

IMPROVED COSMIC RAY SPECTRUM AND INTENSITY
IN MIDDLE ATMOSPHERE (CORSIMA) MODEL
CONSIDERING SIX CHARACTERISTIC ENERGY
INTERVALS

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Abstract

The new model CORSIMA (COsmic Ray Spectrum and Intensity in Middle Atmosphere) is presented in this study. Numerical determinations of the spectrum and intensity of Galactic Cosmic Rays (GCR) for the middle atmosphere and the lower altitudes of the ionosphere (30–80 km) are presented. These altitudes are above the Regener–Pfitzer maximum. The primary spectra of protons and helium (alpha particles) are used. According to the amount of particles, cosmic rays consist of 92% protons, 6% helium nuclei, 1% heavier elements, and 1% electrons (GINZBURG and SIROVATSKY [19]).

We also use the approximation of ionization losses (Bohr–Bethe–Bloch formula) in six characteristic energy intervals, including the charge decrease interval for electron capture. In this way, the accuracy of the obtained results is improved.

Analytical expressions for the contributions of the energy intervals are provided. An approximation of the ionization function on six energy intervals is used and the charge decrease interval for electron capture is studied. Numerical calculations are performed using computational algebra systems.

The development of this research is important for a better understanding of the processes and mechanisms of space weather. The GCR affect the ionization and electrical parameters in the atmosphere and also the chemical processes (ozone formation and depletion in the stratosphere) in it. These effects can be significantly enhanced during strong and moderately strong solar proton events and geomagnetic storms.

Key words: galactic cosmic ray (GCR) spectra and intensity, ionization, middle atmosphere, lower ionosphere

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1. Introduction. The relativistic precipitating particles of cosmic origin viz. cosmic rays (protons and heavier nuclei of galactic and/or solar origin) induce complicated nuclear-electromagnetic-lepton cascades in the atmospheres of Earth, planets and their moons [1,2], eventually leading to an ionization and excitation of the ambient air [3]. The induced by cosmic rays atmospheric ionization is related to possible effect of precipitating particles on atmospheric physics and chemistry [4-7].

The investigation of ionization processes in atmosphere is important for better understanding of space weather and space climate mechanisms [8]. The Galactic Cosmic Rays (GCR) influence the ionization and therefore the electrical parameters in the planetary atmospheres. They change also the chemical processes – for example ozone creation and depletion in the Earth’s stratosphere. In this way they transfer the impact of solar activity into the atmosphere [8,9].

The goal of the present work is to determine the differential spectrum and intensity of galactic cosmic rays when they penetrate at different altitudes (30–80 km) into the middle atmosphere. This is important for establishing the ionization-neutralization processes in the lower ionosphere. For this purpose, we will use some results from our CORIMIA (COsmic Ray Ionization Model for the Ionosphere and Atmosphere) model [10–15], which determines GCR electron production rate in the middle atmosphere.

2. Cosmic Ray Induced Ionization (CRII). The detailed model for calculating the CRII rate ($\text{cm}^{-3}\text{s}^{-1}$) in the middle atmosphere is described in [10–15]. The mathematical expression of the model is as follows:

$$(1) \quad q(h) = \sum_i q_i(h) = \frac{1}{Q} \sum_i \int_{E_i}^{\infty} \int_{A=0}^{2\pi} \int_{\theta=0}^{\pi/2+\Delta\theta} D_i(E) \left(\frac{dE}{dh} \right)_i \sin \theta \, d\theta \, dA \, dE,$$

where A is the azimuth angle, θ is the angle towards the vertical, $\Delta\theta$ takes into account that at a given height the particles can penetrate from the space angle ($0^\circ, \theta_{\max} = 90^\circ + \Delta\theta$), which is greater than the upper hemisphere angle ($0^\circ, 90^\circ$) for flat model. E_i are the energy cut-offs. The summation in the ionization integral (1) is made on the groups of nuclei: protons p, Helium (alpha particles), Light L ($3 \leq Z \leq 5$), Medium M ($6 \leq Z \leq 9$), Heavy H ($Z \geq 10$) and Very Heavy VH ($Z \geq 20$) nuclei in the composition of cosmic rays. Z is the charge of the nuclei, $Q = 35 \text{ eV}$ is the energy which is necessary for formation of one electron-ion pair.

$D_i(E)$ is the corresponding differential spectrum ($\text{cm}^{-2}.\text{s}^{-1}.\text{st}^{-1}.\text{MeV}^{-1}$) which in the case of GCR is calculated as follows [16–18]:

$$(2) \quad D(E) = K(0.939 + E)^{-\gamma} \left(1 + \frac{\alpha}{E} \right)^{-\beta}.$$

Here the first multiplier $K(0.939 + E)^{-\gamma}$ presents the GCR spectrum with kinetic energy E (GeV/nuc). The last multiplier describes the GCR modulation

by the solar wind. The constant 0.939 is the energy of rest of proton. K , γ , α and β are parameters of the spectrum which are determined in [16–18].

3. Model approximations. We introduce five main characteristic energy intervals and a charge decrease interval for electron capture in the ionization losses approximation ($\text{MeV} \cdot \text{g}^{-1} \cdot \text{cm}^2$) according to the Bohr–Bethe–Bloch function using experimental data [10–12]. This approximation for protons ($Z = 1$) has the form: (3)

$$-\frac{1}{\rho} \frac{dE}{dh} = \begin{cases} 2.57 \times 10^3 E^{0.5} & \text{if } kT \leq E \leq 0.15 \text{ MeV/n,} & \text{interval 1} \\ 1540 E^{0.23} & \text{if } 0.15 \leq E \leq E_a = 0.15 Z^2 \text{ MeV/n,} & \text{interval 2} \\ 231 \times Z^2 E^{-0.77} & \text{if } E_a \leq E \leq 200 \text{ MeV/n,} & \text{interval 3} \\ 68 \times Z^2 E^{-0.53} & \text{if } 200 \leq E \leq 850 \text{ MeV/n,} & \text{interval 4} \\ 1.91 \times Z^2 & \text{if } 850 \leq E \leq 5 \times 10^3 \text{ MeV/n,} & \text{interval 5} \\ 0.66 \times Z^2 E^{0.123} & \text{if } 5 \times 10^3 \leq E \leq 5 \times 10^6 \text{ MeV/n.} & \text{interval 6} \end{cases}$$

In this way, the accuracy of the obtained results is improved compared to the accuracy which corresponds to the case of lower number of characteristic energy intervals [14,15].

The model can be realized in sub models that evaluate the contributions of GCR, solar cosmic rays (SCR), or anomalous cosmic rays (ACR), taking into account the ionization in the middle atmosphere and lower ionosphere. Other structures in these sub models are the different contributions of the characteristic energy intervals to the total ionization. This model can be used to investigate the influence of random differential spectra energy intervals on CRII in the middle atmosphere. Satellite measurements of differential spectra are used for this purpose.

4. Model description and main parameter expressions. 4.1. Energy boundary crossing between intervals. The presented CORSIMA model for the general case of GCR will be described here. One part of the next important mathematical expressions is given in this chapter.

There are some parameters which are essential for the model statement and have physical meaning:

- boundary crossing of one limit ($E_{i,i-1}$ for $i = 2, \dots, 6$);
- boundary crossing of two limits ($E_{j,j-2}$ for $j = 3, \dots, 6$);
- boundary crossing of three limits ($E_{k,k-3}$ for $k = 4, \dots, 6$);
- boundary crossing of four limits ($E_{l,l-4}$ for $l = 5, 6$);
- boundary crossing of five limits (E_{61}).

The phenomenon “boundary crossing” is characterized by the changing of particles kinetic energy, when these energies cross the interval limits of the ionization losses function. These parameters enter in the integrand (1) – in the ionization losses function (dE/dh). Mathematical expressions of “boundary crossing of one limit” are given in [10–12]. The next expressions cited above describe the more complex cases – “boundary crossing of more than one limit”.

Boundary crossings of two limits are derived as follows. We start with the travelling substance path (g.cm^{-2}) evaluation in three subsequent energy intervals:

$$(4) \quad \begin{aligned} \tilde{h} &= \tilde{h}_1 + \tilde{h}_2 + \tilde{h}_3 \\ &= \frac{A}{1285}(0.15^{0.5} - E_{31}^{0.5}) + \frac{A}{1185}(E_a^{0.77} - 0.15^{0.77}) + \frac{A}{408.87Z^2}(E_k^{1.77} - E_a^{1.77}). \end{aligned}$$

Equation (4) shows the case of the elapsed quantity of material/substance $\tilde{h}$ lying in intervals 3, 2, and 1 of (4). Here, the initial energy E_k of the particles from the spectrum (2) of the GCR, which is outside the atmosphere, is in interval 3 of the formula of ionization losses (3), and their value at height h after passing the amount of material/substance $\tilde{h}$ from (4) in the atmosphere has decreased to E_{31} in interval (1) in formula (4). From (4) we obtain

$$(5) \quad E_{31}(h) = \left[0.15^{0.5} - \frac{1285}{A}\tilde{h} + 1.08(E_a^{0.77} - 0.15^{0.77}) + \frac{3.14}{Z^2}(E_k^{1.77} - E_a^{1.77}) \right]^2.$$

In analogous way we calculate the next expressions of boundary crossing for start energy E_k outside of the atmosphere in interval 4 of (3) and reduced energy $E_{42}(h)$ in interval 2

$$(6) \quad E_{42}(h) = \left[E_a^{0.77} - \frac{1285}{A}\tilde{h} + \frac{2.9}{Z^2}(200^{1.77} - E_a^{1.77}) + \frac{11.4}{Z^2}(E_k^{1.53} - 200^{1.53}) \right]^{1/0.77}.$$

The next formulas (7)–(14) have the same meaning for the corresponding start and current height energy intervals, whose numbers are shown as energy indices:

$$(7) \quad E_{53}(h) = \left[200^{1.77} - \frac{408.87Z^2}{A}\tilde{h} + 3.93(850^{1.53} - 200^{1.53}) + 214.07(E_k - 850) \right]^{\frac{1}{1.77}},$$

$$(8) \quad E_{64}(h) = \left[850^{1.53} - \frac{104.04Z^2}{A}\tilde{h} + 54.66(5000 - 850) + 179.69(E_k^{0.877} - 5000^{0.877}) \right]^{\frac{1}{1.53}}.$$

Boundary crossings of three limits have the form:

$$(9) \quad \begin{aligned} E_{41}(h) &= \left[0.15^{0.5} - \frac{1285}{A}\tilde{h} + 1.08(E_a^{0.77} - 0.15^{0.77}) + \frac{3.14}{Z^2}(200^{1.77} - E_a^{1.77}) \right. \\ &\quad \left. + \frac{12.3}{Z^2}(E_k^{1.53} - 200^{1.53}) \right]^2, \end{aligned}$$

$$(10) \quad E_{52}(h) = \left[E_a^{0.77} - \frac{1285}{A} \tilde{h} + \frac{2.9}{Z^2} (200^{1.77} - E_a^{1.77}) + \frac{11.4}{Z^2} (850^{1.53} - 200^{1.53}) + \frac{620.42}{Z^2} (E_k - 850) \right]^{1/0.77},$$

$$(11) \quad E_{63}(h) = \left[200^{1.77} - \frac{408.87 Z^2}{A} \tilde{h} + 3.93 (850^{1.53} - 200^{1.53}) + 214.07 (5000 - 850) + 706.17 (E_k^{0.877} - 5000^{0.877}) \right]^{1/1.77}.$$

Boundary crossings of four limits have the form:

$$(12) \quad E_{51}(h) = \left[0.15^{0.5} - \frac{1285}{A} \tilde{h} + 1.08 (E_a^{0.77} - 0.15^{0.77}) + \frac{3.14}{Z^2} (200^{1.77} - E_a^{1.77}) + \frac{12.3}{Z^2} (850^{1.53} - 200^{1.53}) + \frac{672.77}{Z^2} (E_k - 850) \right]^2,$$

$$(13) \quad E_{62}(h) = \left[E_a^{0.77} - \frac{1285}{A} \tilde{h} + \frac{2.9}{Z^2} (200^{1.77} - E_a^{1.77}) + \frac{11.4}{Z^2} (850^{1.53} - 200^{1.53}) + \frac{620.42}{Z^2} (5000 - 850) + \frac{2046.63}{Z^2} (E_k^{0.877} - 5000^{0.877}) \right]^{1/0.77}.$$

Boundary crossing of five limits has the form:

$$(14) \quad E_{61}(h) = \left[0.15^{0.5} - \frac{1285}{A} \tilde{h} + 1.08 (E_a^{0.77} - 0.15^{0.77}) + \frac{3.14}{Z^2} (200^{1.77} - E_a^{1.77}) + \frac{12.3}{Z^2} (850^{1.53} - 200^{1.53}) + \frac{672.77}{Z^2} (5000 - 850) + \frac{2219.34}{Z^2} (E_k^{0.877} - 5000^{0.877}) \right]^2.$$

4.2. Energy boundary crossing by limits transformation. Other important parameters are the transformations of the energy limits when the limits of the characteristic intervals of the kinetic energy are exceeded. The case without boundary crossing is treated in [10–12]. Here we present the mathematical expressions for more than one simultaneous boundary crossing.

The first boundary transformation of the limit between intervals one and two is derived as follows:

$$(15) \quad \tilde{h} = \tilde{h}_2 + \tilde{h}_3 = \frac{A}{1185} (E_a^{0.77} - 0.15^{0.77}) + \frac{A}{408.87 Z^2} (E_{0.15;3}^{1.77} - E_a^{1.77}).$$

The kinetic energy initial value $E_{0.15,3}(h)$, which is situated outside of the atmosphere in interval 3 before the particles transport through the substance

path $\tilde{h}(h)$ in (15) reaches the reduced value 0.15 MeV/n at height h . It is the following formula (16):

From (15) we obtained the new transformation:

$$(16) \quad E_{0.15,3}(h) = \left[E_a^{1.77} + 408.87(Z^2/A) \times \tilde{h} - 0.345Z^2(E_a^{0.77} - 0.15^{0.77}) \right]^{1/1.77}.$$

In analogous way we calculate the expressions of boundary transformations to the corresponding initial energy values in the intervals of formula (3) for the next limits:

$$(17) \quad E_{E_a,4}(h) = \left[200^{1.53} + 104.04 \times (Z^2/A) \times \tilde{h} - 0.254(200^{1.77} - E_a^{1.77}) \right]^{1/1.53},$$

$$(18) \quad E_{200,5}(h) = 850 + 1.91(Z^2/A)\tilde{h} - 0.018(850^{1/1.53} - 200^{1/1.53}),$$

$$(19) \quad E_{850,6}(h) = \left[5000^{0.877} + 0.579 \times (Z^2/A) \times \tilde{h} \right].$$

All energies are given in MeV/nuc. Every formula (16)–(19) expresses the crossing of one interval energy boundary – namely $E_a = 0.15Z^2$, 200, 850, 5000 (MeV/n) by the travelling substance path $\tilde{h}(h)$.

5. Results. In this work, the primary spectra of protons and helium (alpha particles) are used. In terms of the amount of particles, cosmic rays consist of 92% protons, 6% helium nuclei, about 1% heavier elements, and about 1% electrons [19].

In particular, we study the GCR spectrum and intensity at minimum solar activity. We perform a decomposition for the two main groups of GCR nuclei (protons and helium) [19] and for different characteristic energy intervals. The properties of the model in terms of the ionization losses function boundaries are realized and studied.

The main results of the model calculations in this paper concern the cusp region ($R_c = 0$ GV) at different altitudes h (30–80 km). They are shown in Fig. 1 and 2.

The GCR spectrum is composed for calculation of the ionization rates by the main groups of GCR nuclei. Figures 1 and 2 show the spectrum for the two main groups of GCR nuclei – protons and helium, respectively.

As can be seen in Fig. 1 and 2 there is a strong dependence on the type of the nuclei group ($Z = 1$ and 2) for the given energy value.

6. Conclusion. Figures 1 and 2 show the GCR spectra for the Cusp region (solar minimum) calculated with our new model CORSIMA. This model is capable of calculating spectra and performing a comparison with experimentally measured differential spectra. The evaluation of the spectra and the basic statement of the model can be discussed. In the case of six characteristic energy intervals, we achieve accuracy which is consistent with experimental data [14–18]. The model can be applied to different input spectra in interactive mode and different planetary atmospheres.

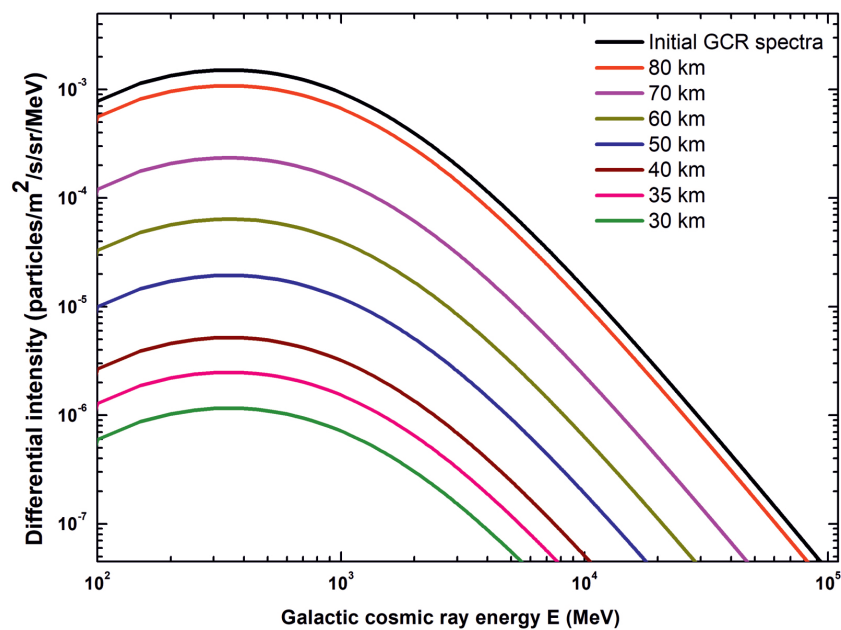


Fig. 1. Differential spectrum of GCR protons at different altitudes in the area of 30–80 km a.s.l.

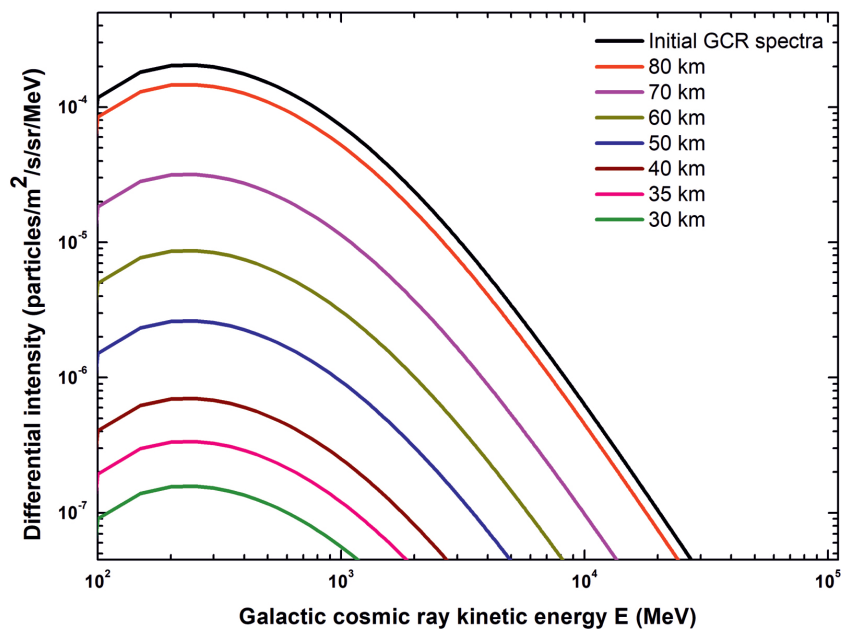


Fig. 2. Differential spectrum of GCR helium nuclei (alpha particles) at different altitudes in the area of 30–80 km a.s.l.

The computational results were obtained using the well-known computer algebra system Wolfram Mathematica, version 7.0 [14,15]. The input data are entered in a special input window. The output data are displayed in the corresponding output window. They show the internal structure of the model.

The CORSIMA model is applicable at altitudes above 25–30 km. The hadron interactions should be taken into account below and especially in the region of the Regener–Pfozter maximum. That is why we use the CORSIKA (**CO**smic **R**ay **SI**mulations for **K**Ascade) nuclear cascade model there [5,6,14,20–22].

The results obtained in the present work are important for solving problems of space physics and space weather. They tie in with the latest developments on these topics [23–29] and provide a quantitative assessment of the influence of cosmic rays on the mechanisms of solar-terrestrial connections.

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