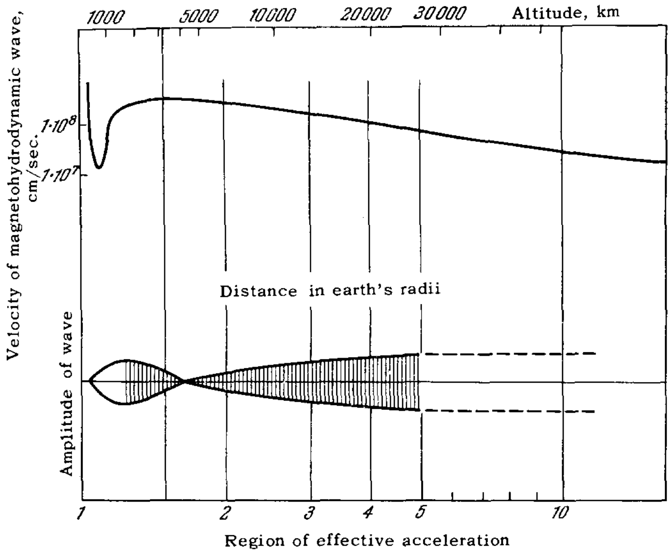

FIG. 21. Regions of effective acceleration of charged particles in the earth's magnetic field (after Obayashi). The shaded region corresponds to the spatial position of the radiation belts.

maximum energy of the protons is found to be $W^* \approx 100$ keV. Obayashi therefore concludes that the Fermi acceleration mechanism does not give sufficient energies corresponding to the proton energies in the radiation belt. We note that a similar mechanism could play a definite role in the production of the low-energy protons of the outer belt (see Sec. 2). Obayashi reaches the conclusion that, owing to the redistribution of energy between the electrons and the protons, the electrons existing in the radiation belt can reach the observed energies with the aid of this mechanism. The heating of the plasma of the outer atmosphere by the magnetohydrodynamic waves should lead to the appearance of inhomogeneities in the hot plasma, which produce, as a result of interaction with the geomagnetic field, unique "magnetic bottles." In favor of such a picture of plasma interactions with the earth's magnetic field can be cited the magnetic measurements of Dolginov and Pushkov [123].

Crawford [113] also considered the Fermi acceleration mechanism. He estimated the acceleration of particles in the boundary region of the earth's magnetosphere. He advanced the idea that the turbulent processes may give rise to closed magnetic loops upon interaction of the solar wind with the earth's magnetic field; these loops constitute traps in which the electrons can be accelerated with the aid of the Fermi mechanism. The characteristic acceleration time is assumed to be equal to the period of the principal phase of the storm, $\sim 4 \times 10^4$ sec. During that time the slow electrons can reach energy on the order of 30 keV. Such an electron energy can be sufficient for the excitation of auroras but is obviously insufficient for the electrons in the radiation belts. The protons, in the author's opinion, cannot be accelerated in similar fashion because of nonconservation of the magnetic moment.

The Fermi mechanism was considered in connection with the radiation belts by other authors, too. It is interesting that all the estimates show the patent inadequacy of the collective acceleration mechanisms for the explanation of the particle energies observed in the radiation belts. Consequently, some authors reached the conclusion that faster acceleration mechanisms are necessary for the charged particles interacting with the magnetohydrodynamic waves. For example, I. P. Ivanenko and V. P. Shabanskiĭ [124] propose that acceleration of a particle in magnetohydrodynamic shock waves coming from the boundary of the magnetosphere is connected with the nonconservation of the magnetic moment of the charged particle in the sharp gradient of the field in the vicinity of the front of the wave. The idea of nonconservation of the magnetic moment of the particle in the shock wave was advanced also by Gold [116]. However, this violation was not related with the particle acceleration.

Since the interaction between the solar corpuscular streams and the earth's magnetic field should lead to appreciable changes in the configuration of the geomagnetic field, some authors (Gold, Dorman, and others) suggested that the high-energy particles can be brought in the magnetic traps of the solar wind and, penetrating into the outer rarefield Stoermer region during the time of a magnetic storm, remain in this region after the passage of the storm.

The usual starting premise is that the perturbations of the earth's magnetic field by the solar wind during the time of the storm are sufficiently large to impart to the penetrating particles the energy observed in the belts. Acceleration due to collective effects ("heating") plays in this case only a partial role. The main acceleration should be the result of the drift of the interacting particles, which accumulate sufficiently high energy (100 keV), in the time-varying magnetic field. An important role can be played here by nonconservation of the corresponding adiabatic invariants of the charged particle, since such nonconservation can be connected with fast and irreversible acceleration of the particle in the alternating magnetic field. The particles of the solar wind can break into the geomagnetic trap during the time of the principal phase of the storm and be accelerated upon restoration of the magnetic field (inverse phase), remaining in the trap because of violation of the second and third invariants of particle motion.

The acceleration of charged particles in the geomagnetic field deformed by the solar wind, and also the nonconservation of the second and third adiabatic invariants, connected with the particle drift in such a field, have been considered in many papers. It is interesting that the first paper in which an estimate was made of the local acceleration of the charged particles of the belts, actually corresponding to nonconservation of the second and third invariants during the time of the magnetic storm, was carried out even before the concept of the third invariant was introduced. This paper belongs to Kellog[117].

On the basis of his earlier papers, which showed the inadequacy of the albedo of the Fermi neutrons as a source of the electrons of the inner radiation belt, Kellog considered the mechanism of local acceleration of electrons under the influence of low-frequency electromagnetic fields. These fields can result either from a change in the geomagnetic field during the time of magnetic storms, or from different collective effects in the plasma of the outer atmosphere. It follows from the author's estimates that during the time of the magnetic storm the charged particle should increase its energy in accordance with the expression

$$\frac{\delta\mathscr{E}}{\mathscr{E}}=10^{-3}\frac{R}{a}, \tag{29}$$

where R is the distance from the particle to the center of the earth and a is the radius of the earth. This acceleration mechanism, in the author's opinion, is applicable only to particles with energy higher than 1 MeV, since lower-energy particles are scattered by collisions at a faster rate than they acquire the necessary energy.

Kellog proposes a particle diffusion mechanism, connected with the fact that the charged particle, acquiring energy in the electromagnetic field, should move into the magnetic field as a result of the constancy of its magnetic moment, towards the earth (Fig. 22). This diffusion is actually the consequence of violation of the third invariant of the particle. For a particle with energy $\mathscr{E}$ = 10 MeV, the diffusion time will be

$$T=10^{11}\left(\frac{a}{R}\right)^3\left(\frac{1}{\mathscr{E}}\right)\approx 10^9\ \text{sec}. \tag{30}$$

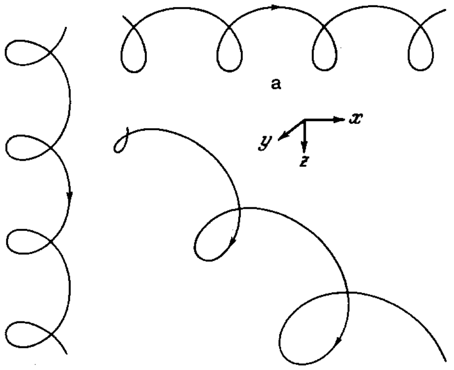

FIG. 22. Drift orbits of particles. a) Electric field E = 0, drift due to the gradient of the magnetic field B; b) dB/dy = 0, drift due to the electric field E; c) combined effect of E and dB/dy, dB/dy < 0.

Parker [114] has likewise shown that nonconservation of the third adiabatic invariant of the particle can cause an irreversible acceleration and a drift towards the earth on the part of the electrons in the outer radiation belt. The physical cause of nonconservation of the third invariant is, according to [114], the non-uniform compression of the geomagnetic field by the solar wind during the time of the first phase of the storm. The sudden compression of the field and its subsequent slow expansion should lead to "spreading out" of narrow beams of charged particles in the geomagnetic field; these particles are situated in the boundary regions of the field. However, the acceleration of the electrons, which is connected with the violation of the third invariant, turns out to be ineffective, in the author's opinion, since the accelerating particles will fall into the dense layers of the atmosphere as a result of the drift to the earth. The characteristic diffusion time also turns out to be very large.

The acceleration mechanism considered in [114] was thoroughly reviewed and supplemented by B. A. Tverskoĭ [125,126].

The main mechanism for the formation of the belts, according to Tverskoĭ, is the effect indicated by Parker, of nonconservation of the third invariant. The investigation of this effect in [125,126] is based on a rigorous investigation of the equations of particle drift. The author gave a method for calculating the electric fields produced in the magnetosphere during the time of a sudden start of the storm, with account of the plasma polarization and the influence of the ionosphere. The equations of the electric drift were investigated accurate to terms quadratic in the perturbation of the magnetic field, inclusive; it is shown that in addition to the diffusion observed by Parker there is a regular flux of particles to the earth. An account of the latter makes it possible to reduce by approximately 20 times the source power necessary to produce the belts.

An equation for the distribution function of the diffusing particles was obtained in [126]. This equation, called by the author the fundamental equation of the belt dynamics, relates the source function of the particles, the radiation of the distribution of the particles as a result of the diffusion, and the variation of the distribution due to the ionization losses. Tverskoĭ concludes that the neutron albedo of the cosmic rays is a sufficiently intense source to be able to explain the particle distribution existing in the radiation belt of the earth with the aid of the mechanism considered above.

The main results which follow from the calculations of B. A. Tverskoĭ reduce to the following:

a) The intensity of protons with energies > 50—100 MeV at L > 1.6—1.7 in the plane of the equator decreases like L^{-10} the integral intensity at the maximum is J ≈ 10^4—10^5 $\text{cm}^{-2}\ \text{sec}^{-1}$.

b) The outer belt of relativistic electrons decays into two components—stationary and alternating.

c) The stationary component of the belt is determined by averaging over a time of ~ 50 years the flux of the albedo neutrons; the maximum of this component coincides with the E_2 zone; the internal boundary is due to the Coulomb losses.

d) The observed main mechanism of relativistic electrons of the E_3 zone is nonstationary and is due to the sharp increase in the flux of solar protons in 1956—1961; during the years of the minimum of the solar cycle, the maximum will become progressively narrower; in 1967 the intensity at the maximum will decrease by approximately one order of magnitude; then at large L a new maximum will be produced and may approach the earth.

e) The energy spectrum of the electrons in the E_3 zone terminates abruptly at energies ~ 3 MeV; because of this circumstance, the decrease in the field during the time of the principal phase of the magnetic storm, by a factor of approximately 2.5 times, leads to a strong reversible decrease in the counting rate (by approximately three orders of magnitude).

It must be noted that the calculated profiles of intensity, obtained in accordance with this theory, are in good agreement with the experimental curves obtained in 1961—1962.

It is also proposed in [126] that besides the belts considered above there are particles of a different nature, not connected with neutron decay. These are, first of all, electrons with energies 10 keV accelerated during the time of the magnetic storms and, second, protons and alpha particles captured at large distances and diffused inside the magnetosphere. The mechanism of capture of such particles, in the author's opinion, is connected with the peculiarities of their drift orbits and, in particular, with the possibility of penetration of particles into the magnetosphere on the night side.

Paper [127] is also devoted to the diffusion of charged particles into the earth's magnetosphere as a result of violation of the second and third invariants upon interaction of high-energy particles with the electromagnetic shock wave coming from the sun. If the relative amplitude of the wave is denoted by

$$\alpha = \frac{\delta H}{H}, \tag{31}$$

then the displacement of the particle due to diffusion in the direction of front propagation is

$$x \sim \left(\frac{\alpha}{\pi}\right)^2 \varrho_L, \tag{32}$$

and in the plane of the front

$$y \sim \frac{\alpha v}{v_a} \varrho_L, \tag{33}$$

where ρ_L is the Larmor radius of the high-energy particle, v_a the velocity of propagation of the magnetohydrodynamic perturbation, and v the particle velocity. After passing through the front of the shock wave, the high-energy particle experiences reversible changes in energy, so that its magnetic moment is conserved.

The shock-wave front responsible for the sudden start of the magnetic storm occurs, in the author's opinion, in such a way that a considerable part of its surface is close to the meridional section of the radiation belt. This should produce, in accordance with (29), a strong radial shift of the high-energy protons towards the night side on both sides of the earth-sun line, and a shift of the high-energy electrons to the morning side of the magnetosphere.

This mechanism can lead to a strong smearing out of the maximum, and consequently to a decrease in the intensity of the outer belt of the high-energy electrons ($\mathcal{E} > 1$—2 MeV), with gradual restoration of the intensity during subsequent days. The author of [127] emphasizes that, unlike the diffusion mechanism considered in [114,125,126], the mechanism proposed by him is considerably faster and can explain many peculiarities of the dynamics of the outer belt of electrons.

In [128] is given an interesting comparison of the theoretically obtained variations of the proton spectrum as a function of the distance from earth and of the angle to the magnetic force line, with the experimental results of [129]. The proposed cause of the variations is the acceleration of the protons of the outer belt, drifting in the direction towards the earth, owing to nonconservation of the third adiabatic invariant Φ of the particle motion. The mechanism of violation of Φ corresponds to [114] or [117]. An essential fact here is that, according to [114,117,126], the drift from one invariant surface to the other does not depend on the proton energy.

Further theoretical investigations devoted to the acceleration of charged particles in the magnetic field upon nonconservation of the adiabatic invariants of motion of the charged particle, and also devoted to particle capture connected with the violation of these invariants, are apparently quite promising from the point of view of localization of the particle sources of the earth's radiation belts. At the present time it remains unclear, for example, whether the accelerated charged particles in the region of the outer belt can fall into the inner radiation belt or not.

The few hypotheses considered above concerning the origin of radiation belts, are only the first step in the development of the complete theory of belts as a component part of the theory of rarefied plasma in the geomagnetic trap. An essential shortcoming of most of these hypotheses is that each touches only on one definite aspect of the problem, and does not concern the kinematics and the dynamics of the belt as a whole. Much work remains to be done in this direction.

It must be noted that many considerable difficulties confront the development of the theory in this direction, connected in particular with the shortcomings of the existing methods of investigating of the nonconservation of the adiabatic invariants of particles, and methods of investigating the "intermediate" states of the plasma, when collective effects are valid in some cases, and in others, on the other hand, it is necessary to consider non-interacting particles. An example of such an intermediate state can be the unique region of instability on the boundary of the magnetosphere between the magnetic field of the earth and the solar stream. Of great help in the theoretical investigation and the elimination of these difficulties should be experiments with which one could study not only the energy and the distribution of the density of the individual groups of particles in radiation belts, but also establish the concommitant concrete geophysical conditions in the earth's magnetosphere, and also estimate the dynamic changes in the radiation belts. In this connection, of tremendous importance is the problem of simulation of the radiation belts under laboratory conditions [130,131].

From our point of view, this will result in appreciable progress in both experimental and theoretical study of the radiation belts as a whole, and especially in the study of such a phase of the phenomenon as the nonconservation of the adiabatic invariance and the resultant behavior of the plasma.

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