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EXPLORING THE DIFFERENTIAL SPECTRA OF GALACTIC, SOLAR AND ANOMALOUS COSMIC RAYS PENETRATING INTO THE ATMOSPHERE

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ABSTRACT

The influence of Multiply Charged Anomalous Cosmic Rays (MC ACRs), 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 (**CO**smic **R**ay **S**pectra and **I**ntensity in **M**iddle **A**tmosphere) 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.

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 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 united model CORIMIA - CORSIMA is further development of the previous models [112,13]. 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].

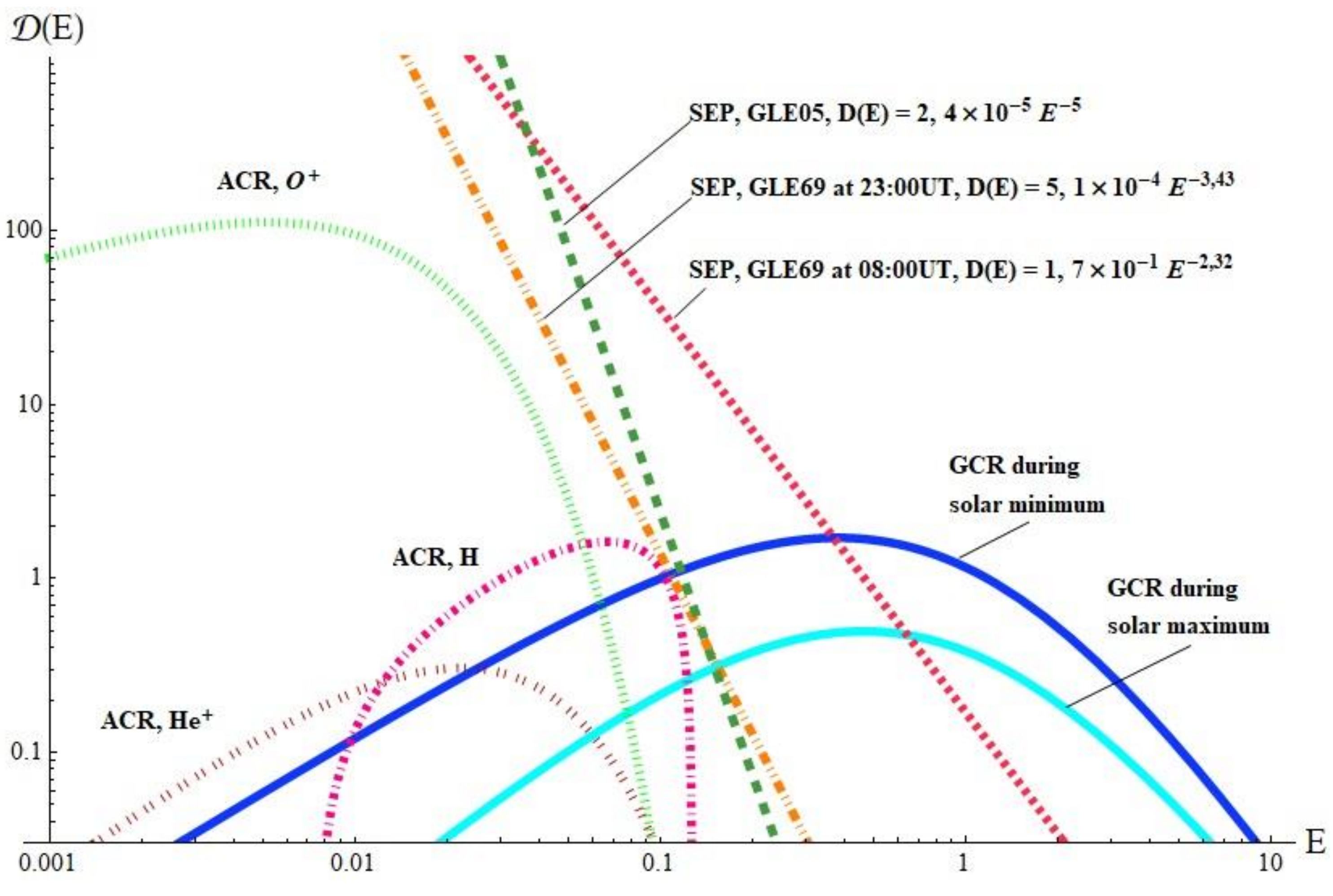

Fig.1. Differential spectra of solar cosmic rays (SCRs) during GLE 05 and GLE 69 (8:00UT and 23:00UT). Here for comparison are presented also galactic cosmic ray (GCR) spectra during solar maximum (light blue) and solar minimum (dark blue) and anomalous cosmic ray (ACR) spectra for O^+, He^+ and H^+.

MC ACR Investigation. 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/nucl 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/nucl (e. However, using data from the Solar, Anomalous, and Magnetospheric Explorer (SAMPEX), Mewaldt et al. [11] found that at energies ≥25 MeV/nucl most ACRs have an ionic charge Q ≥ 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/nucl. The observed fraction (~20%) of multiply-charged to singly-charged O implies that ACRs are accelerated to 10 MeV/nucl within 1-2 years.

Model approximations. We introduce six main characteristic energy intervals in the approximation of ionization losses (MeV.g^{-1}.cm^2) according the Bohr-Bethe-Bloch function using experimental data [12,13]. This approximation for multi charge ACR nuclei (Z > 1) is the following:

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

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 2^* 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 atmosphereOur 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].

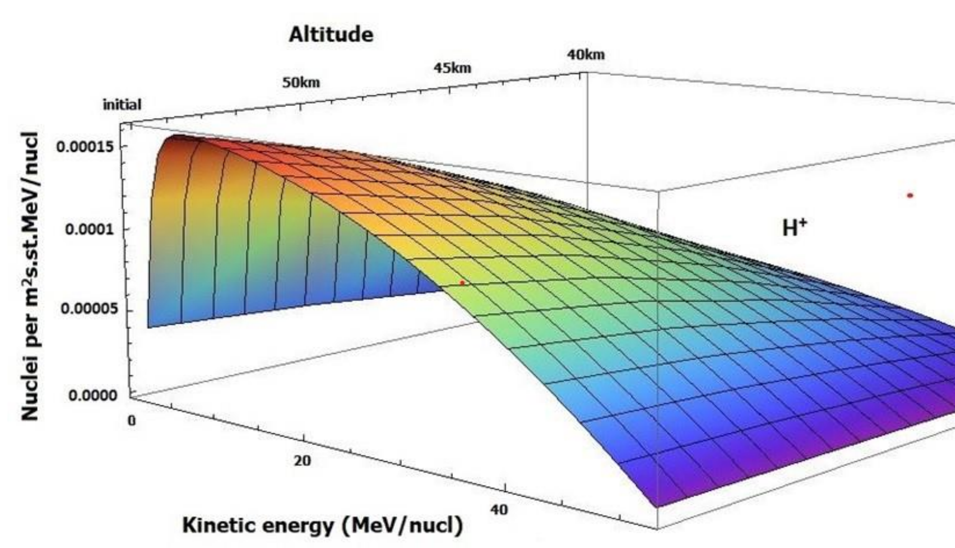

Fig.3. Modeled altitude-dependent differential spectra of hydrogen protons (H+) in anomalous cosmic rays (ACRs), showing flux variation with kinetic energy and altitude in Earth's stratosphere.

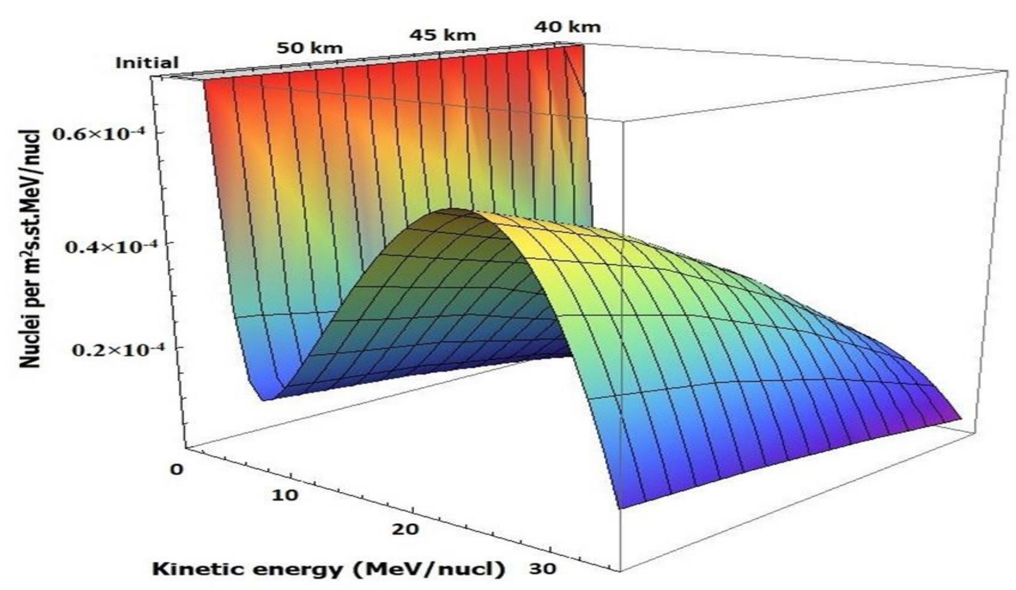

Fig.4. Altitude-dependent modeled differential spectra of helium nuclei (He) in anomalous cosmic rays (ACRs), illustrating flux variation with kinetic energy and altitude in Earth's stratosphere

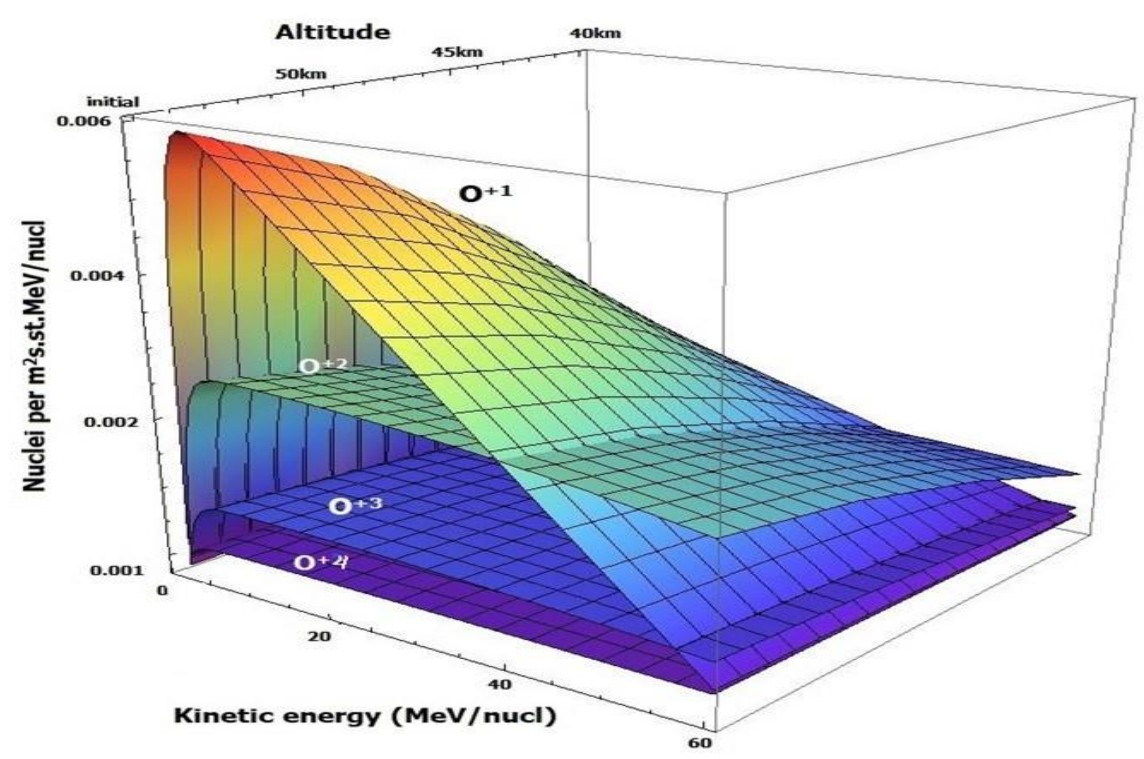

Fig.5. Modeled altitude-dependent differential spectra of multi-charged oxygen nuclei in anomalous cosmic rays (ACRs), showing flux variation with kinetic energy and altitude in Earth's stratosphere.