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QUANTITATIVE EVALUATION OF SPECTRA AND INTENSITY OF ANOMALOUS COSMIC RAYS IN MIDDLE ATMOSPHERE

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Abstract

The influence of Anomalous Cosmic Rays (ACRs) on ionization in the boundary of the ionosphere-middle atmosphere system (40–50 km) is investigated, taking into account the spectrum, intensity, geomagnetic, and atmospheric cut-offs. The ACR spectra and intensity in the middle atmosphere are determined using the CORSIMA (**CO**smic **R**ay **S**pectra and **I**ntensity in **M**iddle **A**tmosphere) model. ACR 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 ACR constituents, including Hydrogen (protons), Helium, Nitrogen, 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. Future studies will also consider Multiply Charged Anomalous Cosmic Rays (MCACRs), which exhibit similar differential spectra to the singly ionized ACR components addressed in this study.

Key words: anomalous cosmic rays (ACRs), spectra, ionosphere, middle atmosphere

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Introduction. Anomalous cosmic rays (ACRs) originate as interstellar neutral atoms that drift into the heliosphere, the region of space influenced by the Sun's solar wind. As these neutral atoms enter the heliosphere, they interact with the solar wind particles and undergo ionization. The ionized particles, known

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as pickup ions, are then solar wind to the outer heliosphere. It is believed that the acceleration of ACRs to high energies, typically in the range of hundreds of MeV, occurs predominantly at the carried by the termination shock of the solar wind. The termination shock is the region where the solar wind slows down and becomes turbulent due to its interaction with the interstellar medium. Current theories propose that the mechanism responsible for this acceleration is diffusive shock acceleration, which occurs at the termination shock [1]. This process plays a crucial role in shaping the energy distribution and characteristics of ACRs.

The most commonly observed species in the population of anomalous cosmic rays (ACRs) are helium and oxygen ions. These ions are thought to originate from the local interstellar medium, which refers to the region of space surrounding our solar system that is influenced by the winds of nearby stars. Within this interstellar medium, the winds from nearby stars interact with the solar wind, leading to the creation of ACRs. In addition to helium and oxygen, ACRs also contain trace amounts of other elements such as carbon, nitrogen, neon, and more. It is important to note that the exact composition of ACRs can vary depending on the specific population being considered and the location within the solar system where they are observed [2]. Understanding the composition of ACRs provides valuable insights into the physical processes governing their production and propagation.

The abundance of each element in the population of ACRs holds significant information about the underlying physical processes involved in their production and transport. For instance, the ratio of helium to oxygen in ACRs can be employed as an indicator to study the efficiency of acceleration and transport mechanisms operating within the interstellar medium. By analyzing the relative abundances of these elements, researchers can gain insights into the interplay between particle acceleration, interstellar transport, and other factors influencing the ACR population. This knowledge contributes to a better understanding of the fundamental mechanisms responsible for the generation and propagation of ACRs in the middle atmosphere and aids in elucidating their role in the ionization processes occurring within the boundary of the ionosphere and middle atmosphere [3].

Overall, although ACRs are considered to be relatively rare compared to other cosmic ray populations, they offer a distinctive opportunity to gain insights into the properties of the local interstellar medium and the intricate processes that influence the cosmic ray spectrum. ACRs exhibit distinct spectral characteristics and abundance patterns that can be used to investigate the physical mechanisms involved in their production and propagation. By studying ACRs, researchers can uncover valuable information about the interstellar environment surrounding our solar system, shedding light on the interactions between interstellar particles, the solar wind, and the dynamics of cosmic ray acceleration. The study of ACRs, therefore, plays a crucial role in advancing our understanding of the broader cosmic ray phenomenon and the underlying physics of the interstellar medium [3].

Study objectives. The energy spectrum of ACRs in the Earth's atmosphere at altitudes ranging from 40 to 50 km is an area that has not been extensively studied, primarily because ACRs are typically measured in space. However, this altitude range is significant because it corresponds to the lower boundary of the ionosphere, which is located around 50 km above the Earth's surface [4].

While the energy spectrum of ACRs remains relatively unchanged at higher altitudes where the atmosphere has minimal influence, as ACRs penetrate deeper into the atmosphere, they interact with air molecules, leading to energy loss and the possible production of secondary particles [5]. Consequently, the energy spectrum of ACRs undergoes modification as they traverse the Earth's atmosphere.

At higher altitudes, ACRs experience minimal effects from the Earth's atmosphere, and their energy spectrum closely resembles that observed in space. However, as ACRs descend and interact with air molecules in the atmosphere, their energy can be attenuated, and secondary particle production may occur [5]. These interactions with the atmosphere contribute to a modification of the energy spectrum of ACRs. The specific shape of the energy spectrum of ACRs in the Earth's atmosphere within the 40–50 km altitude range is influenced by various factors, including the initial energy and composition of the ACRs, as well as the atmospheric conditions at these altitudes. It is expected that the interactions with the atmosphere will lead to a distinct modification in the shape and intensity of the energy spectrum compared to observations made in space [6]. There is a significant difference here from galactic CRs [7,8].

The primary objective of the present study is to determine the energy spectra of ACRs in the middle atmosphere around the lower boundary of the ionosphere, specifically within the altitude range of 40–50 km. This research aims to shed light on the energy distribution of ACRs at these specific altitudes, considering the interactions they undergo with the Earth's atmosphere. By investigating the energy spectra of ACRs in this region, valuable insights can be gained regarding the behaviour of ACRs as they penetrate the Earth's atmosphere and interact with air molecules. This information is crucial for understanding the complex dynamics of ACRs in the middle atmosphere and their implications for the ionization processes and atmospheric conditions within this altitude range.

Model approximations. We introduce five main characteristic energy intervals in the approximation of ionization losses ($\mathrm{MeV.g^{-1}.cm^2}$) according the Bohr–Bethe–Bloch function using experimental data [6–8]. This approximation for protons and singly charged particles ($Z = 1$) has the form [9]:

$$-\frac{1}{\rho}\frac{dE}{dh} = \begin{cases} 2.57 \times 10^3 E^{0.5} & \text{if } kT \le E \le 0.15 \text{ MeV} \quad \text{interval 1} \\ 231 E^{-0.77} & \text{if } 0.15 \le E \le 200 \text{ MeV} \quad \text{interval 2} \\ 68 E^{-0.53} & \text{if } 200 \le E \le 850 \text{ MeV} \quad \text{interval 3} \\ 1.91 & \text{if } 850 \le E \le 5 \times 10^3 \text{ MeV} \quad \text{interval 4} \\ 0.66 E^{0.123} & \text{if } 5 \times 10^3 \le E \le 5 \times 10^6 \text{ MeV} \quad \text{interval 5} \end{cases} \tag{1}$$

Here E is the kinetic energy of the penetrating particles.

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, solar CRs, and anomalous CRs (ACRs), to the ionization in the ionosphere-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) [6, 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 singly charged. That is why we do not introduce the charge decrease interval [12] but we consider the influence of atomic weight A.

When considering the penetration of ACRs into the atmosphere, we calculate the electron production rate within two intervals that pertain to the low-energy range of ionization losses (MeV.g^{-1}.cm^2) following the Bohr–Bethe–Bloch formula. These intervals, which we consider in our model, are as follows [6]:

$$-\frac{1}{\rho}\frac{dE}{dh} = \begin{cases} \dfrac{2.57\times 10^3}{A}E^{0.5} & \text{if } kT \le E \le 0.15 \text{ MeV/nucl} \quad \text{interval 1} \\ \dfrac{231}{A}E^{-0.77} & \text{if } 0.15 \le E \le 200 \text{ MeV/nucl} \quad \text{interval 2} \end{cases}, \tag{2}$$

where A is the atomic weight of ACR particles, $\rho(h)$ (g.cm^{-3}) is the neutral density of the Earth's atmosphere, and E is the kinetic energy of ACRs in MeV/nucl.

These intervals described the part of ionization losses function where ACR spectra are acting. Based on this statement we derived the following expression

for ACR ionization rate submodel:

$$(3)\quad q(h)=\frac{\rho(h)}{Q}\left\{2.57\times10^{3}\int_{E_{\min}}^{0.15}D(E)\,[E_1(h)]^{0.5}\,dE\right.$$
$$\left.+2.57\times10^{3}\int_{0.15}^{E_{0.15;2}(h)}D(E)\,[E_{21}(h)]^{1/2}\,dE+231\int_{E_{0.15;2}(h)}^{200}D(E)\,[E_2(h)]^{-.077}\,dE\right\},$$

where $Q=35$ eV is the energy necessary for the formation of one electron-proton pair, $E_1(h)$, $E_2(h)$ and $E_{21}(h)$ are corresponding interval's energy decrease laws, $D(E)$ is differential spectrum in ($\mathrm{cm}^{-2}.\mathrm{s}^{-1}.\mathrm{sr}^{-1}.\mathrm{MeV}^{-1}$), $E_{\min}$ is energy cut-off which is determined in (1), $E_{0.15;2}(h)$ is the initial energy of particles (before entering of spectrum in the atmosphere), which have energy $E(h)=0.15$ MeV at altitude h (km).

$$(4)\qquad E_{0.15,2}(h)=\left(408.87\tilde{h}+0.15^{1.77}\right)^{0.56}.$$

The contribution of ACR differential spectrum to the electron production is determined by the geomagnetic and atmospheric cut-offs. Its lower boundary for the given point in the Earth's atmosphere is calculated by equation [6, 9, 12]:

$$(5)\qquad E_{\min}=\max\{E_R(\lambda_m),E_A(\tilde{h})\}.$$

Here $E_R(\lambda_m)$ is the geomagnetic cut-off in GeV which depends on geomagnetic latitude λ_m as follows [6, 9]:

$$(6)\qquad E_R(\lambda_m)=\left(14.9\left(\mathrm{Cos}\left[\frac{\pi\lambda_m}{180}\right]^4\right)^2+0.88\right)^{1/2}-0.938,$$

where 0.938 is the rest energy of proton. $E_A\tilde{h}$ is atmospheric cut-off which depends on the travelling substance path $\tilde{h}$ ($\mathrm{g.cm}^{-2}$) [4, 5]. For the first interval in (1) it has the form:

$$(7)\qquad E_{A1}(h)=\left((kT)^{0.5}+1285\tilde{h}\right)^2.$$

The kinetic energy transformations described in equation (3) are as follows: $E_1(h)$ represents the kinetic energy decrease within interval 1, $E_{21}(h)$ represents the kinetic energy decrease when crossing the boundary between interval 1 and interval 2, and $E_2(h)$ represents the kinetic energy decrease within interval 2. These transformations are applicable for the specific height h in the Earth's atmosphere.

Computer code and mathematical program. We have implemented a computer code for the CORSIMA model using advanced computational techniques [13, 14]. The code utilizes numerical methods to solve integration problems

arising from the mathematical expressions involved in the model. This operational model allows for interactive computation, where users can input the required data and obtain computational results for different altitudes and specified geomagnetic latitudes. The code has been designed to be user-friendly, providing an intuitive interface for users to easily navigate and interact with the model.

Results. Evidence that the anomalous component is singly ionized is given in [15]. Figures 1–4 present the spectra of the main ACR species, namely the singly charged particles: Helium (Fig. 1), Oxygen (Fig. 2), Hydrogen (Fig. 3), and Nitrogen (Fig. 4). The spectra are specifically calculated for a geomagnetic latitude of $\lambda_m = 90°$. 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. 3), while below 40 km, the helium spectra decrease due to the influence of the atmospheric cut-off (Fig. 1). Notably, the helium and oxygen spectra exhibit the most prominent intensities among the ACR species.

These figures 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. Figures 1–4 clearly demonstrate the difference in intensity between these two altitudes, with a higher intensity observed at 50 km compared to 40 km.

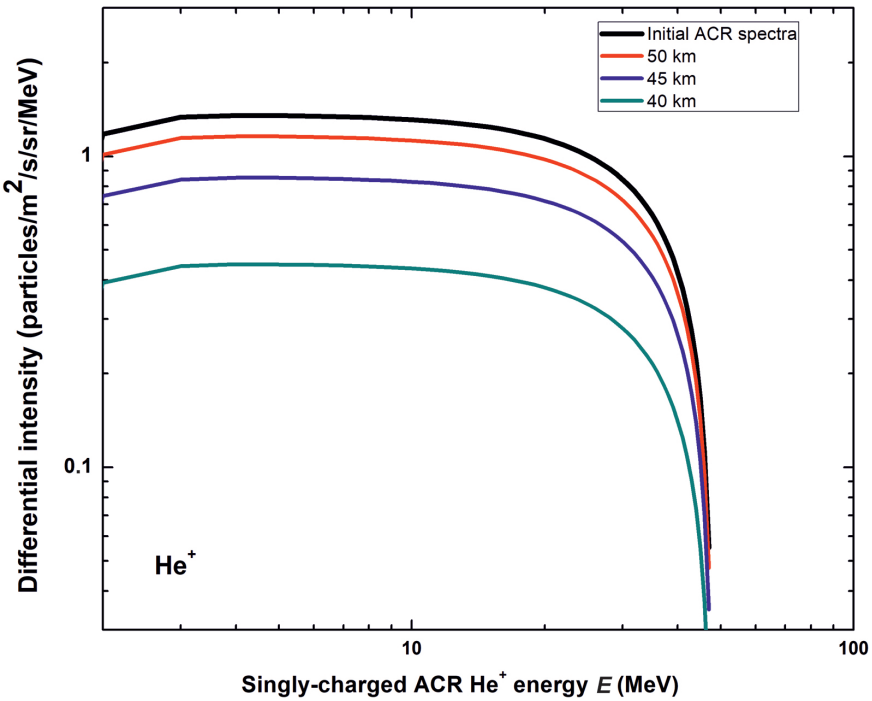


Fig. 1. ACR spectra of singly charged Helium atoms (He^+) at altitudes ranging from 40 km to 50 km

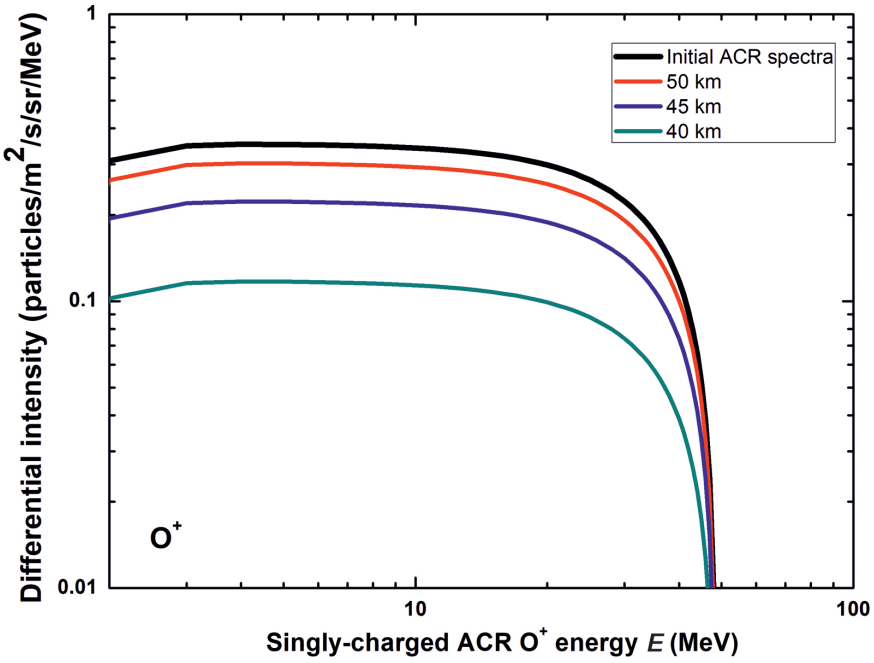


Fig. 2. ACR spectra of singly charged Oxygen atoms (O^+) at altitudes ranging from 40 km to 50 km

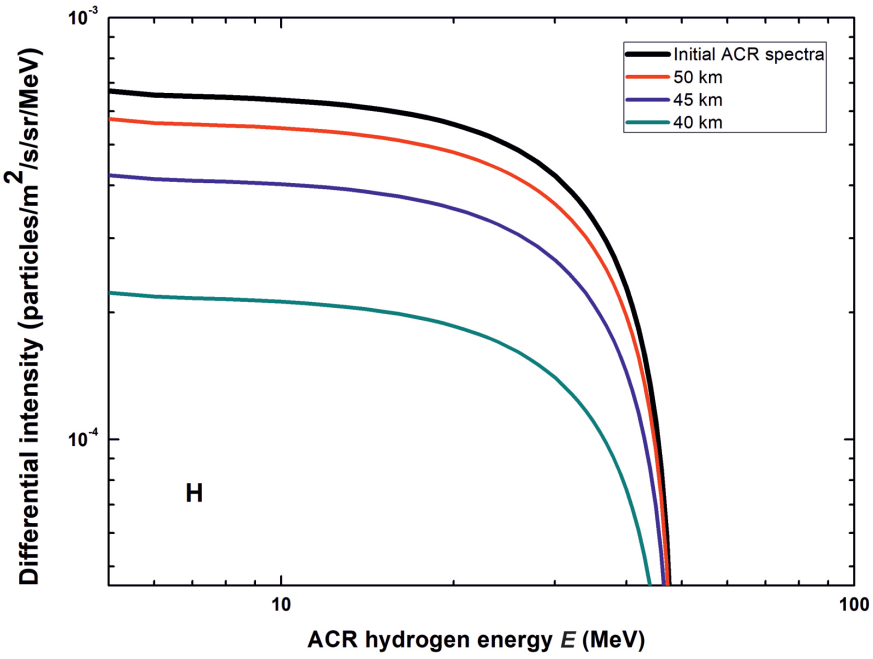


Fig. 3. ACR spectra of Hydrogen (H) at altitudes ranging from 40 km to 50 km

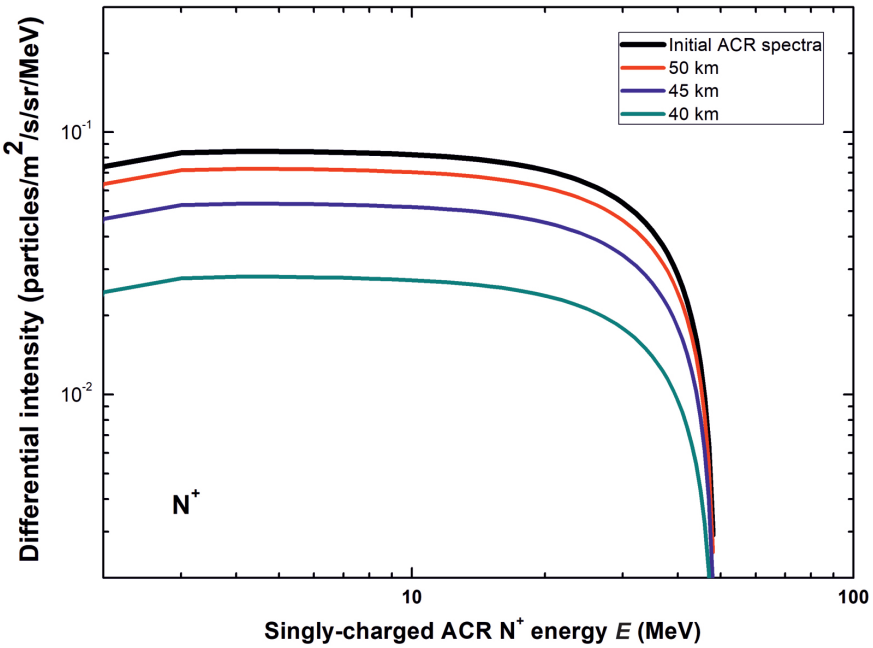


Fig. 4. ACR spectra of singly charged Nitrogen atoms (N^+) at altitudes ranging from 40 km to 50 km

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 this study, we have investigated the spectra of ACRs in the polar cap regions of the Earth's atmosphere at an altitude of 40–50 km. Our analysis focused on the main ACR species, including Helium, Oxygen, Hydrogen, and Nitrogen. We utilized the CORSIMA mathematical program to determine the ACR spectra, taking into account the processes of ionization and possible scattering.

At an altitude of 40–50 km in the Earth's atmosphere, the primary physical process that affects the ACR spectrum is ionization. As ACR particles collide with atmospheric molecules, they can ionize them and produce secondary particles such as electrons and other ions. This process leads to energy loss and the redistribution of ACR particles, thereby modifying their energy spectrum.

Scattering is also a possible process that can affect the ACR spectrum at this altitude range, but its contribution is likely to be smaller compared to ionization. Adiabatic cooling and nuclear interactions are not expected to have a significant impact on the ACR spectrum in this altitude range.

Our results demonstrate that the ACR impact is limited to the polar cap region above a geomagnetic latitude of $\lambda_m = 62°$–$63°$. The obtained ACR spectra

for different species show distinct characteristics, with variations in intensity and shape.

In future studies, we aim to expand our model to include the effects of Multiply Charged Anomalous Cosmic Rays (MCACRs) with $Z > 1$ [16]. The mentioned models CORSIMA and CORIMIA can be applied in space physics for the complex study of the solar-terrestrial connections and space weather [17–20].

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