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Abstract

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THE EARTH'S OUTER RADIATION BELT AT AN ALTITUDE OF 320 km

As a result of investigations carried out on the second and third Soviet artificial Earth satellites, the existence was demonstrated of the Earth' s outer radiation belt, sharply limited to the region of high latitudes ([1]). The scintillation and gas-discharge counters aboard the second Soviet spacecraft made it possible to study in detail the outer radiation belt near the Earth and to establish its boundaries as a function of longitude. The orbit of the second satellite-spacecraft was almost circular and lay at altitudes of 307–339 km ([2]).

The presence on board the spacecraft of an autonomous storage device made it possible to obtain practically simultaneous, continuous information on the radiation intensity at the indicated altitudes over the entire terrestrial globe in the latitude interval $±$65° (Fig. 1). The storage device interrogated the counters every 3 min. The scintillation counter consisted of an FEU-16 photomultiplier and a NaJ (Tl) crystal in the form of a cylinder 14 × 30 mm, and had an energy threshold of the counting channel of 25 keV. A halogen counter, STS-5, was used as the Geiger–Müller counter.

Figure 1 shows the distribution of radiation intensity around the terrestrial globe, recorded by the scintillation counter. The readings of the counter were converted to 1 cm^2 on the assumption of isotropy of the radiation incident on the crystal. It follows from Fig. 1 that, as the satellite-spacecraft passed from the equator to latitudes $±40–50°, *the count rate of the scintillation counter, because of the latitude effect of cosmic r*
sec. It is natural to suppose that this sharp increase in the intensity of x-radiation is due to particles of the Earth' s radiation belts. To prove this assertion, the connection between the zones of enhanced intensity in the Northern and Southern Hemispheres was analyzed, the connection between the boundaries of the region of enhanced intensity and the characteristics of the Earth' s magnetic field was considered, and the composition was established and the energy of the recorded radiation was estimated.

In Fig. 2, the points on the terrestrial globe at which the count rate of the scintillation counter exceeded 30 counts/$cm^2 \cdot$ sec are marked by black circles. Conventionally, the following geographic zones of enhanced intensity may be distinguished: 1) Siberia, 2) North America, 3) the southern Pacific Ocean, 4) the southern Indian Ocean, and 5) the southern part of the Atlantic.

Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

To establish the connection between the zones of the Northern and Southern Hemispheres, conjugate points were found, i.e., the ends of the lines of force of the geomagnetic field, the beginnings of which coincide with the points of increased radiation. The conjugate points, calculated from data of magnetic measurements on the Earth' s surface ([3]), are shown in Fig. 2 by crosses, and some of them are connected with the initial points by dashed lines. It follows from Fig. 2 that the first zone (Siberia) is conjugate with the third (southern Indian Ocean), and the second (North America) with the fourth (southern Pacific Ocean).

On the other hand, the boundary between these zones (Alaska–Chukotka) is conjugate with a region of the Pacific Ocean (New Zealand) where the count rate of the scintillation counter does not exceed 30 counts/cm^2 · sec. Similarly, black circles are absent in the North Atlantic, conjugate with the western edge of the fourth zone. However, analysis of the experimental data showed

Fig. 1. Count rate of the scintillation counter at an altitude of 320 km at various points of the terrestrial globe (in pulses/cm^2 · sec). Dashed lines indicate the lines of maximum recurrence of aurorae. The hatched region is the area in which the increased intensity cannot be explained by the latitude effect of cosmic rays.

Fig. 2. Position of the radiation belts at an altitude of 320 km. **1** –points at which the count rate of the scintillation counter exceeds 30 pulses/cm^2 · sec; **2** –points at which the count rate is 15-30 pulses/cm^2 · sec; **3** –magnetically conjugate points; **4** –lines of maximum recurrence of aurorae; **5** –isolines; **6** –trajectory of mirror points, calculated using the adiabatic integral invariants for particles trapped in the Earth' s magnetic field.

that in the regions of the North Atlantic and New Zealand an increased radiation intensity was also observed, which could not be explained by the latitude effect of cosmic rays. In Fig. 2 the light circles indicate points over which the counting rate lay in the interval from 15 to 30 pulses/cm^2 · sec. The radiation intensity in these places is lower than in the conjugate regions because of the larger value of the magnetic-field intensity modulus, which leads to an increase in the altitude of the mirror points. (Thus, in the Alaska region $B = 0.56$ oersted, and in the conjugate region of New Zealand 0.68 oersted.)

Thus, the zones of increased radiation in the Northern Hemisphere are connected with the zones of the Southern Hemisphere by the lines of force of the geomagnetic field, and the position of the belt of increased intensity at an altitude of 320 km above the Earth is determined by this field.

Standing apart is the fifth zone of increased radiation (south of the Atlantic), associated with an anomaly of the Earth' s magnetic field. This zone, considered in a special article ([6]), will not be discussed in the present work.

The boundary of the belt of increased intensity at altitudes of 300 km on the side of high latitudes in a number of places closely adjoins the line of maximum recurrence of auroras ([3]), shown in Fig. 2 by a dotted line. On the side of low latitudes the boundary of the belt approximately coincides with the isocline $\delta = 70^\circ$ in the Northern Hemisphere and with the isocline $\delta = 66^\circ$ in the Southern Hemisphere (solid lines in Fig. 2), which corresponds to magnetic latitudes $\varphi = +54^\circ$ and $\varphi = -48^\circ$. The magnetic latitudes were determined from the relation $\operatorname{tg}\varphi = \frac{1}{2}\operatorname{tg}\delta$, where δ is the angle of magnetic inclination.

The position of the belt of increased intensity agrees well with the trajectory of mirror points calculated using the adiabatic integral invariants for particles captured in the Earth' s magnetic field ([4]). In Fig. 2 the dash-dotted line shows the trajectory of the mirror points; at longitude $+120^\circ$ the altitude of the mirror point was arbitrarily chosen to be approximately 1500 km. The altitudes of the mirror points at other longitudes are indicated in kilometers every 60° along this trajectory of mirror points.

To determine the composition and estimate the energy of the radiation recorded in the zone of increased intensity, let us compare the readings of the scintillation and Geiger counters (Table 1).

Table 1 gives a series of counter readings during flight through zones of increased intensity. From these readings the readings caused by cosmic rays at the given magnetic latitudes have been subtracted. To determine the cosmic background, use was made of the fact that in the region adja–

Table 1

Counter readings during flight through the zone of increased intensity

Scintillation counter counting rate N_{sc}, pulses/cm$^2\cdot$sec	Energy flux E, released in the crystal, 10^9 eV/cm$^2\cdot$sec	STS-5 counting rate N_g, pulses/cm$^2\cdot$sec	$N_{\text{sc}} - N_{\text{sc},\phi}$, pulses/cm$^2\cdot$sec	$E - E_\phi$, 10^7 eV/cm$^2\cdot$sec	$N_g - N_{g,\phi}$, pulses/cm$^2\cdot$sec	$\frac{E - E_\phi}{N_{\text{sc}} - N_{\text{sc},\phi}}$ keV/pulse	$\frac{N_g - N_{g,\phi}}{N_{\text{sc}} - N_{\text{sc},\phi}} = \frac{\varepsilon_g}{\varepsilon_{\text{sc}}}$
Northern Hemisphere	**Northern Hemisphere**	**Northern Hemisphere**	**Northern Hemisphere**	**Northern Hemisphere**	**Northern Hemisphere**	**Northern Hemisphere**	**Northern Hemisphere**
162	4,4	3,6	148	0,9	0,3	61	$2{,}0 \cdot 10^{-3}$
157	4,4	4,0	143	0,9	0,8	63	$5{,}6 \cdot 10^{-3}$
128	3,7	3,3	114	0,3	0,1	26	$0{,}8 \cdot 10^{-3}$
100	4,8	3,5	86	1,4	0,2	163	$2{,}3 \cdot 10^{-3}$
90	3,1	3,5	76	−0,3	0,2	−40	$2{,}6 \cdot 10^{-3}$
85	5,1	3,6	71	1,6	0,4	226	$5{,}7 \cdot 10^{-3}$
80	4,8	3,5	66	1,4	0,2	213	$3{,}0 \cdot 10^{-3}$
Southern Hemisphere	**Southern Hemisphere**	**Southern Hemisphere**	**Southern Hemisphere**	**Southern Hemisphere**	**Southern Hemisphere**	**Southern Hemisphere**	**Southern Hemisphere**
400	9,8	4,6	388	6,5	1,5	168	$3{,}8 \cdot 10^{-3}$
248	10,1	4,1	236	6,8	1,0	288	$4{,}2 \cdot 10^{-3}$
218	4,8	3,6	206	1,6	0,5	78	$2{,}4 \cdot 10^{-3}$
174	9,0	3,5	162	5,7	0,4	352	$2{,}5 \cdot 10^{-3}$
75	3,5	3,6	63	0,3	0,5	47	$8 \cdot 10^{-3}$

adjacent to the northern magnetic pole, in the longitude interval approximately from -30° to -120°, the belt of increased intensity lies at latitudes less than $+60^\circ$; and in the Southern Hemisphere, in the longitude interval from $+80^\circ$ to $+160^\circ$, this belt is likewise located at latitudes less than -60° (Fig. 1). For the Northern Hemisphere the following values were obtained for the background due to cosmic rays:

$$N_{\text{sc. b}} = (13.9 \pm 0.3)\ \text{imp/cm}^2 \cdot \text{sec}; \qquad E_{\text{b}} = (3.46 \pm 0.15) \cdot 10^7\ \text{eV/cm}^2 \cdot \text{sec};$$

$$N_{\text{g. b}} = (3.26 \pm 0.05)\ \text{imp/cm}^2 \cdot \text{sec},$$

and for the Southern Hemisphere:

$$N_{\text{sc. b}} = (12.0 \pm 0.4)\ \text{imp/cm}^2 \cdot \text{sec}; \qquad E_{\text{b}} = (3.27 \pm 0.07) \cdot 10^7\ \text{eV/cm}^2 \cdot \text{sec};$$

$$N_{\text{g. b}} = (3.08 \pm 0.05)\ \text{imp/cm}^2 \cdot \text{sec}.$$

Subtracting the background, we obtain the counter readings due to the radiation causing the increased intensity. From Table 1 it follows that the mean value of the ratio of the registration efficiencies of this radiation by the Geiger and scintillation counters is $\varepsilon_\gamma/\varepsilon_{\text{sc}} = 3 \cdot 10^{-3}$. Consequently, this radiation is γ-radiation with energy $\sim$ 100–300 keV. The mean energy of the γ-radiation, determined directly from the readings of the scintillation counter, has the same order of magnitude in both hemispheres (Table 1).

Thus, the unambiguous connection of the zones of increased intensity in the Northern and Southern hemispheres by the lines of force of the Earth's magnetic field, the coincidence of the geographic position of the zones with the trajectory of the mirror points for particles captured by the geomagnetic field, and the determination of the nature of the recorded radiation and of its energy indicate that the recorded increased intensity is due to electrons of the outer radiation belt being braked in the skin of the spacecraft-satellite.

As stated above, in individual zones a lower intensity is observed at points with a greater magnetic-field strength. However, over the entire map no clear connection is found between the intensity and the magnetic-field strength. This is apparently connected with the short lifetime of the electrons of the outer radiation belt at the altitudes under consideration, compared with the drift time around the Earth.

Assuming that at an altitude of 300 km the atmospheric density is $3.5 \cdot 10^9$ atoms/cm^3, we obtain a lifetime for electrons with energy 10^5 eV at this altitude of the order of several seconds ([5]). This time is much shorter than the drift time around the Earth of electrons with energy 10^5 eV. Therefore the electrons perish in the atmosphere after a comparatively small number of oscillations from one hemisphere to the other and do not have time to shift appreciably in longitude.

Knowing the number of oscillations, the electron flux at an altitude of 300 km (from measurements on the second spacecraft-satellite, of the order of $5 \cdot 10^4$ el/cm^2·sec) and the width of the radiation belt around the Earth at this altitude, one can determine the lower limit of the complete leakage of electrons from the outer radiation belt and, consequently, estimate the upper limit of the lifetime of electrons in the belt. The estimates carried out gave, for electron energies of 300 keV, a value of $10^6 \div 10^8$ sec, and show that, of the two hypotheses for the origin of energetic electrons in the outer radiation belt, the hypothesis of local acceleration of electrons within the geomagnetic field is more likely to be correct than the neutron hypothesis.

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Note: Figure translations are in progress. See original paper for figures.