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Abstract

Full Text

Physics

K. I. Gringauz and S. M. Rytov

On the Relation between the Results of Measurements by Charged-Particle Traps on Soviet Space Rockets and Measurements of the Magnetic Field on the American Satellite “Explorer-VI” and the Rocket “Pioneer-V”

(Presented by Academician A. L. Mints, 15 X 1960)

In describing the results obtained in 1959 in the vicinity of the Earth by means of three-electrode charged-particle traps installed on Soviet space rockets (¹), it was indicated that at distances of 55,000–75,000 km from the Earth’s surface, fluxes of electrons with a density of $\sim 10^8 \text{ el} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$ and energies $\geq 200 \text{ eV}$ were detected. This made it possible to conclude that there exists an outermost belt of charged particles surrounding the Earth (^{2,3}), located beyond the radiation zones (⁴⁻⁷). It was suggested that the boundaries of this belt run along the lines of force of the geomagnetic field (^{2,3}).

In 1960, preliminary results were published of measurements of the geomagnetic field carried out on the satellite “Explorer-VI” (launched in the USA on 7 VIII 1959, with an apogee of 48,800 km, an orbital period of 12.45 min., and an orbit in a plane inclined to the geographic equator at an angle of 47°) (⁸) and on the space rocket “Pioneer-V” (launched on 11 III 1960) (^{9,10}). These measurements showed that, at distances from the Earth’s center of less than 5–6 Earth radii R_E , good agreement was observed between the measured values of the geomagnetic field and the theoretical values calculated using its values at the Earth’s surface and the model of an eccentric dipole according to (¹¹).

At greater distances from the Earth, systematic large-scale deviations from the theoretical field values were recorded, observed constantly—both on magnetically disturbed and on magnetically quiet days—although varying somewhat with time. The authors of works (⁸⁻¹⁰) concluded that the indicated disturbances of the geomagnetic field recorded on the “Explorer-VI” satellite are caused by a permanently existing system of electric currents, localized in a definite way and lying beyond the radiation zones, possibly in a toroidal region surrounding the Earth. To determine the characteristics of this current system, a hypothetical model of it was considered in the form of a current flowing through a cylinder with a circular cross section, whose center lies on the geomagnetic equator,

with a current density constant over the cross section. The total magnetic field determined by the geomagnetic field and the magnetic field of the current ring was calculated. These calculations were compared with the measured values in order to test the suitability of the chosen current-ring model and to determine the parameters of the current system that best satisfy the experimental data.

Measurements carried out on the rocket “Pioneer-V,” which passed through a different section of the region under consideration than did “Explorer-VI,” and crossed the presumed current system, showed that at distan-

at distances from the center of the Earth of $5 \div 7R_E$, as on *Explorer VI*, reduced values of the geomagnetic field were observed. At distances greater than $13R_E$, values were found that were increased in comparison with those determined by the theoretical law $1/R^3$. These results confirmed the hypothesis of the existence of a current ring causing persistent perturbations of the geomagnetic field at geocentric distances $> 5R_E$.

The results of calculations of the parameters of the current system, based on the model indicated above, are as follows:

- a) for *Explorer VI*, $R_0 = 60\,000$ km, $I = 5 \cdot 10^6$ A, $a = 3R_E$ (or less), where R_0 is the distance from the center of the Earth to the center of the circular cross section of the cylinder, I is the total current strength, and a is the radius of the cylinder;
- b) for *Pioneer V*, $R_0 = 50\,000$ km, $I = 5 \cdot 10^6$ A, $a = 3R_E$.

In ⁽¹⁰⁾ it is noted that agreement between calculations based on the indicated current model and the experimental data is not obtained for $a < 3R_E$.

A comparison of the preliminary results described above for measurements of the geomagnetic field on the satellite *Explorer VI* and the rocket *Pioneer V* with the published ⁽¹⁻³⁾ data on the outermost belt of charged particles, containing electrons with energies $200 \text{ eV} < E < \sim 10^4 \text{ eV}$, discovered with charged-particle traps on Soviet space rockets, is of unquestionable interest.

As can be seen from Fig. 3 of paper ⁽³⁾, the Soviet space rockets crossed the geomagnetic equator at an altitude of $\sim 60\,000$ km above the Earth’s surface, i.e., precisely in the region where the center of the current ring is located, the existence of which follows from the American magnetic-measurement data. As can be seen from Fig. 4 ⁽¹⁾, the center of the region in which fluxes of electrons with $E > 200 \text{ eV}$ were detected during the flight of the second space rocket on 12 IX 1959 is at an altitude of $\sim 60\,000 \div 65\,000$ km above the Earth’s surface (i.e., near the center of the cross section of the “current ring” according to the *Explorer VI* data). The maximum density of the electron fluxes lies in a region of extent $\sim 20\,000$ km (at altitudes of 55,000–75,000 km), and the extent of the entire region in which electron fluxes were detected is $\sim 40\,000$ km, which is very close to the cross-sectional diameter of the current ring, $2a \simeq 6R_E$, calculated in ⁽¹⁰⁾.

The current density (electron flux), according to the experiments with charged-particle traps, increases as one approaches the center of the region of their existence and decreases at the boundaries of the region, whereas in ⁽¹⁰⁾ it is taken to be constant over the cross section of the “current ring.” However, in ⁽¹⁰⁾ it is clearly indicated that such a model of the current ring was adopted only to simplify the calculations. The average current density in the “current ring,” determined according to ⁽¹⁰⁾, is $\sim 4 \cdot 10^{-13}$ A/cm², whereas the density of the electron flux at the maximum of the outermost belt of charged particles, according to ⁽¹⁻³⁾, is $\sim 2 \cdot 10^8$ el/cm² · s = $3.2 \cdot 10^{-11}$ A/cm².

It should be borne in mind, however, that with traps in the experiments ⁽¹⁾ it is possible to determine the density of the *total* flux of electrons with $E > 200$ eV, whereas measurements of the geomagnetic field can be produced only by a *component* of this flux perpendicular to the lines of force of the geomagnetic field. Such a component must exist owing to the well-known phenomenon of drift of charged particles in an inhomogeneous magnetic field (see, for example, ⁽¹²⁾).

In order to make estimates of the drift-current density and of the current to the trap possible, we shall regard the geomagnetic field as a dipole field and assume that the electron velocity distribution is Maxwellian. This assumption is, of course, conditional. We introduce the Maxwellian distribution only as a certain effective distribution, i.e., one giving the same current to the trap as that actually observed.

Under the stated assumptions, from the general formulas for drift in an inhomogeneous magnetic field (12) one obtains the following expression for the drift-current density in the plane of the magnetic equator:

$$j_{\text{dr}} = \frac{6c\Theta N}{BR} = \frac{6c\Theta NR^2}{B_0 R_E^3},$$

where c is the speed of light, Θ and N are the energy temperature and concentration of the electrons; R_E is the radius of the Earth; B_0 is the field at the Earth's surface; B is the field at a distance R from the dipole. Of course, positive ions also contribute to the drift current (in thermal equilibrium the expression given would have to be doubled), but, as will be seen below, taking this into account—an addition that is uncertain to a sufficient degree—does not play a role in the subsequent estimates.

Under the same assumptions, the current density to a trap cutting off electrons with normal kinetic energies, relative to the surface of the trap collector, below eV eV is

$$j_t = eN \sqrt{\frac{\Theta}{2\pi m}} e^{-x}, \quad x = \frac{eV}{\Theta},$$

where e and m are the charge and mass of the electron. Dividing j_{dr} by j_t and expressing Θ in terms of the parameter x , we obtain

$$\frac{j_{\text{dr}}}{j_t} = \frac{6cR^2}{B_0 R_E^3} \sqrt{2\pi \frac{m}{e} V} \frac{e^x}{\sqrt{x}}.$$

Taking $R = 10R_E$ ($R_E = 6.4 \cdot 10^8$ cm), $B_0 = 0.5$ gauss, $eV = 200$ eV, and substituting the values of the remaining constants, we find

$$\frac{j_{\text{dr}}}{j_t} = 1.55 \cdot 10^{-6} \frac{e^x}{\sqrt{x}}.$$

The observed ratio of the current densities (of the order 10^{-2}), if the root $x \sim 10^{-7}$, corresponding to an inordinately high temperature, is discarded, corresponds to $x \cong 9.5$, i.e. $\Theta \cong 21$ eV, or $230\,000^\circ$ abs. Let us note that for such values of x , the magnitude of x depends only very weakly (logarithmically) on the ratio of the currents, the distance from the dipole, and the cutoff potential on the trap.

Using the obtained value of Θ , one can compute the value of the electron concentration N from the formula for j_t , or (more simply) from the formula for j_{dr} . With $j_{\text{dr}} \cong 4 \cdot 10^{-13}$ A/cm² = $1.2 \cdot 10^{-3}$ CGSE, we obtain $N \cong 600$ el/cm³.

The estimates obtained show that, within the framework of the crude assumptions made (a dipole field and a Maxwellian distribution of electron velocities), it is possible to reconcile in a reasonable way the magnitude of the electron flux recorded by charged-particle traps in the outermost belt discovered on Soviet space rockets, and the magnitude of the disturbances of the geomagnetic field observed in the same region in American experiments. At the same time, if the distribution of electrons by velocities is indeed close to Maxwellian, then when the cutoff potential V is reduced a considerable increase of the current in the traps should be observed, since a trap with $V = 200$ V operates, as is clear from the value obtained, $\Theta \cong 21$ eV, on the tail of the effective Maxwellian distribution. In further study of the outermost belt of charged particles, it is therefore very important to determine what the energy spectrum of the electrons is (for example, by simultaneously using traps with different values of V).

The considerations set forth give grounds to believe that the results of measurements using three-electrode traps on Soviet space...

rockets and by means of magnetometers on the satellite *Explorer VI* and the rocket *Pioneer V* are mutually consistent. Thus, these independent investigations, carried out by different methods, apparently confirm and complement one another and indicate that the "current ring" detected in magnetic measurements is nothing other than a drift current, caused by the inhomogeneity of the geomagnetic field, in the outermost belt of charged particles, which exists constantly at altitudes of $\sim 60\,000$ km. Further direct investigations of this belt

will make it possible to refine its properties, in particular its variability in time and space, as well as the energy spectrum of the electrons that produce the effects observed in the Soviet and American experiments.

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