

1 **Earth's radiation belts ions: patterns of the spatial-energy structure**
2 **and its solar-cyclic variations**

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6 **Abstract** Spatial-energy distributions of the stationary fluxes of protons, helium and ions of
7 carbon-nitrogen-oxygen (CNO) group, with energy from $E \sim 100$ keV to 200 MeV, in the
8 Earth's radiation belts (ERB), at $L \sim 1-8$, are considered here using data from satellites in the
9 period 1961–2017. It has been found that the results of these measurements line up in the space
10 $\{E, L\}$ following some regular patterns. Solar-cyclic (11-year) variations in the distributions of
11 protons, helium and CNO group ions fluxes in the ERB are studied. It has been observed that in
12 the inner regions of the ERB, fluxes decrease with increasing solar activity and that the solar-
13 cyclic variations of fluxes of $Z \geq 2$ ions are much greater than for protons; moreover, it seems
14 that they increase with increasing atomic number Z . Finally, the possible physical mechanisms
15 leading to formation of this spatial-energy structure and to the solar-cyclic variations of the
16 ERB ion fluxes are discussed.

17
18 **Keywords.** Magnetospheric physics (energetic particles, trapped). Radiation belts.

19

20 1 Introduction

21 The ERB consist mainly of charged particles with energy from $E \sim 100$ keV to several hundreds of
22 megaelectronvolt (MeV). These particles are trapped by the geomagnetic field at altitudes from \sim
23 200 kilometers to ~ 50 –70 thousands kilometers. The ERB consist mainly of electrons and
24 protons, but there are also helium nuclei and other $Z > 2$ ions (like oxygen etc), where Z is the
25 charge of the atomic nucleus with respect to the charge of the proton. During geomagnetic
26 disturbances, ion fluxes, and their distributions are changed. These fluxes depend also on the phase
27 of the solar cycle, conditions in the interplanetary space, and other factors.

28 Particles with different energy E and pitch angles α (α is the angle between \mathbf{a} the local vector of
29 the magnetic field and the vector of a particle velocity), which are injected into some point of the
30 geomagnetic trap, drift conserving the adiabatic invariants (μ, K, Φ) and populate a narrow layer
31 surrounding the Earth (Alfvén and Fälthammar, 1963; Northrop, 1963). This layer is called the
32 drift shell. Therefore, experimental data on the ERB are often represented in coordinates $\{L, B\}$,
33 where L is the drift shell parameter and B is the local induction of the magnetic field (McIlwain,
34 1961). For the dipole magnetic field, L is a distance, in the equatorial plane, from the given
35 magnetic field line to the center of the dipole itself (in Earth's radii R_E).

36 The stationary fluxes J of the ERB particles with given energy and pitch angle α decrease
37 usually when the point of observation is shifted from the equatorial plane to higher latitudes along
38 a certain magnetic field line (if we exclude the peripheral regions of the geomagnetic trap, where
39 the drift shells of the captured particles are split and branched). This dependence is described by
40 the functions $J(B/B_0)$, were B and B_0 are values of the magnetic field at the point of observation
41 and in the equatorial plane on the same magnetic field line, respectively.

42 Outer and inner regions of the ERB are maintained in dynamic equilibrium with the
43 environment by different mechanisms (see review Kovtyukh, 2018).

44 The outer belt ($L > 3.5$) is formed mainly by the mechanisms of radial diffusion of ions towards
45 the Earth under the action of fluctuations of both electric and magnetic fields resonating with their
46 drift periods. This transport is accompanied by the betatron acceleration and by the ionization
47 losses of the ions as a result of their interactions with the plasmasphere and with residual
48 atmosphere.

49 The inner belt ($L < 2.5$) of protons with $E > 10$ MeV is formed ~~by~~ mainly as a result of decay of
50 neutrons knocked from the nuclei of the atmospheric atoms by the Galactic Cosmic Rays. For
51 protons with $E < 10$ MeV this, mechanism (CRAND) is supplemented by the radial diffusion of
52 particles from the outer to the inner belt. The inner belt of ions with $Z > 4$ is formed mainly from
53 the ions of the Anomalous component of Cosmic Rays.

54 In the intermediate region ($2.5 < L < 3.5$) , the mechanism ~~is operated also the mechanism~~ of a
55 ion capture from Solar Cosmic Rays takes place during strong magnetic storms (see, e.g.,
56 Selesnick et al., 2014).

57 Thus, the main mechanisms of formation of the ERB, together with the sources of injection and
58 losses of ions, are known. However, for a comprehensive verification of the physical models and to
59 identify the mathematical models and their parameters, the formulation of complete and reliable
60 empirical ~~models~~ **representations** of the ERB for each of the ion components, is necessary; it is
61 also necessary for ensuring the safety of space flights.

62 These models can be created only using experimental data, obtained over many years and
63 decades; such models (see, e.g., Ginet et al., 2013) were already created for protons (AP8/AP9)
64 and they are widely used in space research. On the contrary, measurements of $Z \geq 2$ ion fluxes
65 suffer from technical problems due to small statistics and high background of protons and
66 electrons. For this reasons, empirical and semi-empirical models for $Z \geq 2$ ions, are applicable
67 only to very limited regions of the space $\{E, L\}$.

68 One of the main problems of this work is to consider the possibility to create a sufficiently
69 complete and reliable empirical models of the ERB for these ions based on currently available
70 experimental data.

71 In the following sections, the spatial-energy structure of the ERB in the $\{E, L\}$ space for
72 protons, helium and CNO group ions are considered (Sect. 2) together with possible physical
73 mechanisms of formation of these structures and their solar-cyclic variations (Sect. 3). Finally, the
74 main conclusions of this work are given (Sect. 4).

75 2 Spatial-energy distributions of the ion fluxes near the equatorial plane

76 There can be ions trapped in drift shells only with energies less than some maximum values,
77 determined by the Alfvén's criterion: $\rho_i(L, E, M_i, Q_i) \ll R_c(L)$, where ρ_i is the gyroradius of ions,
78 and R_c is the radius of curvature of the magnetic field near the equatorial plane (M_i and Q_i are mass
79 and charge of ions with respect to the corresponding values for protons). According to this
80 criterion and to the theory of stochastic motion of particles, the geomagnetic trap can capture and
81 durably hold only ions with E (MeV) $< 2000 \times (Q_i^2/M_i) L^{-4}$ (Ilyin et al., 1984). The green line in
82 Figs 1-6 represents this very boundary.

83 When comparing the data of various experiments in the ERB, the question arises about the
84 compatibility of these results with each other and the reasons for their discrepancies. A significant
85 number of these discrepancies can be connected to the differences in their trajectories; in the
86 construction of the instruments and their angular characteristics; in the energy ranges and sets of
87 energy channels. For the stationary ERB, these discrepancies can also be associated with
88 differences in the general state of the Sun, heliosphere and magnetosphere of the Earth during
89 various periods of data-taking. These factors influence the fluxes of ions with $Z \geq 2$ in the ERB
90 more significantly with respect to proton fluxes (see, e.g., Kovtyukh, 2018).

91 In this section, experimental data of various satellites, which were obtained for quiet periods
92 ($K_p < 2$) and near the equatorial plane of the ERB for ions with equatorial pitch angles $\alpha_0 \approx 90^\circ$
93 have been used. In the regions of E and L shells, where these data were obtained, the ion fluxes are
94 not distorted by the background of other particles.

95 In many important experiments, the instruments were not able to separate fluxes of ions by their
96 charge. Moreover, for the ions of the CNO group, the separation by mass are not usually
97 performed. For heavier species, for example for Fe ions, we have very small data-sets. Therefore,
98 this work presents data on helium ions (without any charge separating) and CNO ions (without any
99 mass or charge separation).

100 To solve the aforementioned problems, it is important to choose the form of representation
101 (space of variables), in which the results of every experiment can be compared to the others. In our
102 case, the space $\{E, L\}$ has been used; this choice is very efficient to better organize fragmentary
103 experimental data obtained in different ranges of E and L .

104 Figures 1-6 show the spatial-energy distributions of the fluxes of protons, helium ions, and ions
105 of the CNO group near the equatorial plane. Odd figures refer to periods near the minima, and
106 even figures refer to periods near the solar activity maxima. The values E and L in these figures are
107 presented in logarithmic scales. Statistical and methodical errors of the experimentalal points on
108 these figures do not exceed of the size of these points. The markers are connected by lines of equal
109 intensity of ion fluxes (iso-lines); the decimal logarithms of the fluxes J , in unit of $(\text{cm}^2 \text{ s ster}$
110 $\text{MeV/n})^{-1}$, are shown near each iso-lines.

111 Such representations of the experimental data are not only visual, but also very convenient and
112 rather universal. Obviously, Figs. 1-6 actually show both radial profiles of the fluxes of ions for a
113 given energy and ion energy spectra for a given L shell.

114 The points in Figs. 1-6 have been obtained from the radial profiles of fluxes $J(L)$ for the
115 average energies of the ions in the channels of the instruments. Unlike electron fluxes or ion fluxes

116 measured during geo-active conditions, the ion fluxes considered here (i.e. during quiet periods),
117 **for ions usually** have only one maximum in the functions $J(L)$. As a result, for each experiment, 1
118 or 2 points were obtained (on the outer and inner edges of these profiles) with certain values of E
119 and L for a given level of ion fluxes. Sometimes, especially for fluxes, only one point was
120 obtained: in these cases, the radial profile of the ion fluxes was cutoff at small values of L due to a
121 significant background of contaminating particles and no interpolation/extrapolation has been
122 performed whatsoever.

123 Each iso-line, shown in these figures, has been evaluated separately from the corresponding set
124 of experimental points (icons); then it was transferred (along with the icons) to the corresponding
125 figure; thus, in more abundantly populated sectors of the plots (i.e. for protons with $E > 1$ MeV at
126 $L > 2$) such iso-lines are mixing in Figs. 1–2. In case of a large distance between neighboring
127 points, the corresponding segments of the iso-lines are shown as dashed arcs.

128 The radial profiles of the differential fluxes $J(L)$ of particles with different energy tend to
129 intersect with each other in those regions where the energy spectra present some local maximum or
130 minimum. On the contrary, the iso-lines cannot intersect with each other: because this would mean
131 that, at the same point in the space $\{E, L\}$, the ion fluxes differ very significantly (by an order of
132 magnitude). Such uncertainty does not have a physical sense and a special analysis is needed to
133 identify other possible sources of errors.

134 Representing plots in a different space of variables would lead only to more significant
135 methodological errors and uncertainties, because of the natural differences in the instrumentation
136 of the experiments taken into account; thus, a series of approximations or
137 interpolation/extrapolation techniques would become inevitable.

138 **2.1 Spatial-energy structure of the proton fluxes**

139 There is a large number of experimental data concerning ERB protons; the most important of them
140 are presented in Figs. 1 and 2. These figures serve as a comparison with similar distributions of $Z \geq$
141 2 ions (Figs. 3–6).

142 Figure 1 sums up results from the satellites Relay-1 (Freden et al., 1965); Ohzora or EXIS C:
143 Exospheric Satellite C, Akebono or EXOS-D: Exospheric Satellite D and ETS-VI: Engineering Test
144 Satellite (Goka et al., 1999). These results have been collected during minimum periods of various
145 solar cycles, i.e. between 19th / 20th (1963), 21th / 22th (1984–1985), and 22th / 23th (1994–1996) of
146 the solar activity cycles.

147 Figure 2 sums up results from the satellites 1968-81A (Stevens et al., 1970), Injun-5 or
148 Explorer-40 (Krimigis, 1970; Venkatesan and Krimigis, 1971; Pizzella and Randall, 1971), 1969-
149 025C or OV1-19: Orbiting Vehicle 1-19 (Croley et al., 1976), Azur or GRS A: German Research
150 Satellite A (Hovestadt et al., 1972; Westphalen and Spjeldvik, 1982), Molniya-1 (Panasyuk and
151 Sosnovets, 1973), GEOS-2: Geodetic Earth Orbiting Satellite 2 (Wilken et al., 1986), CRRES: The
152 Combined Release and Radiation Effects Satellite (Albert et al., 1998; Vacaresse et al., 1999), GEO-
153 3: Geostationary Orbit 3 (Selesnick et al., 2010) and Van Allen Probes (Selesnick et al., 2014,
154 2018). These results were obtained during maximum periods of 20th (1968–1971), 22th (1990–
155 1991), 23th (2000), and 24th (2012–2017) solar cycles.

156 The data of the satellites Explorer-45 (Fritz and Spjeldvik, 1979, 1981) and ISEE-1:
157 International Sun-Earth Explorer 1 or Explorer-56 (Williams, 1981; Williams and Frank, 1984) are
158 given in both Figs. 1 and 2 because solar-cyclic variations of the ERB proton fluxes are negligible
159 at $L > 2.5$ (see, e.g., Vacaresse et al., 1999).

160 From a comparison of Figs. 1 and 2, one can see that at $L < 2.5$ (especially at $L < 1.4$) the proton
161 fluxes during solar minima (Fig. 1) are higher than during maxima (Fig. 2). In addition, in the
162 former the inner edge of the proton belt is less steep and it can reach smaller L shells (for $E > 1$
163 MeV). The distributions of protons in the space $\{\mu, L\}$ (see, e.g., Kovtyukh,(2016a,b) , which have
164 been constructed from Figs. 1 and 2 confirm these conclusions.

165 In Figs. 1 and 2, the iso-lines of proton fluxes are almost parallel to each other on $L > 3$ at
166 sufficiently high energies. Since these iso-lines have separated from each other by approximately
167 equal intervals on a logarithmic scale of the energy, this region in the space $\{E, L\}$ corresponds to
168 power-law spectra of the ERB protons: for power-law spectra, $J \propto E^{-\gamma}$, where the index $\gamma = -$
169 $\Delta(\log J)/\Delta(\log E)$. In these figures, this region is located between the green and red lines.

170 The red line corresponds to the lower boundary (E_b) of the power-law tail of the proton spectra.
171 For this line, $E_b \sim 36 \times L^{-3}$ MeV. Some changes in the slope of these iso-lines at $L > 6$ can be
172 connected to a discrepancy between the real configuration of the magnetic field lines and the
173 dipolar configuration (used here for L shells calculation).

174 For the dipole magnetic field region, the points on the red line correspond to particles with a
175 specific value of the 1st adiabatic invariant of motion (μ_b). For Figs. 1 and 2, the average value μ_b
176 is ~ 1.16 keV nT⁻¹. Segments of an iso-lines, that are parallel to the red line, also correspond to
177 certain values of the invariant μ . In this region of the space $\{E, L\}$ the ionization and other losses
178 of the ERB protons during radial drift can be neglected, and changes of fluxes with changing L are
179 practically reduced to adiabatic transformations in a magnetic field.

180 It results from these figures that at $L = 3\text{--}6$, the value $\gamma = 4.8 \pm 0.5$. At $L > 6$ the distances
181 between these iso-lines increase with L , and the value γ is decreased from $\sim 4.7\text{--}5.0$ at $L = 6$ to \sim
182 $4.1\text{--}4.5$ at $L = 8$. This is due to the deviation of the magnetic field from the dipole configuration as
183 well as to the increasing variability of this field with increasing L .

184 According to the data of satellites considered in (Kovtyukh, 2001), invariant parameters μ_b and γ
185 were found only at $L > 3$. In this work, a wider range of L and E is considered, and for protons with
186 $E > 10$ MeV these parameters can be traced to $L \sim 2$. At $L = 2$, $\gamma = 4.4 \pm 0.6$ (Fig. 1) and $\gamma = 4.7 \pm 1.3$
187 (Fig. 2). This is due to the fact that the energy range is significantly extended toward higher values
188 (up to 200 MeV), but here the ionization losses for protons rapidly decrease (see, e.g., Schulz and
189 Lanzerotti, 1974; Kovtyukh, 2016a).

190 2.2 Spatial-energy structure of the helium ion fluxes

191 In Figs. 3 and 4 helium ion fluxes, averaged for quiet periods ($K_p < 2$), are presented.

192 Figure 3 sums up results from the satellites Molnija-2 (Panasyuk et al., 1977), Prognoz-5
193 (Lutsenko and Nikolaeva, 1978), ISEE-1: The International Sun-Earth Explorer 1 (Hovestadt et al.,
194 1981); Akebono or EXOS-D: Exospheric Satellite D and ETS-VI: Engineering Test Satellite (Goka et
195 al., 1999). These results have been collected during minimum periods of various solar cycles, i.e.
196 between 20th / 21th (1975–1977), 21th / 22th (1984–1985), and 22th / 23th (1994–1996) of the solar
197 activity cycles.

198 Figure 4 sums up results from the satellites OV1-19: Orbiting Vehicle 1-19 (Blake et al., 1973;
199 Fennell and Blake, 1976), Explorer-45 (Fritz and Spjeldvik, 1978, 1979; Spjeldvik and Fritz,
200 1981), SCATHA: Spacecraft Charging At High Altitudes (Blake and Fennell, 1981; Chenette et al.,
201 1984). These results were obtained during maximum periods of 20th (1968–1971) and 21th (1979)
202 solar cycles.

203 From a comparison of Figs. 1–2 with Figs. 3–4, one can see that at $L > 2$ for helium ions the
204 solar-cyclic (11-year) variations are greater than for protons. For example, at $L \sim 2\text{--}3$ from
205 maximum to minimum of solar activity fluxes of protons with $E > 1$ MeV practically do not
206 change, and the fluxes of helium ions with $E > 1$ MeV/n are increased by one order of magnitude.

207 Figures 3 and 4 show the same patterns as for protons, but the distribution of helium ion fluxes
208 is slightly shifted towards higher values of L shell (with respect to protons). Unlike protons, there
209 are significant “white spots” in these figures: because there are no experimental data for helium
210 ions in these regions.

211 The red line on these figures corresponds to the lower boundary of the power-law tail of the
212 helium ions spectra. For this line, $E_b/M_i \sim 43.4 \times L^{-3}$ MeV/n (Fig. 3) and $E_b/M_i \sim 21.7 \times L^{-3}$ MeV/n

(Fig. 4). If one takes into account that at $L < 6$ for helium ions with $E > 0.2$ MeV/n the average charge $Q_i = +2$ (see, e.g, Spjeldvik, 1979), then for the considered boundary we get: $\mu_b \sim 1.4 \times Q_i$ keV/n×nT⁻¹ at the maximum of solar activity and $\mu_b \sim 1.4 \times M_i$ keV/n×nT⁻¹ at the minimum of solar activity (for the dipole magnetic field region). The iso-lines of helium ion fluxes in Figs. 3 and 4, which pass above the red line at $L > 2.5$, correspond to an average value of $\gamma \sim 5.5$.

For helium spectra, as for protons ones, the values of the parameters of the power-law tail are in good agreement with what has been found in (Kovtyukh, 2001).

At the same time, one can see that the iso-lines of the fluxes of helium ions in the region above the red line (i.e. in the region of power-law spectra) substantially deviate from the slope of the red line. At $L > 3$ the fluxes of helium ions with given energy are increase with decreasing L slower than expected from adiabatic transformation (see Kovtyukh, 2001). This means that the ionization losses of the ERB helium ions significantly exceed these losses for protons, in agreement to well-known calculations (see, e.g., Schulz and Lanzerotti, 1974).

2.3 Spatial-energy structure of the CNO group ions fluxes

In Figs. 5 and 6 CNO group ions fluxes, averaged for quiet periods ($K_p < 2$), are presented.

Figure 5 sums up results from the satellites ATS-6: Applications Technology Satellite 6 (Spjeldvik and Fritz, 1978; Fritz and Spjeldvik, 1981) and ISEE-1: The International Sun-Earth Explorer 1 (Hovestadt et al., 1978). These results have been collected during minimum period between 20th / 21th of the solar activity cycles (1974–1975, 1977).

Figure 6 sums up results from the satellite Explorer-45 (Spjeldvik and Fritz, 1978; Fritz and Spjeldvik, 1981). These results were obtained during maximum period of activity in 20th solar cycle (1971–1972).

On Figs. 5–6 the spatial-energy patterns of the ion fluxes of the CNO group are even more shifted towards higher values of L shell and its configuration differ significantly from Figs. 1–4.

From a comparison of Figs. 1–2 with Figs. 5–6 one can see that, for ions of CNO group, the solar-cyclic (11-year) variations are greater than for protons. For example, at $L \sim 3–5$ from maximum to minimum of solar activity fluxes of protons with $E > 1$ MeV practically do not changed, but the fluxes of the CNO group increase by one order of magnitude or more. From a comparison of Figs. 3–4 with Figs. 5–6 it is seen also that the fluxes of CNO group change several times more than the fluxes of helium ions do.

This means that, for ions of the CNO group, the ionization losses at $L = 3–5$ are much larger than for ions with $Z \leq 2$ and these losses have a significant effect even on the power-law segment of the spectra of the CNO ions (in the part which is seen on Figs. 5–6). Therefore, the lower boundary of the power-law tail of these ions spectra have not been obtained by the experiments collected in Figs. 5 and 6. The red line on these figures corresponds to adiabatic laws (see Kovtyukh, 2001); this line let us estimate the deviations from these laws. As can be seen from Fig. 5–6, ionization losses for ions of the CNO group are especially large at the peak of solar activity (Fig. 6): during these times, the slope of iso-lines on $L > 3$ is significantly less than the slope of the red line.

At the same time, at $L > 4$ in Fig. 5 and at $L > 3$ in Fig. 6, the iso-lines of fluxes pass almost parallel to each other and at approximately equal distances from each other; the average value of γ corresponding to them is ~ 6 . Thus, for sufficiently large values of E and L , the CNO group ions spectra in the ERB have a power-law form, but these spectra are softer in comparison with the spectra of protons.

The red line corresponds here to the dependences $E_b/M_i \approx 43.4 \times L^{-3}$ MeV/n (on Fig. 5) and $E_b/M_i \sim 12.4 \times L^{-3}$ MeV/n (on Fig. 6), which are taken from (Kovtyukh, 2001) where this boundary was more clearly defined also for the ions of the CNO group. If one takes into account that at $L \sim 3–5$ for the CNO group ions with $E > 0.1$ MeV/n the average charge $Q_i = +4$ (see, e.g., Spjeldvik and

261 Fritz, 1978), then for this boundary one can get: $\mu_b \sim 1.4 \times Q_i \text{ keV/n} \times \text{nT}^{-1}$ at the maximum of solar
 262 activity and $\mu_b \sim 1.4 \times M_i \text{ keV/n} \times \text{nT}^{-1}$ at the minimum of solar activity (for the dipole magnetic field
 263 region).

264 3 Discussion

265 Let us consider the conclusions following the results obtained here for solar-cyclic variations in the
 266 fluxes of ERB ions. Solar-cyclic (11-year) variations of proton fluxes with $E > 1 \text{ MeV}$ in the inner
 267 region of the ERB have been studied in many works (see, e.g., Pizzella et al., 1962; Hess, 1962;
 268 Blanchard and Hess, 1964; Filz, 1967; Nakano and Heckman, 1968; Vernov, 1969; Dragt, 1971;
 269 Huston et al., 1996; Vacaresse et al., 1999; Kuznetsov et al., 2010; Qin et al., 2014). These
 270 variations reach one order of magnitude at $L = 1.14$ and are reduced rapidly with increasing L (see,
 271 e.g., Vacaresse et al., 1999).

272 In these works, such variations of the proton fluxes of the inner belt are connected to the solar-
 273 cyclic variations of the energy loss rates of protons in this region. However, solar-cyclic variations
 274 of fluxes of ions with $Z \geq 2$ have not been considered in these works.

275 In quiet periods, only the mechanism of ionization loss is significant for the ERB protons
 276 trapped in small L shells (see, e.g., Schulz and Lanzerotti, 1974). Energy loss rates and lifetimes of
 277 the ERB protons are determined, in this mechanism, by the density of atmospheric atoms and
 278 ionospheric plasma (N) in a geomagnetic trap. This density depends on the intensity of the
 279 ultraviolet radiation of the Sun.

280 With decreasing solar activity (with a transition from maximum to minimum of the solar cycle),
 281 the densities of atmospheric atoms and ionospheric plasma in a geomagnetic trap are decreased. If
 282 the proton supply rates to the inner belt, under the action of the CRAND mechanism, remain
 283 unchanged or the effect of these changes is weaker than the effect connected with changes of loss
 284 rates of the protons, the stationary proton fluxes will increase with decreasing solar activity.

285 The lifetimes of protons increase with L ; this leads to a decrease in the amplitude of the solar-
 286 cyclic variations of proton fluxes. A proton lifetime on a given L shell depends on its energy and is
 287 less than 11 years at $L < L^*(E)$. For example, for protons with $E \sim 10 \text{ MeV}$ the value L^* is ~ 2.5
 288 (see, e.g., Kovtyukh, 2016a). Figs. 1 and 2 show that for protons the solar-cyclic variations of
 289 fluxes are small and localized at $L < 2.5$ (mainly at $L < 1.4$).

290 In contrast to protons, Figs. 3–6 show significant solar-cyclic variations of fluxes of helium ions
 291 and CNO group ions at $L \sim 2–5$. These variations can be explained by the same mechanism—that
 292 has been suggested for protons at $L < 2.5$.

293 For ions with $Z \geq 2$ in the ERB, ionization losses are more significant than for protons and this
 294 can be connected to the absence of ions with $Z \geq 2$ at $L < 2$ (or very low values of these fluxes)
 295 during quiet geomagnetic conditions. Such short lifetimes are manifested also in the slope of the
 296 experimental curves in Fig. 4 and 6 (this was noted in sections 2.2 and 2.3, respectively).
 297 Consequently, for ions with $Z \geq 2$, the regions in which variations can manifest, should be
 298 located on higher L shells (at the same energies as for protons).

299 The lifetimes of ions in the energy ranges considered here are $\tau \propto M_i^{-1/2} Q_i^{-2} N^{-1} E^{3/2}$ (Schulz and
 300 Lanzerotti, 1974). In a first approximation, for $N \propto L^{-4}$, we obtain the value $L_i^* \sim (M_i^{1/2} Q_i^2)^{1/4} L^*$,
 301 where L^* corresponds to the L shell of protons of the same energy of the other ions under study. For
 302 helium ions ($M_i = 4$, $Q_i = 2$) with $E \sim 10 \text{ MeV}$, we obtain $L_i^* \sim 4.2$. For ions of CNO group ($M_i = 14$,
 303 $Q_i = 4$) with $E \sim 10 \text{ MeV}$ we obtain $L_i^* \sim 6.9$. These are very rough estimations, but they are in
 304 agreement with the results presented in Figs. 3–6.

305 These estimates are based on the following assumption: during variations in solar activity, the rates
 306 of ion supply on $L < L_i^*$ remains unchanged (or these changes are weaker than the effect of changes of
 307 the rate of ion losses). This assumption is real for protons with $E > 10–20 \text{ MeV}$ at $L < 2.2$; in fact,

308 these protons form mainly under the action of the CRAND mechanism. However, at $L > 2.2$ the
309 stationary ion fluxes of the ERB form mainly under the action of radial diffusion (see, e.g., Schulz and
310 Lanzerotti, 1974; Kovtyukh, 2016b, 2018). Therefore, the solar-cyclic variations of $Z \geq 2$ ion fluxes
311 can be motivated only under the assumption that the effect related with an increase in the ionization
312 losses of such ions significantly exceeds the effect connected with the possible enhance of radial
313 diffusion of ions during the rising phase of solar activity.

314 In the experimental results presented here for the ERB ions, the region of the power-law tail of
315 the ion spectra is distinguished. For many experiments, especially for heavy ions, the values of the
316 parameter of a power-law tail spectra are determined much more accurately by the dependences
317 $J(L)$ of the ion fluxes (in logarithmic scale) for different pairs of energy channels (see Kovtyukh,
318 2001). For example, the range of L , in which these dependences for two energy channels are
319 parallel to each other is connected to the power-law tail of the spectra. Instead, on smaller values
320 of L , these fluxes begin to converge and the radial dependences of these fluxes intersect with each
321 other, which is related to the maximum in the spectra.

322 The main source of ions in the outer regions of the ERB is the solar wind, and usually the high-
323 energy part of these spectra have an exponential shape (see, e.g., Ipavich et al., 1981a, 1981b).
324 Immediately before being captured into the magnetosphere, these ions pass through a highly
325 turbulized regions, but the high-energy part of their spectra usually retains an exponential shape.
326 Therefore, the question arises: what physical mechanism converts the form of ion spectra from
327 exponential to power-law?

328 Evidently, the power-law tail of the ERB ions spectra must be generated in the outer regions of
329 the magnetosphere. The most likely region for this to happen is the plasma sheet (PS) of the
330 magnetospheric tail, which is adjacent to the geomagnetic trap. The high-energy part of the ion
331 spectra in the PS, at $R \sim 20-40 R_E$, has a power-law shape and the exponents of these spectra are
332 close to the corresponding parameters of the spectra of ions in the ERB. On the data of the
333 satellites IMP-7 and IMP-8 (Sarris et al., 1981; Lui et al., 1981) and also satellite ISEE-1 (Christon
334 et al., 1991), the shape of the ion spectra of the PS usually do not change during substorms; they
335 produce only parallel shifts of the spectra along logarithmic axes E and J . These results point out
336 that the time scales of formation processes of these ion spectra in the PS exceed the times of
337 substorms.

338 Parameters of the power-law tail of the ion spectra of the outer belt (γ and μ_b) reflect,
339 apparently, the most fundamental features of the mechanisms of acceleration of ions in the tail of
340 the magnetosphere. One can try to connect the values of these parameters with the most general
341 representations of the mechanisms of ion acceleration in the PS of the magnetospheric tail.

342 Most likely, this part of the ion energy spectra is formed in the PS by stochastic mechanisms of
343 ion acceleration; this hypothesis is supported by many experimental results. The statistical aspect
344 of these mechanisms reveals itself, in particular, in the fact that the ratios of fluxes (and partial
345 densities) of ions with different Z can differ, even greatly, at low and high energies. During their
346 wander in the phase space, ions gradually loose information about their origin and, therefore, the
347 high-energy tails of their spectra contain ambiguous information on the partial densities of
348 different components of ions in the source (see, e.g., Kovtyukh, 2001).

349 The high-energy part of the ion spectra of the PS can be generated by the mechanisms of
350 acceleration of particles on magnetic irregularities moving with respect to each other (Fermi
351 mechanism). The fractal structures of the PS are revealed on scales from ~ 0.4 to ~ 8 thousands
352 kilometers, for example, in the data of the satellite Geotail (Milovanov et al., 1996). If the mass of
353 the ions are small compared to the mass of the magnetic irregularities in the PS, the average values
354 of the index γ of the power-law tail should not depend on mass and charge of such nuclei.

355 Under equilibrium conditions, this parameter is determined by the average part of energetic ions
356 in the total energy density of particles and magnetic irregularities ($\bar{\beta}$). From the theory which was
357 developed by Ginzburg and Syrovatskii (1964), it follows: $\gamma - 1 \approx (1 - \bar{\beta})^{-1}$. With increasing $\bar{\beta}$ in

358 the interval $0 < \bar{\beta} < 1$, the value γ increases monotonically and $\gamma \rightarrow \infty$ for $\bar{\beta} \rightarrow 1$. For real
359 average values $\bar{\beta}$ in the central PS, we get $\gamma \sim 3.5\text{--}7.0$ ($\gamma \sim 4.3$ at $\bar{\beta} \sim 0.7$).

360 Spectra with power-law tail and quasi-exponential segment at lower energies can be generated
361 when the value $\Delta B / \bar{B}$ for magnetic irregularities is proportional to their size δr and their spectral
362 density decreases rapidly with increasing δr for $\delta r < r_s$, but for $\delta r > r_s$ it remains almost
363 unchanged. Apparently, the spectra of magnetic irregularities in PS with thickness r_s have just such
364 form. Then, the lower boundary μ_b of the power-law tail corresponds to the condition $r_s/\rho_i \sim 10$ (ρ_i
365 is the gyroradius of ions), i.e. $\mu_b \sim 0.02(Q_i^2/M_i)B_s r_s^2$ keV nT⁻¹, where B_s is the average magnetic
366 field induction in the PS (in nT) and r_s is normalized to the Earth's radius. Using $B_s \sim 30$ nT and r_s
367 $\sim 1.3 R_E$ it can be obtained: $\mu_b \sim 1.0 (Q_i^2/M_i)$ keV nT⁻¹.

368 The energy spectra of ions in the radiation belts of such planets as Jupiter and Saturn have the
369 form analogous to that of ion spectra in the ERB (see, e.g., Krimigis et al., 1981; Cheng et al.,
370 1985). As that in the ERB, these spectra have a long power-law tail, which is formed, apparently,
371 by mechanisms of stochastic acceleration of ions as a result of their interactions with the current
372 layer of the magnetospheric tail.

373 5 Conclusions

374 In this work, the experimental results for the stationary fluxes of the main ion components of the
375 ERB (protons, helium ions and ions of the CNO group) in the near equatorially plane, have been
376 analyzed. It is has been found that in the outer belt these fluxes line up in the certain regular
377 patterns in the space $\{E, L\}$. The degree of such similarity increases with increasing E and L and it
378 is linked to the nature of the main sources and on the universality mechanisms of transfer,
379 acceleration and losses of ERB ions in the outer belt (radial diffusion which conserves μ and K of
380 ions, betatron acceleration and ionization losses).

381 Moreover, solar-cyclic (11-year) variations of the spatial-energy distributions of the ERB ion
382 fluxes have been investigated. It has been noted that the ERB ions fluxes are weaker with
383 increasing solar activity and this effect increases with increasing atomic number Z . This kind of
384 dependence of the amplitude of flux changes on Z is typical, also, for faster variations in the fluxes
385 of the ERB ions, during geomagnetic storms and other disturbances of the Earth's magnetosphere,
386 as has been underlined in the review Kovtyukh (2018).

387 The figures presented here make it possible to determine in which regions of the space $\{E, L\}$
388 near the equatorial plane the ionization losses of ions during their radial diffusion can be neglected
389 and where this cannot. These results indicate also that with variations in the level of solar activity
390 the coefficient D_{LL} of the radial diffusion of the ERB ions change much less than the ionization
391 losses rates of ions with $Z \geq 2$.

392 In addition, the figures given here reveal the localization of "white spots", especially extensive for
393 ions with $Z \geq 2$ and $E > 1$ MeV/n at $L < 3$. As Z and energy become larger and L becomes smaller,
394 the uncertainties in the values of the ERB fluxes become larger. These gaps must be filled by the
395 results of future experiments on satellites; for now, the extensive gaps in $Z \geq 2$ ion data do not allow
396 to create sufficiently complete and reliable empirical models of the ERB for these ions.

397

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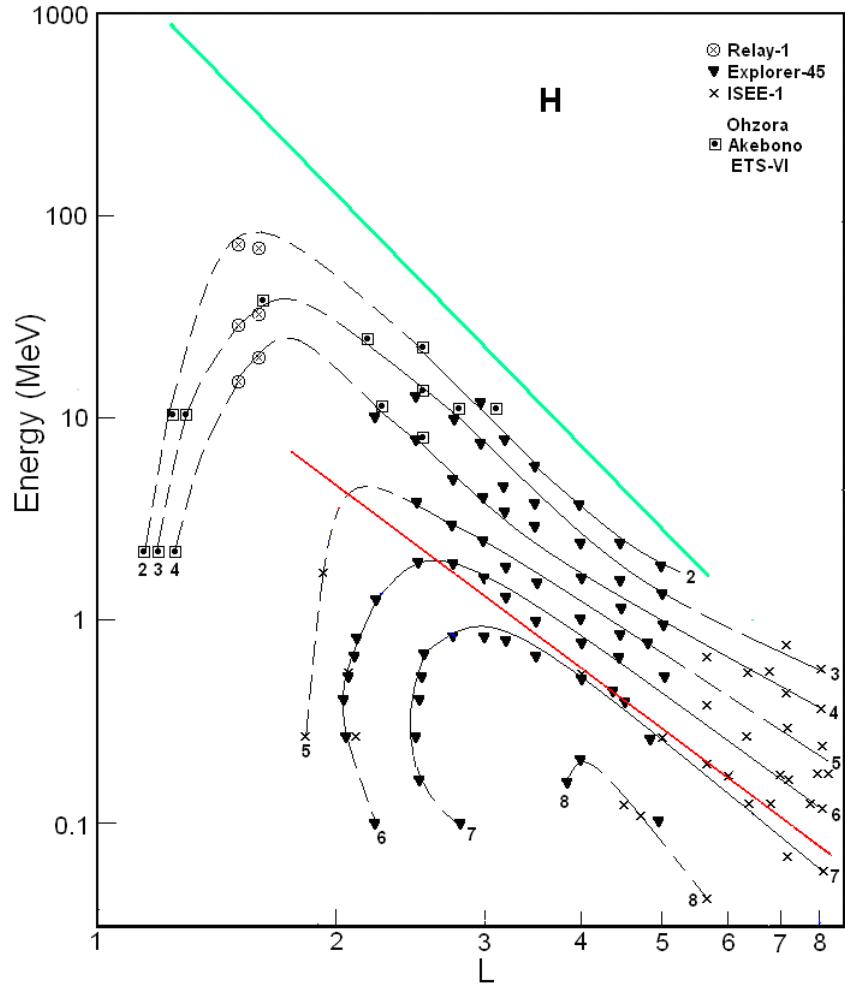
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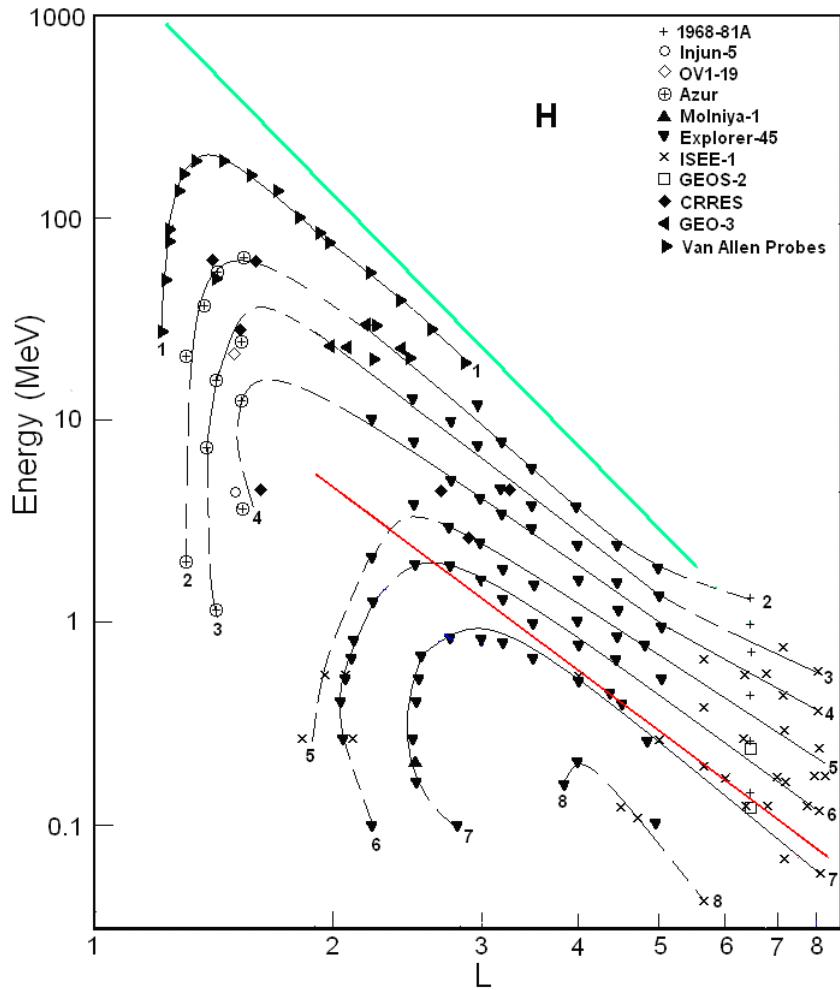
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Figure 1. Proton fluxes in the ERB near minima of the solar activity. The numbers on the curves refer to the values of the decimal logarithms of J , which is given in units of $(\text{cm}^2 \text{ s ster MeV})^{-1}$, is the differential fluxes of protons with $\alpha_0 \approx 90^\circ$ (near the plane of the geomagnetic equator). Data of satellites are associated with different symbols. The red line corresponds to the lower boundary of the power-law tail of the proton spectra; while green line corresponds to the maximum energy of protons trapped in the ERB (Ilyin et al., 1984).



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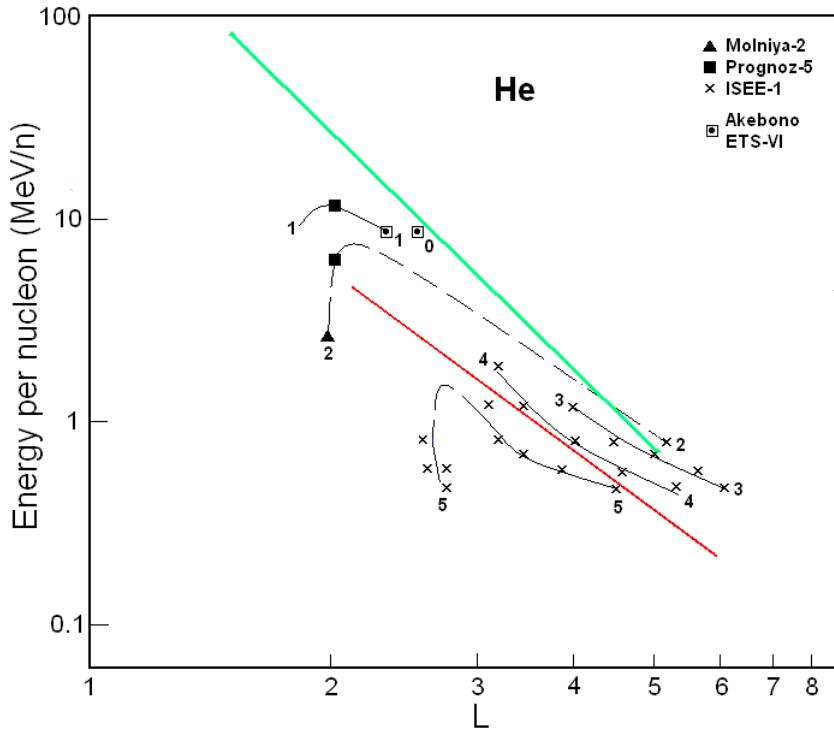
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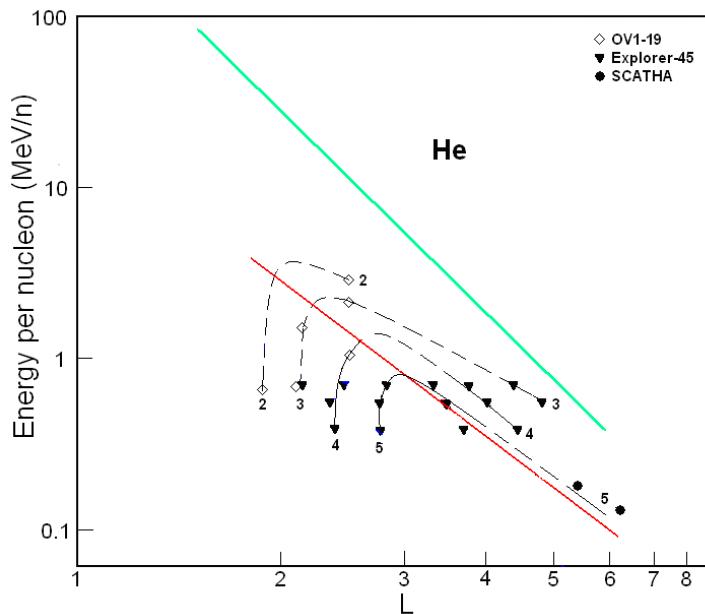
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Figure 2. Proton fluxes in the ERB near maxima of the solar activity. The numbers on the curves refer to the values of the decimal logarithms of J , which is given in units of $(\text{cm}^2 \text{ s ster MeV})^{-1}$, is the differential fluxes of protons with $\alpha_0 \approx 90^\circ$ (near the plane of the geomagnetic equator). Data of satellites are associated with different symbols. The red line corresponds to the lower boundary of the power-law tail of the proton spectra; while green line corresponds to the maximum energy of protons trapped in the ERB (Ilyin et al., 1984).



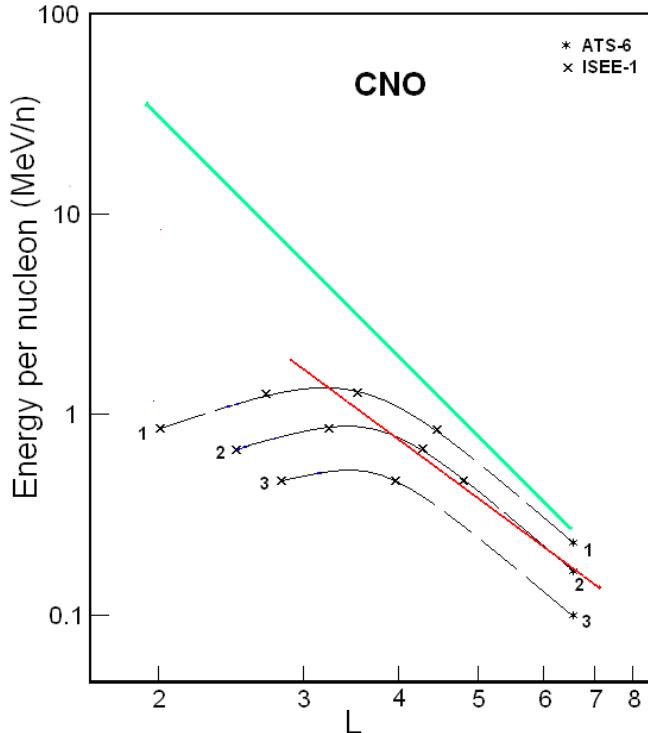
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Figure 3. Helium ion fluxes in the ERB near minima of the solar activity. The numbers on the curves refer to the values of the decimal logarithms of J , which is given in units of $(\text{cm}^2 \text{ s ster MeV/n})^{-1}$, is the differential fluxes of helium ions with $\alpha_0 \approx 90^\circ$ (near the plane of the geomagnetic equator). Data of satellites are associated with different symbols. The red line corresponds to the lower boundary of the power-law tail of the helium spectra; while green line corresponds to the maximum energy of these ions trapped in the ERB (Ilyin et al., 1984).



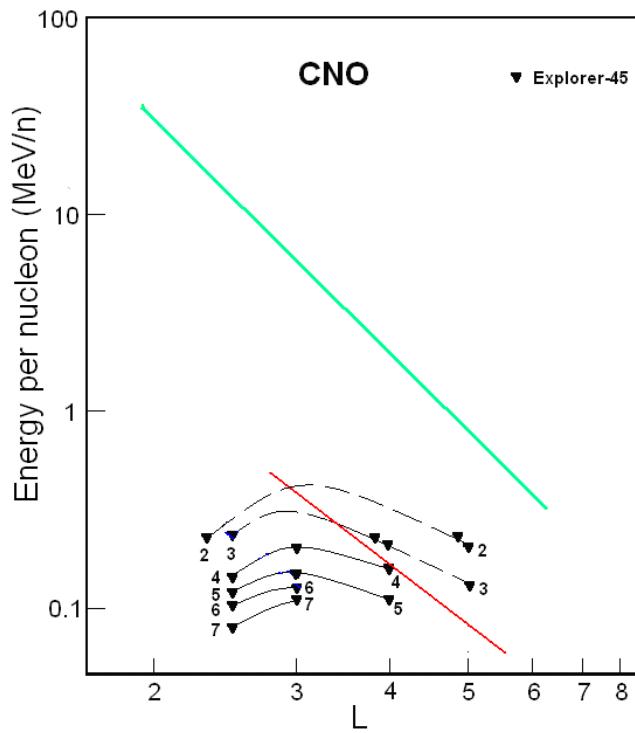
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Figure 4. Helium ion fluxes in the ERB near maxima of the solar activity. The numbers on the curves refer to the value of the decimal logarithms of J which is given in units of $(\text{cm}^2 \text{ s ster MeV/n})^{-1}$, is the differential fluxes of ions with $\alpha_0 \approx 90^\circ$ (near the plane of the geomagnetic equator). Data of satellites are associated with different symbols. The red line corresponds to the lower boundary of the power-law tail of the helium spectra; while green line corresponds to the maximum energy of these ions trapped in the ERB (Ilyin et al., 1984).



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Figure 5. CNO ion fluxes in the ERB near minima of the solar activity. The numbers on the curves refer to the values of the decimal logarithms of J , which is given in units of $(\text{cm}^2 \text{ s ster MeV/n})^{-1}$, is the differential fluxes of ions with $\alpha_0 \approx 90^\circ$ (near the plane of the geomagnetic equator). Data of satellites are associated with different symbols. The red line corresponds to the lower boundary of the power-law tail of the CNO ion spectra; while green line corresponds to the maximum energy of these ions trapped in the ERB (Ilyin et al., 1984).



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Figure 6. CNO ion fluxes in the ERB near the maximum of the solar activity. The numbers on the curves refer to the values of the decimal logarithms of J , which is given in units of $(\text{cm}^2 \text{ s ster MeV/n})^{-1}$, is the differential fluxes of ions with $\alpha_0 \approx 90^\circ$ (near the plane of the geomagnetic equator). Data of satellites are associated with different symbols. The red line corresponds to the lower boundary of the power-law tail of the CNO ion spectra; while green line corresponds to the maximum energy of these ions trapped in the ERB (Ilyin et al., 1984).