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An Empirical Model of the Radiation Belt of Helium Nuclei

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Abstract—Based on satellite data, we present the results of modeling the spatial and energy distributions of integral fluxes of He nuclei (α particles) with $E > 1$, 2, 4, and 7 MeV at $L = 1.1$–6.6 in a broad range of B/B_0 (E is the kinetic energy of particles, L is the drift shell parameter, and B/B_0 is the magnetic field ratio). Some ways of practically applying the model are considered. The results of calculation of α-particle fluxes for a circular orbit with a height of 300 km and an inclination of 50° are presented.

INTRODUCTION

Wide introduction of new technologies into space instrumentation including microprocessor technique sensitive to an impact of radiation entails a necessity of creation of reliable and sufficiently complete models of space radiation. First of all, it concerns the models of the Earth's radiation belts (ERB) that exert the main influence on the working capacity of near-Earth spacecrafts. For ERB protons and electrons such models were developed (for example, see [1, 2]), and in spite of some known imperfections of these models they are widely used for practical purposes. However, there are no such models for ions and nuclei with $Z > 1$. At the same time, atomic nuclei with $Z > 1$ lead to the most serious failures in the operation of microprocessor engineering onboard satellites.

Some important features of the ERB of He nuclei have been predicted on the basis of the radial diffusion theory (under the action of SC) taking into account the Coulomb deceleration of ions [3]. In many papers (for example, see [4–6]) a computer simulation of the ion ERB structures was carried out taking into account the radial diffusion, Coulomb deceleration, and charge exchange of ions with the exosphere atoms. However, the uncertainty in many characteristics and parameters of the physical processes occurring in the ERB complicates strongly such a simulation for ERB ions with $Z > 1$. These models describe well experimental data only in limited ranges of E, L, and B/B_0.

The results of our modeling of He nuclei (α-particles) fluxes in the ERB based on the experimental data are presented below. The fluxes of α-particles with $E > 1$ MeV in ERB considered in this paper have been detected in experiments onboard the satellites *Injun-4* [7–8], *1966-70A* and *1968-26B* [9], *OGO-4* [10], *Injun-5* [8, 11], *OV1-19* [12], *1972-076B* [13], *Molniya-2* [14], *Prognoz-5* [15], *Explorer-45* [4, 16–18], *ATS-6* [19], *ISEE-1* [20], *CRRES* [21], *OHZORA (ETS VI)* and *Akebono* [22], *SAMPEX* [23], and some other satellites. However, reliable experimental data on the He nuclei in ERB are much more scarce than those on protons, and these data are incomplete (there are considerable "blank spots" in spatial and energy distributions of α-particles]). Therefore, the choice of correct and physically valid methods of interpolation and extrapolation of the experimental data into adjacent spatial and energy regions are of great importance at constructing empirical models on the basis of these data.

DESCRIPTION OF THE MODEL

The modeling was performed on the basis of the experimental results presented in [4, 7–10, 12–20], and also using the data of the *Kosmos* series satellites (due to some reasons these data have never been published). In the same way as it has been done for the empirical model of proton fluxes [1], the averaged values of integral omnidirectional fluxes J were tabulated for our model of He ions. The fluxes of He ions with $E > 1$, 2, 4, and 7 MeV at $L = 1.1$–2.1 (with a step $\Delta L = 0.1$), 2.3, 2.5, 2.8, 3.0, 3.3, 3.5, 4.0, 4.5, 5.0, and 6.6 are considered in broad intervals of B/B_0.

For the sake of illustration, the model values of the fluxes of α-particles with $E > 7$ MeV at $L = 2.0$ and 3.5 (and for various values of B/B_0) are shown in Table 1. The values of the anisotropy index (A) of pitch-angle distributions of α-particles at $L = 2.0$ and 3.5 calculated by the formula

$$J \propto (B/B_0)^{-A/2}\sin^A\alpha$$

for adjacent pairs of J and B/B_0 values are also presented in Table 1. The parameter A characterizes both the anisotropy of pitch-angle distributions and the steepness of the altitude behavior of particle fluxes (the dependence of J on B/B_0): the larger A the steeper the altitude behavior of particle fluxes at a given L.

Figures 1–3 show some examples of a graphic presentation of the model fluxes of He ions in the ERB.

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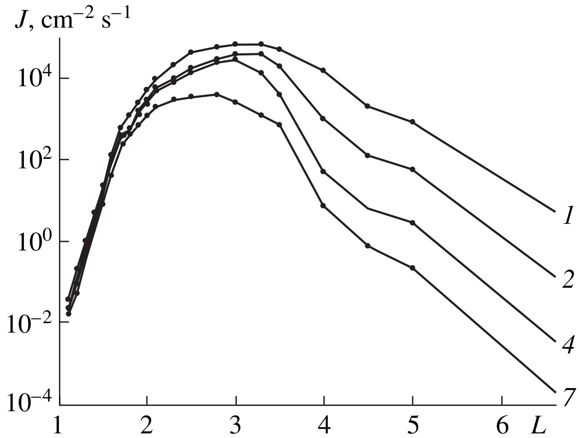

Fig. 1. Radial profile of the fluxes of He nuclei with $E > 1$, 2, 4, and 7 MeV in the geomagnetic equator plane.

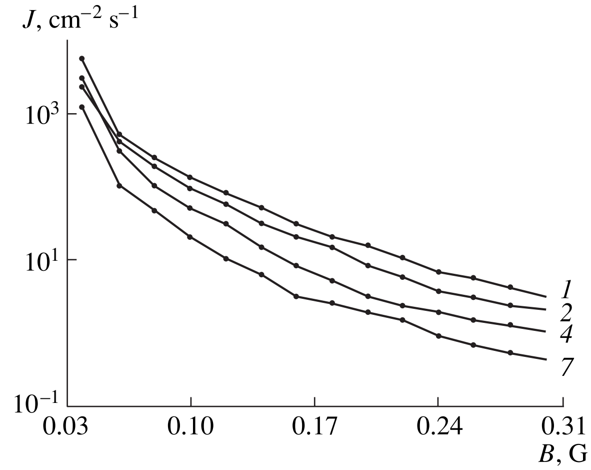

Fig. 2. Altitude behavior of the fluxes of He nuclei with $E >$ 1, 2, 4, and 7 MeV at $L = 2$.

One can find the complete table presentation of our model of spatial and energy distributions of He ion fluxes in the ERB at the website http://spacerad.nm.ru.

DISCUSSION

When constructing the model of ERB α-particles we met considerable difficulties related mainly to incompleteness of the experimental data available. Therefore, in many cases the fluxes measured in different years and at different phases of the solar cycle were averaged, various interpolations and extrapolations of the data being considered. In addition, for creation of a sufficiently complete dataset of He nuclei fluxes in the ERB, we had to combine the data obtained in quiet geomagnetic conditions and during geomagnetic storms. Since during geomagnetic disturbances the ion fluxes may be changed by 1–2 orders of magnitude (for example, see [17, 18, 21]) such a method of data averaging leads to a spreading of the model parameters (especially at large L).

Table 1

$L = 2.0$			$L = 3.5$		
B/B_0	J, cm^{-2} s^{-1}	A	B/B_0	J, cm^{-2} s^{-1}	A
1.0	1200		1.0	700	
1.54	100	11.7	1.37	130	10.8
2.06	45	5.6	2.74	10	7.4
2.57	20	5.0	4.12	5	3.3
3.08	10	7.5	5.5	2.5	4.8
3.6	6	6.8	8.23	1.6	3.4
4.11	3	7.0	11.0	1.2	2.1
4.62	2.4	9.4	13.7	0.85	3.2
5.13	1.8	5.6	16.5	0.65	3.0
5.64	1.4	5.5	19.2	0.55	2.3
6.16	0.85	10.7	21.7	0.47	2.3
6.67	0.65	6.9	24.4	0.4	2.6
7.2	0.5	6.9	27.2	0.28	7.0
7.7	0.4	5.3	29.9	0.26	1.4
			32.6	0.23	3.0
			35.3	0.18	5.8
			38.0	0.16	3.2
			40.7	0.14	2.9

However, the problem of creation of even preliminary model of ERB α-particles is very topical. Such model may be used for planning space experiments, comparing its results to new experimental data, and estimating the impact of α-particles on spacecrafts. Being open, such a model may be promptly supplemented with new experimental data and permanently improved.

Figure 4 shows an example of comparison of our model with experimental data. The results of measurements of α-particle fluxes onboard the *Injun-5* satellite [11] were considered as particular data. One can see in Fig. 4 a sufficiently good agreement between the experimental fluxes and the model values at $1.7 < L < 4.5$. It is also seen in Fig. 4 that our model needs further improvement, especially at $L > 4.5$. One should bear in mind that the α-particle fluxes may strongly vary at an increase of geomagnetic activity (for example, see [17, 18, 21]).

Quantitative relationships between the main parameters of the quasi-stationary energy spectra and spatial distributions of fluxes of the main ion constituents in the ERB were found in [24, 25]. In these papers the entire set of published experimental results obtained onboard satellites during 1961–1994 was involved into the process of cross analysis and calculations of the main structural parameters of the ERB. On the basis of the analysis of experimental data, it was shown in [24,

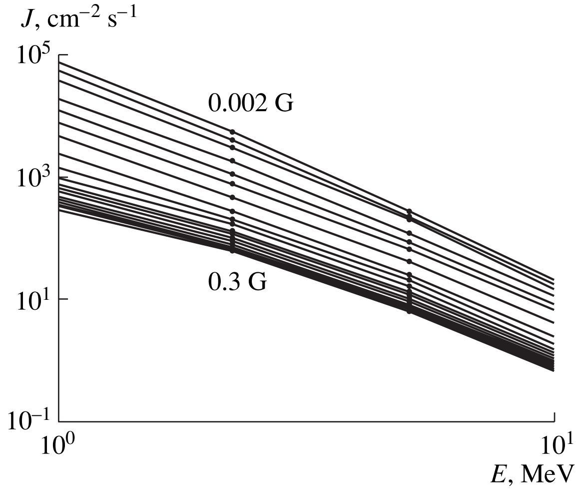

Fig. 3. Energy spectra of the fluxes of He nuclei at $L = 5$ for the values of B from 0.002 to 0.3 G with a step of 0.02 G $(B/B_0) = 1–150$).

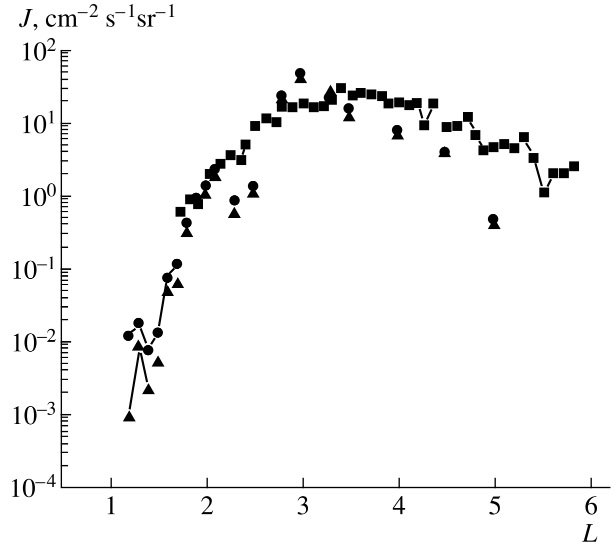

Fig. 4. Model radial profiles of the fluxes of He nuclei with $E = 1–7$ MeV for $B = 0.18$ G (circles) and 0.20 G (triangles) in comparison with the *Injun-5* data [11] (squares) obtained at $B = 0.19$ G.

25] that at $E > E_m$ the averaged differential energy spectra of He nuclei have the following form:

$$j(E) \propto \begin{cases} a\exp(-E/E_0), & \text{for} \quad E_m < E \le \gamma E_0 \\ (E/E_0)^{-\gamma}, & \text{for} \quad E \ge \gamma E_0, \end{cases} \tag{1}$$

where $a \approx 0.155$. For the most reliable data obtained onboard the satellites *Molniya-2*, *Explorer-45*, *ISEE-1*, and *AMPTE/CCE* at $B/B_0 \sim 1$ at $L > 2$ in the range from several tens of keV to tens of MeV, the following parameters of the α-particle spectra were obtained: $\gamma \approx 4.8 \pm 0.8$ and $E_0 \approx (24 \pm 12)L^{-3}$ MeV. The analytical laws relating the energy spectra to pinch-angle distributions of the ERB ions were found in [26], and it was shown that the altitude behavior of the ERB ion fluxes should become less steep at an increase of B/B_0.

The main radial, energy, and altitude regularities in the behavior of the He nuclei fluxes obtained in our model do not contradict the conclusions made in [24–26]. For example, one can see in Fig. 2 and Table 1 that (in agreement with the conclusions of [26]) the altitude behavior of α-particle fluxes becomes less steep at an increase of B/B_0. One can see in Fig. 3 that (in accordance with [24, 25] and formula (1)) He nuclei spectra have the form close to the exponential one at $E > 1$ MeV and $B/B_0 \sim 1$. For the spectra presented in Fig. 3 the index of the exponential tail of the spectra is $\tilde{\gamma} \approx 3.25$. Since these spectra are integral, for differential spectra corresponding to them $\gamma = \tilde{\gamma} + 1 = 4.25$. This value falls almost into the middle of the range obtained in [24] for the parameter γ of α-particle spectra. The value of γE_0 in formula (1) is 1 ± 0.5 MeV at $L = 5$ (at $B/B_0 = 1$), which also does not contradict our model (see Fig. 3).

PRACTICAL APPLICATION OF THE MODEL

In order to estimate the radiation conditions onboard a spacecraft, we have developed a special representation of the fields of He nuclei fluxes in the ERB. The method of generalization of L and B coordinates proposed in [27] (the method involves splitting of the space $\{L, B\}$ into elementary regions (cells)) was used. The average values of the particle flux and the total time of a spacecraft flight through it are determined for each such cell. The obtained results make it possible to estimate using simple arithmetical calculations the fluences of particles impacting a spacecraft during its flight. In addition, this method makes it possible to determine the contributions of various space regions into the total fluence of particles and to correct it upon changes in spatial and energy distributions of ERB particles.

As an example, the values of average integral fluxes (J_{av}) of He nuclei with the threshold energy $E > 1$, 2, 4, 7, and 10 MeV impacting a spacecraft with a circular orbit at a height of 300 km and inclination of 50° are presented in Table 2. In this case, the entire region of the $\{L, B\}$ space crossed by the spacecraft was split into 181 cells.

Table 2

E, MeV	>1	>2	>4	>7	>10
J_{av} (cm^{-2} s^{-1})	1.50	0.32	$2.0 \cdot 10^{-2}$	$1.79 \cdot 10^{-2}$	$1.08 \cdot 10^{-2}$

CONCLUSIONS

An empirical model of He nuclei in the ERB was developed on the basis of satellite data. This model describes the spatial and energy distributions of the integral fluxes of He nuclei with $E > 1$, 2, 4, and 7 MeV in the $L = 1.1$–6.6 range and in a wide range of B/B_0 (almost along the entire magnetic field lines). This model is presented in the form convenient for practical use.

Comparison of this model with more general results of the analysis of the experimental spatial and energy distributions of ERB ions presented in [24, 25] and also with the particular experimental data demonstrates a satisfactory mutual agreement of the results.

An example of the use of this model for estimation of the radiation conditions onboard a spacecraft with the orbit at a height of 300 km and an inclination of 50° is presented.

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