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Cosmic ray spectra and intensity in middle atmosphere (CORSIMA) model. Use and application for galactic cosmic rays

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This investigation is based on a new model CORSIMA (COsmic Ray Spectra and Intensity in Middle Atmosphere). Numerical simulations of Galactic Cosmic Ray (GCR) spectra and intensity for the middle atmosphere and lower altitudes of the ionosphere (30-80 km) are presented. These altitudes are above the Regener-Pfotzer maximum. The full GCR composition (protons p, alpha particles α, and heavier nuclei groups: light L, medium M, heavy H, very heavy VH) is used [1]. Analytical expressions for the energy interval contributions are provided. An approximation of the ionization function on six energy intervals is used and the charge decrease interval for electron capture is studied.

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

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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 [2, 3], eventually leading to an ionization and excitation of the ambient air [4]. The induced by cosmic rays atmospheric ionization is related to possible effect of precipitating particles on atmospheric physics and chemistry [5–8].

The investigation of ionization processes in atmosphere is important for better understanding of space weather and space climate mechanisms [9]. The Galactic Cosmic Ray (GCR) influence the ionization and therefore into the electrical parameters in the planetary atmospheres. They change also the chemical processes - for example ozone creation and depletion in the Earth's stratosphere. On this way they transfer the impact of solar activity into the atmosphere [9, 10].

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 [11–16], which determines GCR electron production rate in the middle atmosphere.

2. Cosmic Ray Induced Ionization (CRII)

The detailed model for calculating the CRII rate ($cm^{-3}s^{-1}$) in the middle atmosphere is described in [11–16]. The mathematical expression of the model is as follows:

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

where A is the azimuth angle, θ is the angle towards the vertical, $\triangle\theta$ takes into account that at a given height the particles can penetrate from the space angle (0°, θ_{max}max=90°+$\triangle\theta$), which is greater than the upper hemisphere angle (0°, 90°) 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 eV is the energy which is necessary for formation of one electron-ion pair.

$D_i(E)$ is corresponding differential spectrum ($cm^{-2}.s^{-1}.st^{-1}.MeV^{-1}$) which in the case of GCR is calculated as follows [17–19]:

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

Here the first multiplier $K(0.939 + E)^{-\gamma}$ presents the GCR spectrum with kinetic energy E (GeV/nucl). 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 [17–19].

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3. Model approximations

We introduce five main characteristic energy intervals and a charge decrease interval for electron capture in the ionization losses approximation (MeV.g^{-1}.cm^{2}) according to the Bohr-Bethe-Bloch function using experimental data [11–13]. This approximation for protons (Z=1) has the form:

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

In this way, the accuracy of the obtained results is improved compared to the case of lower number of characteristic energy intervals [15, 16].

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 Section.

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,. . . ,6); boundary crossing of two limits ($E_{j,j-2}$, for j=3,. . . ,6); boundary crossing of three limits ($E_{k,k-3}$, for k=4,. . . ,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 intersect 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 [11–13]. The next expressions cited above describe the more complex cases – "boundary crossing of more than one limit".

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

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

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).

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 [11–13]. 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:

$$\tilde{h} = \tilde{h}_2 + \tilde{h}_3 = \frac{A}{1185}\left(E_a^{0.77} - 0.15^{0.77}\right) + \frac{A}{408.87Z^2}\left(E_{0.15,3}^{1.77} - E_a^{1.77}\right). \tag{5}$$

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 (5) reaches the reduced value 0.15 MeV/n at height h. It is the following formula (6):

From (5) we obtained the new transformation:

$$E_{0.15,3}(h) = \left[E_a^{1.77} + 408.87\frac{Z^2}{A} \times \tilde{h} - 0.345Z^2\left(E_a^{0.77} - 0.15^{0.77}\right)\right]^{1/1.77}. \tag{6}$$

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:

$$E_{E_a,4}(h) = \left[200^{1.53} + 104.04\frac{Z^2}{A} \times \tilde{h} - 0.254\left(200^{1.77} - E_a^{1.77}\right)\right]^{1/1.53}, \tag{7}$$

$$E_{200,5}(h) = 850 + 1.91\frac{Z^2}{A} \times \tilde{h} - 0.018\left(850^{1/1.53} - 200^{1/1.53}\right), \tag{8}$$

$$E_{850,6}(h) = \left[5000^{0.877} + 0.579\frac{Z^2}{A} \times \tilde{h} - 0.303\,(5000 - 850)\right]^{1/0.877}. \tag{9}$$

All energies are given in MeV/nucl. The expressions (6 - 9) represent the crossing of one interval energy boundary – namely $E_a = 0.15Z^2$, 200, 850, 5000 (MeV/n) by the traveling 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 [1].

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) [1] and for different

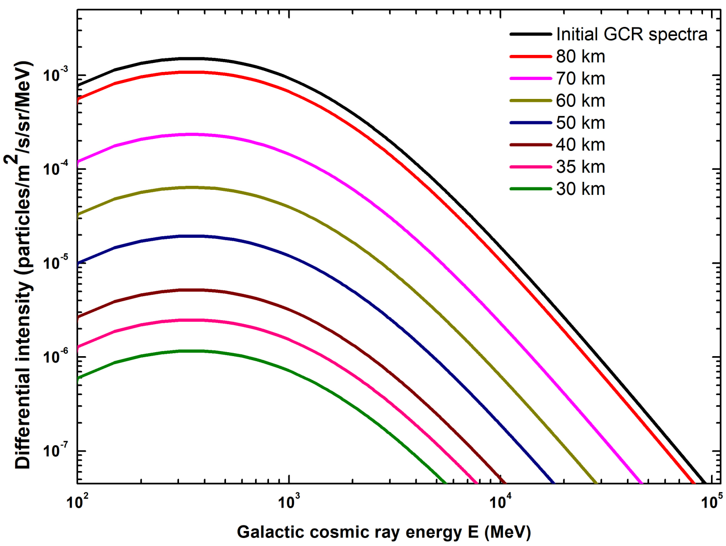

Figure 1: Differential spectrum of GCR protons at different altitudes in the area of 30-80 km a.s.l.

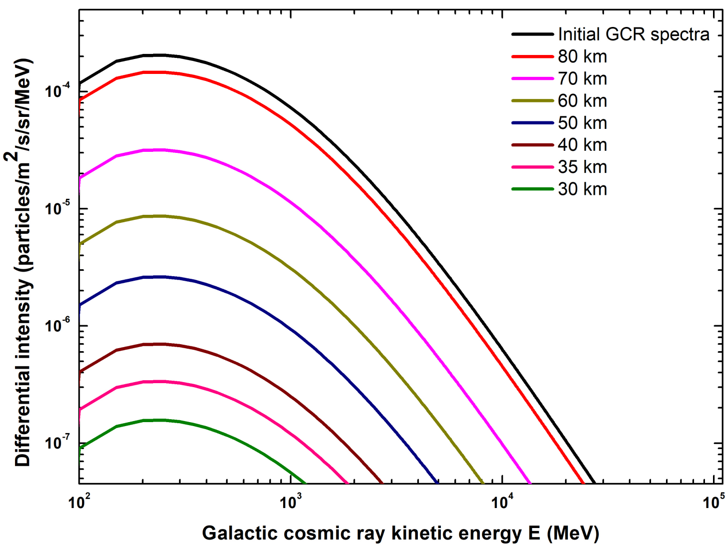

Figure 2: Differential spectrum of GCR helium nuclei (alpha particles) at different altitudes in the area of 30-80 km a.s.l.

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 Figures 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 it can be seen on Figs. 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 [15–19]. The model can be applied to different input spectra in interactive mode and different planetary atmospheres.

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-Pfotzer maximum. That is why we use the CORSIKA (COsmic Ray SImulations for KAscade) nuclear cascade model there [6, 7, 15, 20–22].

The results obtained in the present work are important for solving problems of space physics and space weather [23–26]. They tie in with the latest developments on these topics and provide a quantitative assessment of the influence of cosmic rays on the mechanisms of solar-terrestrial connections [27–33].

References

[1] V.L. Ginzburg and S.I. Sirovatsky, *The origin of cosmic rays. Publishing House of the USSR Academy of Sciences, Moscow,* (1963), 385.

[2] I. Usoskin, L. Desorgher, P.I.Y. Velinov, M. Storini, E. Flueckiger, R. Buetikofer and G. Kovalstov, *Ionization of the Earth's atmosphere by solar and galactic cosmic rays, Acta Geophys.* **57** (2009), no. 1 88–101.

[3] G. Gronoff, C. Mertens, J. Lilensten, L. Desorgher, E. Fluckiger and P.I.Y. Velinov, *Ionization processes in the atmosphere of Titan-III. Ionization by high-Z nuclei cosmic rays, Astron. Astrophys.*, **529** (2011), A143.

[4] P.I.Y. Velinov, H. Ruder, L. Mateev, M. Buchvarova and V. Kostov, *Method for calculation of ionization profiles caused by cosmic rays in giant planet ionospheres from Jovian group, Adv. Space Res.* **33** (2004), no. 2 232-239.

[5] P.I.Y. Velinov, *ionization in the ionospheric D-region by galactic and solar cosmic rays, J. Atmos. Solar-Terr. Phys.*, **30** (1968), no 11 1891–1905.

[6] P.I.Y. Velinov, A. Mishev and L. Mateev, *Model for induced ionization by galactic cosmic rays in the Earth atmosphere and ionosphere. Adv. Space Res.*, **44** (2009), 1002-1007.

[7] A. Mishev, P. I. Y. Velinov and L. Mateev, *Atmospheric ionization due to solar cosmic rays from 20 January 2005 calculated with Monte Carlo simulations. C. R. Acad. Bulg. Sci.*, **63** (2010), no 11 1635-1642.

[8] N. Kilifarska, Bakmutov V. and G. Melnyk, *The hidden link between Earth's magnetic field and climate, Elsevier Science Publishing*, ISBN: 9780128193464 (2020), 228 p.

[9] I. Tsagouri, A. Belehaki, N. Bergeot, C. Cid, V. Delouille, T. Egorova, N. Jakowski, I. Kutiev, A. Mikhailov, M. Nunez, M. Pietrella, Al. Potapov, R. Qahwaji, Y. Tulunay, P.I.Y.I. Velinov and A. Viljanen, *Progress in space weather modeling in an operational environment, J. Space Weath. Space Clim.*, **3** (2013), A17, 1-72.

[10] M. Abunina, A. Abunin, A. Belov, A. Gaidash, Y. Tassev, P.I.Y. Velinov, L. Mateev and P.Tonev, *Properties of magnetic fields in coronal holes and geoeffective disturbances in solar cycle 24. C. R. Acad. Bulg. Sci.*, **67** (2014), no 5 699-704.

[11] P.I.Y. Velinov and L. Mateev, *Ionization model for cosmic ray protons in the ionosphere and atmosphere with 5 interval approximation of the ionization losses function, C. R. Acad. Bulg. Sci.*, **60** (2007), no 8 839-844.

[12] P.I.Y. Velinov, L. Mateev and H. Ruder, *Generalized model of ionization profiles due to cosmic ray particles with charge Z in planetary ionospheres and atmospheres with 5 energy interval approximation of the ionization losses function. C. R. Acad. Bulg. Sci.*, **61** (2008), no 1 133-146.

[13] Velinov P. I. Y. and L. Mateev, *Improved cosmic ray ionization model for the system ionosphere - atmosphere. Calculation of electron production rate profiles. J. Atmos. Solar-Terr. Phys.*, **70** (2008), no 2-4 574-582.

[14] P.I.Y. Velinov, S. Asenovski and L. Mateev, *Improved COsmic Ray Ionization Model for the Ionosphere and Atmosphere (CORIMIA) with account of 6 characteristic intervals. C. R. Acad. Bulg. Sci.*, **65** (2012), no 8 1137-1144.

[15] P.I.Y. Velinov, S. Asenovski and L. Mateev, *Numerical calculation of cosmic ray ionization rate profiles in the middle atmosphere and lower ionosphere with relation to characteristic energy intervals. Acta Geophys.*, **61** (2013), no 2 494-509.

[16] P.I.Y. Velinov, S. Asenovski, K. Kudela, J. Lastovicka, L. Mateev, et al., I*mpact of cosmic rays and solar energetic particles on the Earth's ionosphere and atmosphere. Journal of Space Weather and Space Climate*, **3** (2013), A14, pp. 1-17.

[17] P.I.Y. Velinov, H. Ruder, U. Zellhuber and L. Mateev, *A Model for 11-Year cosmic ray variations in the lower ionosphere. C. R. Acad. Bulg. Sci.*, **50** (1997), no 3 39-42.

[18] M. Buchvarova and P.I.Y. Velinov, *Modeling spectra of cosmic rays influencing on the ionospheres of Earth and outer planets during solar maximum and minimum, Adv. Space Res.*, **36** (2005), no 11 2127-2133.

[19] M. Buchvarova and P.I.Y. Velinov, *Empirical model of cosmic ray spectrum in energy interval 1 MeV - 100 GeV during 11 - year solar cycle. Adv. Space Res.*, **45** (2010), no 8 (1) 1026-1034.

[20] A. Mishev and P.I.Y. Velinov, *Determination of medium time scale ionization effects at various altitudes in the stratosphere and troposphere during Ground Level Enhancement due to solar cosmic rays on 13.12.2006 (GLE 70) C. R. Acad. Bulg. Sci.* **68** (2015), no 11 1425-1430.

[21] A. Mishev and P.I.Y. Velinov, *Ionization effect due to cosmic rays during Bastille day event – GLE 59 on short and mid time scales, C. R. Acad. Bulg. Sci.* **69** (2016), no 11 1479-1484.

[22] A. Mishev and P.I.Y. Velinov, *Ionization effect in the region of Regener–Pfotzer maximum due to cosmic rays during Halloween GLE events In October–November 2003, C. R. Acad. Bulg. Sci*. **73** (2020), no 2 244-251.

[23] R. Bojilova and P. Mukhtarov, *Relationship between the critical frequencies of the ionosphere over Bulgaria and geomagnetic activity. C. R. Acad. Bulg. Sci.*, **73** (2020), no 8 1113-1122.

[24] P.I.Y. Velinov, Y. Tassev and D. Tomova, *Study of unpredicted first geomagnetic storm of 2020, due to interaction of ICME with near Earth space on April 20, C. R. Acad. Bulg. Sci.*, **73** (2020), no 11 1571-1578.

[25] P.I.Y. Velinov and A. Mishev, *Influence of Forbush effect on atmospheric ionization due to solar energetic particles, C. R. Acad. Bulg. Sci.*, **74** (2021), no 6 868-878.

[26] B. Andonov, R. Bojilova and P. Mukhtarov, *Global distribution of total electron content response to weak geomagnetic activity, C. R. Acad. Bulg. Sci.*, **74** (2021), no 7 1032-1042.

[27] P.I.Y. Velinov and L. Mateev, *Modelling of the maximum spectrum of cosmic rays and their ionization during the minimums of solar cycles 23/24 and 24/25, C. R. Acad. Bulg. Sci.*, **74** (2021), no 12 1789-1798.

[28] P.I.Y. Velinov, *Major X-Class solar flare from Earth-facing active region AR12887 on October 28, 2021 and first cosmic Ray GLE 73 in solar cycle 25, C. R. Acad. Bulg. Sci.*, **75** (2022), no 2 248-258.

[29] A. Mishev and P.I.Y. Velinov, Global maps of galactic cosmic ray induced ionization at different altitudes in planetary atmosphere, C. R. Acad. Bulg. Sci., **75** (2022), no 5, 700-708.

[30] P.I.Y. Velinov, *Derivation of a formula for electron production rate in the ionosphere under the influence of cosmic rays. C. R. Acad. Bulg. Sci.*, **19** (1966), no 2, 109-112.

[31] S. Asenovski and L. Mateev, *Determination of the spectra and ionization of anomalous cosmic rays in polar atmosphere, C.R. Acad. Bulg. Sci.* **66** (2013), no. 6 865 - 870.

[32] A. Mishev and P. I.Y.Velinov, *Time evolution of ionization effect due to cosmic rays in terrestrial atmosphere during GLE 70. Influence of low energy hadron interaction models on atmospheric ionisation due to cosmic ray heavy nuclei, C.R. Acad. Bulg. Sci.* **67** (2014), no. 6 843 - 854.

[33] P.I.Y. Velinov, L. Mateev and N. Kilifarska, *3-D model for cosmic ray planetary ionisation in the middle atmosphere, Annales Geophysicae* **23** (2005), no. 9, 3043 - 3046.