

VALIDATION OF IONIZATION MODEL CORSIMA APPLIED FOR MULTIPLY CHARGED ANOMALOUS COSMIC RAYS

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Abstract

During the acceleration of anomalous cosmic rays (ACRs) some singly-charged ions are stripped of additional electrons. The resulting multiply-charged (MC) ions are accelerated more efficiently, and most ACRs with ≥ 30 MeV/nuc are multiply-charged. This paper considers some implications of multiply-charged ACRs, including their penetration and ionization in the system ionosphere-middle atmosphere.

The influence of Multiply Charged Anomalous Cosmic Rays (MCACRs) on ionization in the boundary of the ionosphere-middle atmosphere system (40–50 km) is investigated, taking into account the spectra, intensity, geomagnetic, and atmospheric cut-offs. The MCACR spectra and intensity in the middle atmosphere are determined using the CORSIMA (COsmic Ray Spectra and Intensity in Middle Atmosphere) model. MCACR spectra are presented for various atmospheric altitudes within the range of 40–50 km, with the lower boundary of the ionosphere at approximately 50 km. Experimental satellite measurements are utilized for the main MCACR constituents, including Hydrogen (protons), Helium and Oxygen nuclei. It is found that the influence of MCACRs extends to the polar cap regions above 65° – 70° geomagnetic latitude, and certain MCACR ionization rate values in these regions are comparable to Galactic Cosmic Ray (GCR) ionization rates.

Key words: Multiply Charged Anomalous Cosmic Rays (MCACRs), spectra, ionosphere, middle atmosphere

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Introduction. A new component of quiet time cosmic ray flux with anomalous composition and energy spectra was discovered ~ 50 years ago, since then called Anomalous Cosmic Rays (ACRs) [1]. During the acceleration of anomalous cosmic rays some singly-charged ions are stripped of additional electrons. The resulting multiply-charged (MC) ions are accelerated more efficiently, and most ACRs with ≥ 30 MeV/nuc1 are multiply-charged [2,3]. This paper considers some implications of multiply-charged ACRs, including their penetration and ionization in the system ionosphere-middle atmosphere [4–8].

The pickup-ion origin implies that ACRs should be singly-ionized [9,10], and several studies have shown that this is true of most ACRs with ~ 10 MeV/nuc1. However, using data from the Solar, Anomalous, and Magnetospheric Explorer (SAMPEX), MEWALDT et al. [11] found that at energies ≥ 25 MeV/nuc1 most ACRs have an ionic charge $Q \geq 2$. They interpreted this as evidence that some ACRs are stripped while being accelerated, and that ACRs gain energy in proportion to their ionic charge during acceleration as suggested by JOKIPII [2]. This work explains how some ACR oxygen are accelerated to energies as high as ~ 100 MeV/nuc1. The observed fraction ($\sim 20\%$) of multiply-charged to singly-charged O implies that ACRs are accelerated to 10 MeV/nuc1 within 1–2 years.

Further SAMPEX measurements showed that the $Q = 1/Q \geq 1$ ratio for N, O, and Ne crosses the 50% point at a common total energy of ~ 360 MeV. Using new stripping cross sections and including stripping on neutral He and O [7], the cutoffs in the singly-charged spectra were well fit by the Jokipii model [2].

The ionization effect of Multiply Charged ACRs (MCACRs) on the boundary of the ionosphere-middle atmosphere system (40–50 km) will be investigated, taking into account the spectrum, intensity, geomagnetic, and atmospheric cut-offs. The MCACR spectra and intensity in the middle atmosphere are determined using the CORSIMA (COsmic Ray Spectra and Intensity in Middle Atmosphere) model [12]. ACR spectra will be presented for various atmospheric altitudes within the range of 40–50 km, with the lower boundary of the ionosphere at approximately 50 km. Experimental satellite measurements are utilized for the main ACR constituents, including Hydrogen (protons), Helium and Oxygen nuclei. It is found that the influence of ACRs extends to the polar cap regions above 65° – 70° geomagnetic latitude, and certain ACR ionization rate values in these regions are comparable to Galactic Cosmic Ray (GCR) ionization rates.

Model approximations. We introduce six main characteristic energy intervals in the approximation of ionization losses (MeV.g⁻¹.cm²) according the Bohr–Bethe–Bloch function using experimental data [12,13]. This approximation for multi charge ACR nuclei ($Z > 1$) is the following:

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

Here E is the kinetic energy and Z is the charge of the particles.

For the case of multi charge ACRs (MCACRs) we introduce the corresponding charge decrease interval and the respective initial energy values for the interval boundaries.

By introducing multiple characteristic energy intervals in our model, we enhance the accuracy of the obtained results compared to previous approximations with fewer intervals [10, 11].

Our model is designed to analyze the contributions of different types of cosmic rays (CRs), including galactic CRs (GCRs), solar CRs (SCRs), and anomalous CRs (ACRs), to the ionization in the ionosphere and middle atmosphere. Each submodel within our framework focuses on evaluating the specific contributions of these CR types and considers the distinct characteristic energy intervals in the total ionization process. To investigate the impact of random differential spectrum energy intervals on the ionization in the middle atmosphere, we utilize satellite measurements of differential spectra, with a particular emphasis on ACR spectra in this study. Through decomposing the ACR spectra into different groups of ACR nuclei and characteristic energy intervals, we gain insights into their properties and examine their effects on the ionization losses function boundaries.

Our newly developed code, CORSIMA (**CO**smic **R**ay **S**pectra and **I**ntensity in **M**iddle **A**tmosphere), builds upon the results and advancements of our previous model, CORIMIA (**CO**smic **R**ay **I**onization **M**odel for **I**onosphere and **A**tmosphere) [12]. By leveraging the capabilities of CORSIMA and incorporating the refined analysis of energy intervals, we aim to provide a comprehensive and improved understanding of ACR spectra and their influence on the ionization in the middle atmosphere.

Model description for ACRs. The submodel for the calculation of the ACR ionization rate profiles has different properties in comparison with GCR or SCR submodels. In the presented calculation ACR constituents are multiply charged. That is why we introduce the charge decrease interval [12, 13]. We consider also the influence of atomic weight A .

When considering the penetration of ACRs into the atmosphere, we calculate the electron production rate within three intervals that pertain to the low-energy range of ionization losses ($\text{MeV.g}^{-1}.\text{cm}^2$) following the Bohr–Bethe–Bloch formula. Unlike the case of single ionized particles, now we include the new interval

dependencies. In this way, the expression of the ionization losses function becomes more general than the case $Z = 1$.

$$(2) \quad -\frac{1}{\rho} \frac{dE}{dh} = \begin{cases} 2.57 \times 10^3 E^{0.5} & \text{if } kT \leq E \leq 0.15 \text{ MeVn,} & \text{int. 1} \\ 1540 E^{0.23} & \text{if } 0.15 \leq E \leq E_a = 0.15 Z^2 \text{ MeVn,} & \text{int. 2*} \\ 231 \times Z^2 E^{-0.77} & \text{if } E_a \leq E \leq 200 \text{ MeVn,} & \text{int. 2} \end{cases}$$

We will show the interval values which are important for the model calculations of CR spectra and intensities and also for the ionization rates in the middle atmosphere and the lower ionosphere. All particle energies are given in units (MeV/nuc).

The lower energy bound is the value of parameter kT which reflects the thermal state of the charged particles. Intervals 1 and 2*

$$kT < E < 0.15 < E_a = 0.15 Z^2$$

show the descending and ascending phases of CR spectrum when the intensities of particles change their slope approximately at the bound 0.15 MeV/nuc. The interval 2* is the charge decrease interval because of electron capturing which occurs during their penetration downwards in the atmosphere. The first two intervals show also the ionization losses increases as it can be seen in formula (1).

In the next interval 2

$$E_a < E < 200$$

begins the decrease of the ionization losses energy values as also of the spectrum intensities. This decrease continues for the ionization losses in the next interval 3

$$200 < E < 850$$

with less slope which reflects the real physical process.

In the next energy interval 4

$$850 < E < 5000$$

and interval 5

$$E > 5000$$

are situated the relativistic particles whose energies increase in higher ranges. Beyond the interval 5 is situated the characteristic knee in the CR spectrum E $3-4 \times 10^{15}$ eV. The CR energies increase up to $E > 10^{18}$ eV for Ultra High Energy Cosmic Rays (UHECRs) and to $E > 10^{20}$ eV for Extremely High Energy Cosmic Rays (EHECR) (see <https://home.cern/science/physics/cosmic-rays-particles-outer-space>).

Now we will show the energy subintervals which are needed in the ionization rate models CORIMIA and CORSIMA:

$$(3) \quad kT < E_{\text{eff}} < 0.15 < E_{0.15,2^*} < E_a < E_{a,2} < 200 < E_{200,3} < 850 < E_{850,4} \\ < 5000 < E_{5000,5} < \infty.$$

This case of energy boundaries sequence of inequalities is applied in [13]. These subintervals are defined as is shown in the inequality consequences (3) with calculation of their bounds which are situated between the corresponding bounds of the main energy intervals which reflect the physical nature of the particles. These intermediary bounds characterize the properties of the CORIMIA and CORSIMA models and depend on the travelling substance path which is taken into account in the corresponding formulas.

We will present the case of mathematical expression for ionization rate calculation when the effective rigidity of particles penetration is situated in interval 1 from (1), (2) and is less than its upper boundary:

$$(4) \quad q(h) = \frac{\rho(h)}{Q} \left(\int_{E_{\text{eff}}}^{0.15} D(E) \left(\frac{dE}{dh} \right) dE_k + \int_{0.15}^{E_{0.15,2(h)}} D(E) \left(\frac{dE}{dh} \right) dE_k \right. \\ \left. + \int_{E_{0.15,2}}^{E_a} D(E) \left(\frac{dE}{dh} \right) dE_k + \int_{E_a}^{E_{a,2(h)}} D(E) \left(\frac{dE}{dh} \right) dE_k \right. \\ \left. + \int_{E_{a,2}}^{200} D(E) \left(\frac{dE}{dh} \right) dE_k + \int_{200}^{E_{200,3(h)}} D(E) \left(\frac{dE}{dh} \right) dE_k \right),$$

where $Q = 35$ eV is the energy necessary to form one electron-proton pair [4, 8]. At this place it is necessary to show the notifications in formula (4). The integral bounds are given with formulas (1), (14) and in [13]. The ionization losses function without boundary crossings are calculated in (5)–(7) for the terms I, II, III of (4). The ionization losses function with boundary crossings are calculated in (8), (9) and [13] for the terms II, IV, VI of (4). The integration bounds of term VI of (4) are explained in [13].

The electron production rate expression is characterized by the following main terms: $\rho(h)$ is the atmospheric density at height h ; $E_1(h)$, $E_2(h)$, $E_3(h)$, $E_{21}(h)$ and $E_{32}(h)$ are the corresponding interval energy decrease laws, which form the corresponding ionization losses functions for the respective energy intervals. $D(E)$ is the differential spectrum in $(\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{st}^{-1} \cdot \text{MeV}^{-1})$. $E_{\text{min}} = E_{\text{eff}}$ is the energy cut-off which is calculated on the basis of formula (13) and the geomagnetic cut-off E_R . It is also possible for the evaluation of the general cut-off rigidity E_{min} to take into account the influence of the atmospheric electric fields [4, 12, 13]. $E_{0.15,2^*}(h)$ and $E_{a,2}$ are the initial energies of particles (before entering the spectrum in the atmosphere), which have energy $E(h) = 0.15$ and $E(h) = E_a$ (MeV) at altitude h (km), respectively [12].

Formulas (5)–(7) show the kinetic energy losses for energy decreases in intervals 1, 2, 3, respectively, without boundary crossings:

$$(5) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_1 = 2570 E_1^{0.5}(h) = 2570 \left(E_k^{0.5} - \frac{1285}{A} \tilde{h} \right),$$

$$(6) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_{2^*} = 1540 E_{2^*}^{0.23}(h) = 1540 \left(E_k^{0.77} - \frac{1185.5}{A} \tilde{h} \right)^{0.3},$$

$$(7) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_2 = 231 Z^2 E_2^{-0.77}(h) = 231 Z^2 \left(E_k^{1.77} - \frac{408.87 Z^2}{A} \tilde{h} \right)^{-0.43}.$$

Formulas (8) and (9) show the case of energy boundary crossings when the charged particles penetrate from interval 2* in interval 1 and from interval 2 in interval 2*:

$$(8) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_{2^*1} = 2570 E_{2^*1}^{0.5}(h) = 2570 \left(0.15^{0.77} - \frac{1285}{A} \tilde{h} + 1.08 (E_a^{0.77} - 0.15^{0.77}) \right),$$

$$(9) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_{22^*} = 1540 E_{22^*}^{0.23}(h) = 1540 \left(E_a^{0.77} - \frac{1185.8}{A} \tilde{h} + \frac{2.9}{Z^2} (E_k^{1.77} - E_a^{1.77}) \right)^{0.36}.$$

Formula (10) shows the initial value of the lower boundary energy for interval 2* before entering the atmosphere.

$$(10) \quad E_{0.15,2^*}(h) = \left(0.15^{0.77} + \frac{1185.8}{A} \tilde{h} \right)^{1.3}.$$

A possible case also is the following expression:

$$(11) \quad E_{0.15,2}(h) = \left(E_a^{1.77} + \frac{408.87 Z^2}{A} \tilde{h} - 0.34 Z^2 (E_a^{0.77} - 0.15^{0.77}) \right)^{0.56}.$$

It takes into consideration energy values above the upper boundary of interval 2 which are characteristic for the spectra in Table 1 (related to Fig. 2). It is valid for other combinations of values for the evaluated parameters and for other mathematical expressions of the models CORSIMA – CORIMIA which reflect the actual energy range which is taken into account. The energy values and the energy intervals for ACR expand up to 5 GeV and greater bounds which enter the respective calculations [14].

We present now the initial energies of the interval boundaries which are effective for the electron production rate by MC ACR expressed in formula (10). It depends namely on the depth of penetration in the atmosphere. The initial

T a b l e 1

Subtracted differential spectra for Helium observed by several telescopes (LET1, red and HET B, blue) of the ISOIS instrument onboard Parker Solar Probe (PSP) [14, Fig. 10a]. Here are the source data for the calculations of Fig. 2

Energy (MeV nucl ⁻¹) PSP-ISOIS:LET1 (red colour line)	Flux [cm ⁻² s ⁻¹ sr ⁻¹ MeV nucl ⁻¹] PSP-ISOIS: LET1 (red colour line)
1.2	7e-4
1.35	3.2e-4
1.6	1.6e-4
1.9	1.4e-4
2.2	1.1e-4
2.6	5e-5
3.0	2.4e-5
3.7	2e-5
4.3	2.1e-5
5.1	2.5e-5
6.1	2.8e-5
7.1	3.8e-5
8.7	3.8e-5
11	4e-5
13	4.5e-5
16	4.4e-5
18	4.6e-5
21	4.5e-5
25	4.6e-5
30	3.8e-5
Energy (MeV nucl ⁻¹) ISOIS:HET B (blue colour line)	Flux [cm ⁻² s ⁻¹ sr ⁻¹ MeV nucl ⁻¹] ISOIS:HET B (blue colour line)
16	4.4e-5
18	4.2e-5
21	3.9e-5
25	3.6e-5
30	3.5e-5
35	3.4e-5
41	3.4e-5
50	3.1e-5

energy for $E_{\min} = kT$, when it is situated in interval 2* from (2) is as follows:

$$(12) \quad E_{A2}(h) = \left(E_a^{1.77} + \frac{408.87Z^2}{A} \tilde{h} - 0.32Z^2 (0.15^{0.5} - (kT)^{0.5}) - 0.34Z^2 (E_a^{0.77} - 0.15^{0.77}) \right)^{0.56}.$$

The following initial energy which is situated in interval 1 from (1), (2) is given by formula

$$(13) \quad E_{A1}(h) = \left((kT)^{0.5} + \frac{1285}{A} \tilde{h} \right)^2.$$

The initial energy of the boundary E_a before the spectrum penetration in the atmosphere, when it is situated in interval 2, is given by formula

$$(14) \quad E_{a,2}(h) = \left(E_a^{1.77} + \frac{408.87 Z^2}{A} \tilde{h} \right)^{0.56}.$$

Computer code and mathematical program. For the solution of the mathematical problems the computer algebra system Mathematica v. 7.0 (2008) is applied: <https://www.wolfram.com/mathematica/>.

The corresponding procedures which realize numerical methods are suitable for the integrand types which arise in the equations shown above. An operational model is created which computes the mathematical expressions in interactive regime. The input data are included in the input window. The input spectra are computed effectively in the numerical procedure **FindRoot**. The output window shows some parameters of the model and directly the computational results for cusp region and for given input geomagnetic latitude. The computer code is user friendly oriented.

Results. Figures 1–3 present the spectra evolution of the main ACR species – protons (Fig. 1), helium (Fig. 2) and oxygen (Fig. 3).

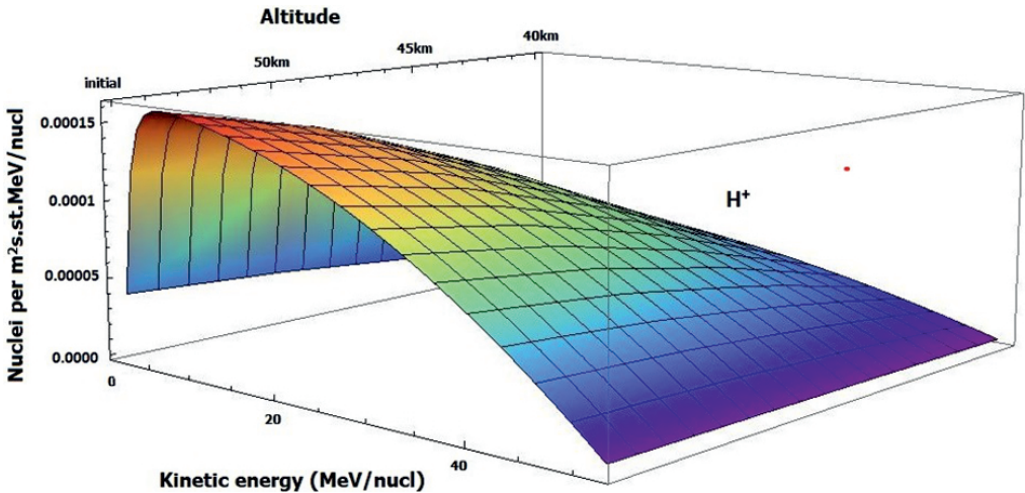


Fig. 1. Modelled altitude-dependent differential spectra of hydrogen protons (H^+) in anomalous cosmic rays (ACRs), showing flux variation with kinetic energy and altitude in Earth's stratosphere

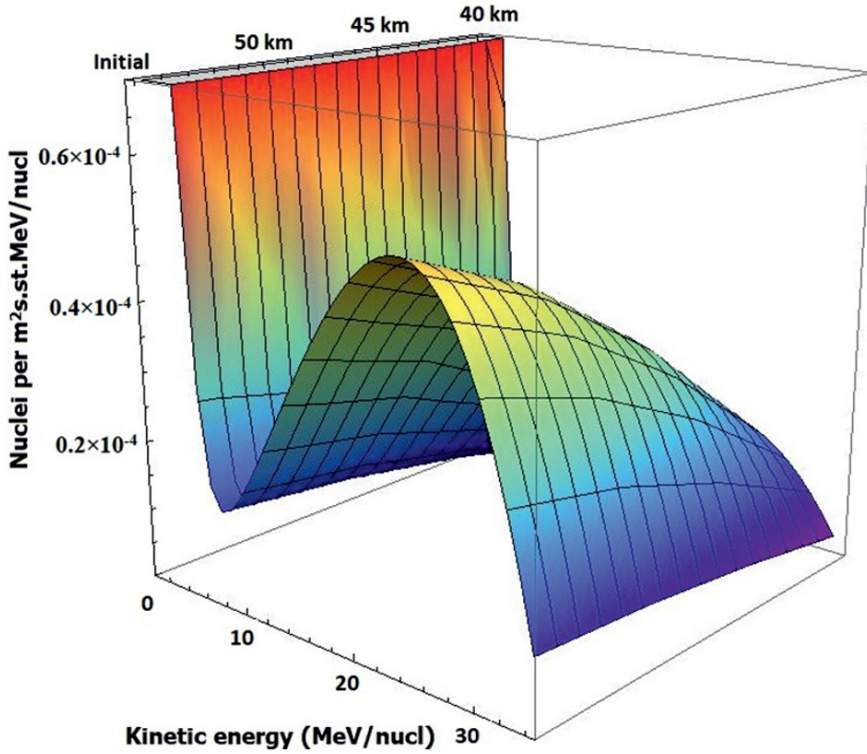


Fig. 2. Altitude-dependent modelled differential spectra of helium nuclei (He) in anomalous cosmic rays (ACRs), illustrating flux variation with kinetic energy and altitude in Earth's stratosphere

The spectra are specifically calculated for a geomagnetic latitude of $\lambda_m = 90^\circ$. In the lower portion of the profiles, the proton and helium spectra are primarily affected by the atmospheric cut-offs. For protons, the spectrum becomes zero below 40 km (Fig. 1), while below 40 km, the helium spectra decrease due to the influence of the atmospheric cut-off (Fig. 2). Notably, the helium and oxygen spectra exhibit the most prominent intensities among the ACR species.

Figure 1 illustrates a 3D model of the energy spectra for hydrogen (protons) (H^+) within the anomalous cosmic rays. On the x -axis, kinetic energy is measured in Mega-electronvolts per nucleon, capturing the range of energies that ACR protons may possess. The y -axis indicates an altitude range from 40 km to 50 km within the Earth's atmosphere. The z -axis quantifies the differential flux, showing the calculated intensity of protons at each energy level.

The surface plot, marked by a colour gradient, visualizes the expected intensities of hydrogen (proton) flux at various energies and altitudes. This is pivotal for understanding the distribution and penetration of ACR protons into the Earth's stratosphere. This model is constructed upon the initial spectra extracted from [9, 10].

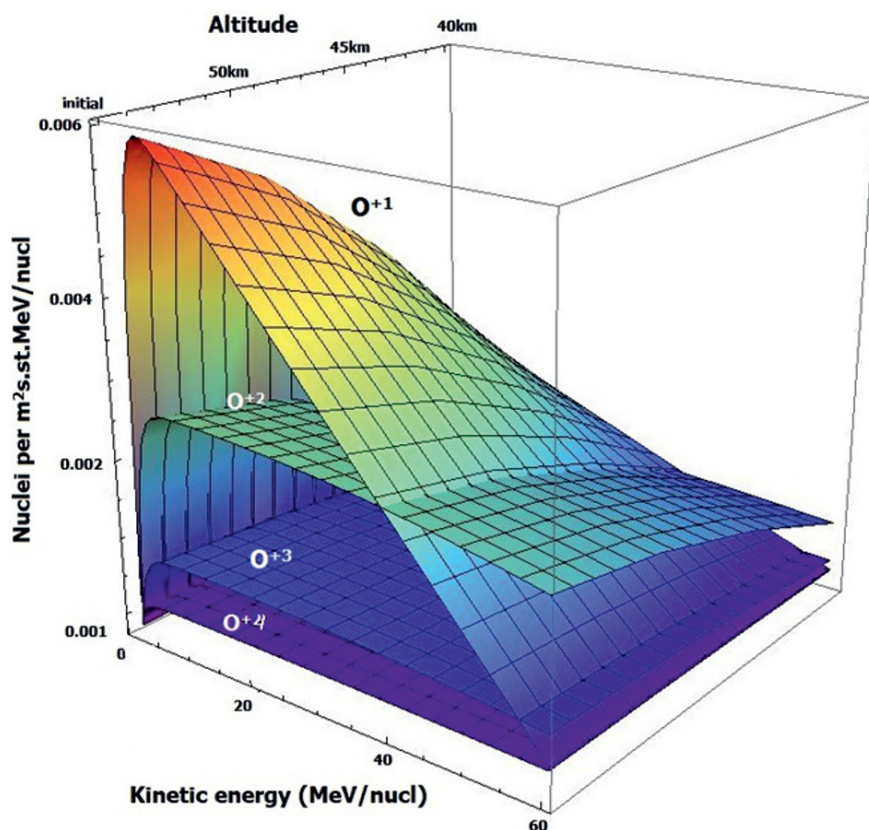


Fig. 3. Modelled altitude-dependent differential spectra of multi-charged oxygen nuclei in anomalous cosmic rays (ACRs), showing flux variation with kinetic energy and altitude in Earth's stratosphere

Figure 2 illustrates a 3D model of the energy spectra for ACR helium nuclei (helium++). The x -, y - and z -axes are the same as in Fig. 1. Figure 2 is related to Table 1 [14].

Table 1 presents event-subtracted spectra for Helium observed by two telescopes (LET1, red and HET B, blue) of the ISOIS instrument onboard Parker Solar Probe (PSP) [14]. Data were taken during the ~ 2018.7 to ~ 2019.9 and ~ 2018.7 to ~ 2021.2 time-frames, respectively. The particles in the energy range 1–3 MeV/nuc represent solar CRs or solar energetic particles (SEPs), in the range 3–60 MeV/nuc are ACRs, and above 60 MeV/nuc are GCRs. GCRs at 1 AU were simulated using the HelMod-4 (Heliospheric Modulation Model, v. 5.1) online calculator (<https://www.helmod.org>).

The initial MC ACR He spectrum before entering the atmosphere is described with the mathematical expression

$$(15) \quad D(E) = 3.34 \times 10^{-7} \times E^2 + 9.19 \times 10^{-9} \times E^3 + 1.49 \times 10^{-3} \times e^{-E},$$

obtained by means of Wolfram Mathematica (2008). It is modified by the travelling substance path $\tilde{h}$ during the particle penetration towards the Earth surface. Figure 2 shows the spectrum shapes at the heights above 40 km.

This MC ACR He spectrum is calculated on the basis of the numerical values in Table 1 which are given on the basis of observations from the telescopes LET1 and HET B of the ISOIS instrument onboard Parker Solar Probe (PSP) [14].

Figure 3 presents modelled altitude-dependent differential spectra of multi-charged oxygen nuclei in ACRs, showing flux variation with kinetic energy and altitude in Earth stratosphere. It provides a theoretical visualization of the differential spectra of ACRs based on computational modelling. It is not a representation of experimental data but an illustrative output from simulations that predict ACR behaviour at different altitudes within Earth atmosphere. The x -axis signifies the kinetic energy of ACRs, measured in MeV per nucleon, a range that captures the variance in particle energy. The y -axis defines the altitudinal levels in the stratosphere, specifically from 40 km to 50 km above sea level, where the presence and interaction of ACRs with the atmosphere become significant. The z -axis measures the differential flux, indicating the density of cosmic ray particles at each energy level per nucleon. Our model is based on initial spectra for different charge states of oxygen nuclei presented in [11].

The plots surface, marked by a gradient of colours, demonstrates the modelled flux intensities across the specified altitudes and energies. The colour intensities and the shape of the surface indicate the expected distribution and peak densities of ACRs. The model further distinguishes between different charge states of oxygen nuclei, labelled as O +1, O +2, O +3, and O +4 representing ionized oxygen. These distinctions are essential for understanding the ionization states of ACRs and their potential interactions as they traverse the upper atmosphere.

Overall, Fig. 3 aims to provide a theoretical framework for the expected behaviour of ACRs, offering insights into how their differential spectra might vary with altitude due to atmospheric absorption and other environmental factors. This model can be a valuable tool for hypothesizing the potential impact of ACRs on the atmosphere and for planning experimental procedures to verify these predictions.

Figures 1–3 represent the variation in the intensity of the anomalous cosmic ray spectra with altitude, specifically between 50 and 40 km in the Earth’s atmosphere. They clearly demonstrate the difference in intensity between these two altitudes, with a higher intensity observed at 50 km compared to 40 km. This change in the spectra provides significant insights into the dynamics of the Earth’s upper atmosphere and the interactions between cosmic rays and atmospheric particles at different altitudes.

Conclusion. In the present study we apply the computer programs CORSIMA [12] and CORIMIA [13] (for multiply charged particles, which is observed in many cases [1–3,9–11]) for determination of the effect of anomalous cosmic rays in the polar caps of the Earth ionosphere. We used experimental data from satellite

measurements [9–11,14] for the input spectra. We obtained ionization spectra for the main ACR species (proton, helium, oxygen) in the high latitude regions for altitudes 40–50 km. We observe characteristic spectra variations in these regions because of the atmospheric cut off effect. The ACR impact is limited in the polar cap region above geomagnetic latitude $\lambda_m = 62^\circ\text{--}63^\circ$.

The united model CORIMIA – CORSIMA is a further development of the previous models [12,13]. The mentioned united model CORIMIA – CORSIMA can be applied for the complex study of the connection between astroparticles, space weather and Earth environment [15–17] with special application in ionospheric physics [18–20].

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