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SPECTRA OF ANOMALOUS COSMIC RAYS IN THE ATMOSPHERE. SINGLY IONIZED AND MULTIPLY CHARGED ACR COMPONENTS

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Abstract

The Anomalous Cosmic Ray (ACR) spectra and intensity in the middle atmosphere are determined using the CORSIMA (COsmic Ray Spectra and Intensity in Middle Atmosphere) 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 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. Our studies also consider Multiply Charged Anomalous Cosmic Rays (MCACRs), which exhibit similar differential spectra to the singly ionized ACR component4.

Introduction

In 1972 and 1973 several groups observed during solar quiet times enhanced fluxes of helium, oxygen, and nitrogen at energies of ≈10 MeV/nuc (N, O) and ≈ <50 MeV/nuc (He), respectively. These flux increases showed peculiar elemental abundances and energy spectra, e.g. a C/O ratio ≤ 0.1 at ≈10 MeV/nuc, significantly different from the abundances of Solar Cosmic Rays (SCR) and Galactic Cosmic Rays (GCR). Since then, this “Anomalous” Cosmic Ray (ACR) component has been studied extensively and several elements have been found (He, N, O, Ne, Ar, and, to a lesser extent, H and C) whose energy spectra show anomalous increases above the quiet time solar and galactic energetic particle spectrum. There have been several models proposed to explain the ACR component. The presently most plausible theory for the origin of ACR ions identifies neutral interstellar gas as the source material. After penetration into the inner heliosphere, the neutral particles are ionized by solar UV radiation and by charge exchange reactions with the solar wind protons. After ionization, the now singly charged ions are picked up by the interplanetary magnetic field and are convected with the solar wind to the outer solar system.

There 0the ions are accelerated to high energies, possibly at the solar wind termination shock, and then propagate back into the inner heliosphere. A unique prediction of this model is that ACR ions should be singly ionized. Meanwhile, several predictions of this model have been verified, e.g. low energy pickup ions have been detected and the single charge of ACR ions in the energy range of ≈10 MeV/nucleon has been observed [1, 2, 3]. Later, Multiply Charged Anomalous Cosmic Rays (MCACRs) were discovered.

In this paper, the spectra and intensities of ACRs will be calculated using our CORSIMA (COsmic Ray Spectra and Intensity in Middle Atmosphere) model. 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 behavior 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 (MeV.g^{-1}.cm^{2}) according to the Bohr-Bethe-Bloch function using experimental data [6–8]. This approximation for protons and singe charge particles (Z = 1) has the form [9]:

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

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 ionization in the middle atmosphere, we utilize satellite measurements of differential spectra, with a particular emphasis on ACR spectra in this study. By 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 ionization in the middle atmosphere.

Model description for single ionized 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 don’t 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]:

$$-\frac{1}{\rho}\frac{dE}{dh}=\begin{cases}\dfrac{2.57\times 10^{3}}{A}E^{0.5} & \text{if } kT\le E\le 0.15\,\text{MeV/nucl} \qquad \text{interval1}\\ \dfrac{231}{A}E^{-0.77} & \text{if } 0.15\le E\le 200\,\text{MeV/nucl} \qquad \text{interval2}\end{cases} \tag{2}$$

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

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

$$q(h)=\frac{\rho(h)}{Q}\Big\{2.57\times 10^{3}\int_{E_{\min}}^{0.15}D(E)\,\{[E_1(h)]^{0.5}+ \\ 2.57\times 10^{3}\int_{0.15}^{E_{0.15;2}(h)}D(E)[E_{21}(h)]^{1/2}dE+ \\ 231\int_{E_{0.15;2}(h)}^{200}D(E)[E_2(h)]^{-.077}dE\Big\} \tag{3}$$

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 the differential spectrum in ($cm^{-2}.s^{-1}.sr^{-1}.MeV^{-1}$). 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).

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

The contribution of the ACR differential spectrum to 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 with equation [6, 9, 12]:

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

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

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

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

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

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 and 2 present the spectra of the main ACR species, namely the singly charged particles: Helium (Fig. 1) and Oxygen (Fig. 2). The spectra are specifically calculated for a geomagnetic latitude of $\lambda_m = 90^o$. In the lower portion of the profiles, the helium spectra are primarily affected by the atmospheric cut-offs. 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 ACR spectra with altitude, specifically between 50 and 40 km in the Earth's atmosphere. Figures 1 and 2 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.

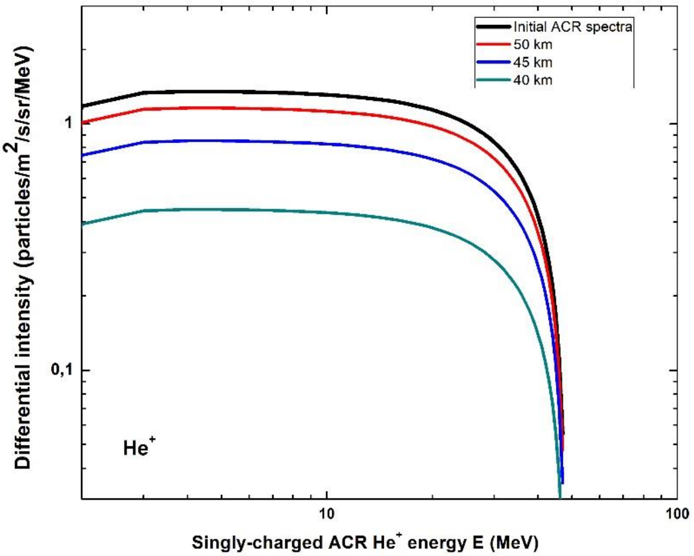

Fig. 1. Energy Spectrum of Singly-charged ACR He^{+} Particles at Different Altitudes

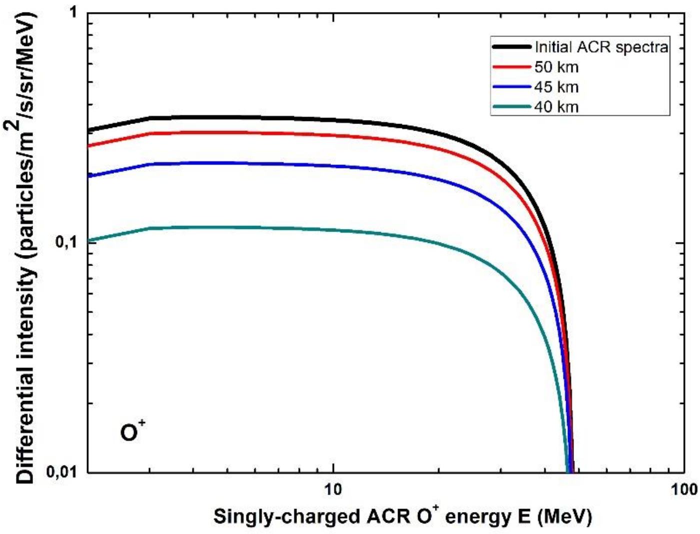

Fig. 2. Energy Spectrum of Singly-charged ACR O^{+} Particles at Different Altitudes

Model description for multiply charged 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, i.e. we have the case of MCACRs [16]. That is why we introduce the charge decrease interval [12]. We consider also the influence of atomic weight A.

When considering the penetration of MCACRs into the atmosphere, we calculate the electron production rate within three intervals that pertain to the low-energy range of ionization losses (MeV.g^{-1}.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 loss function becomes more general than the case $Z = 1$ [10]

(8) $$-\frac{1}{\rho}\frac{dE}{dh} = \begin{cases} 2.57\cdot 10^{3} E^{0.5} & \text{if } kT \le E \le 0.15 \text{ MeV/n}, \quad \text{interval 1} \\ 1540 E^{0.23} & \text{if } 0.15 \le E \le E_a = 0.15Z^2 \text{ MeV/n}, \quad \text{interval 2} \\ 231\cdot Z^2 E^{-0.77} & \text{if } E_a \le E \le 200 \text{ MeV/n}, \quad \text{interval 2} \end{cases}$$

The electron production rate expression is characterized by the following main terms:

(9) $$q(h) = \frac{\rho(h)}{Q}\Bigg\{ 2.57\cdot 10^{3} \int_{E_{\min}}^{0.15} D(E)[E_1(h)]^{0.5} dE + 2.57\cdot 10^{3} \int_{0.15}^{E_{0.15;2}(h)} D(E)\,[E_{21}(h)]^{0.5} dE + 1.54\cdot 10^{3} \int_{0.15;2(h)}^{E_a} D(E)\,[E_2(h)]^{0.23} dE + 1.54\cdot 10^{3} \int_{E_a}^{E_{a;3}(h)} D(E)\,[E_{32}(h)]^{0.23} dE + 231\cdot Z^2 \int_{E_{a;3}}^{200} D(E)\,[E_3(h)]^{-0.77} dE$$

where $Q = 35$ eV is the energy necessary to form one electron-proton pair [xxx]; $\rho(h)$ 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. $D(E)$ is the differential spectrum in (cm^{-2}.s^{-1}. st^{-1}.MeV^{-1}). $E_{\min}$ is the energy cut-off. $E_{0.15;2}(h)$ and $E_{a;3}$ 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]. We present now the initial energies of the interval boundaries which are effective for the electron production rate by MCACR expressed in formula (10). It depends namely on the depth of penetration in the atmosphere. The initial energy for $E_{\min} = kT$, when it is situated in interval 2 from (9) is the following:

(10) $$E_{A2}(h) = \left(0.15^{1.77} + 408.87\tilde{h} - 0.318(0.15^{0.5} - (kT)^{0.5})\right)^{0.56}$$

This initial energy is situated in interval 1 from (9), it is given by formula (8).

The initial energy of the boundary E_a before the spectrum penetration in the atmosphere is given by formula (12):

(11) $$E_{a,3}(h) = \left(200^{1.53} + \frac{104.04Z^2}{A}\tilde{h} - 0.25(200^{1.77} - E_a^{1.77})\right)^{0.65}$$

Conclusion

In this study, we have investigated the spectra of ACRs and MCACRs 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 and Oxygen. 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 λ_m = 62º-63º. The obtained ACR spectra for different species show distinct characteristics, with variations in intensity and shape.

The mentioned models CORSIMA and CORIMIA, as also CORSIKA can be applied in space physics for the complex study of the solar-terrestrial connections and space weather [17–21].

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СПЕКТРЫ АНОМАЛЬНЫХ КОСМИЧЕСКИХ ЛУЧЕЙ В АТМОСФЕРЕ. ОДНОИОНИЗОВАННЫЕ И МНОГОЗАРЯДНЫЕ КОМПОНЕНТЫ АКЛ

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Абстракт

Спектры и интенсивности Аномальных Космических Лучей (АКЛ) в средней атмосфере определяются с использованием модели CORSIMA (COsmic Ray Spectra and Intensity in Middle Atmosphere). Спектры АКЛ представлены для различных высот атмосферы в диапазоне 40–50 км, с нижней границей ионосферы примерно на 50 км. Экспериментальные спутниковые измерения используются для определения основных компонентов ACR: ядер гелия и кислорода. Установлено, что влияние АКЛ распространяется на области полярной шапки выше 65°-70° геомагнитной широты, а некоторые значения скорости ионизации АКЛ в этих регионах сравнимы со скоростями ионизации Галактических Космических Лучей (ГКЛ). В наших исследованиях также рассматриваются многозарядные аномальные космические лучи (MCACR), которые имеют дифференциальные спектры, аналогичные одноионизованному компоненту АКЛ.