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COSMIC RAY SPECTRUM AND INTENSITY IN MIDDLE ATMOSPHERE (CORSIMA) MODEL. USE AND APPLICATION FOR SOLAR COSMIC RAYS

Peter Velinov, Simeon Asenovski, Lachezar Mateev

Space Research and Technology Institute – Bulgarian Academy of Sciences

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Abstract

The new model CORSIMA (COsmic Ray Spectrum and Intensity in Middle Atmosphere) is presented. The spectra and intensities of solar cosmic rays (SCR) from GLE (Ground Level Enhancement) 05 on 23 February 1956 and GLE 69 on 20 January 2005 at different altitudes are calculated. For this purpose, the operational CORSIMA model is applied. In the final version of the CORSIMA program, an approximation in 6 characteristic energy intervals of the Bohr-Bethe-Bloch function is used, including the charge decrease interval. Analytical expressions for the contributions of the energy intervals are provided. For the first time we present a quantitative and qualitative appreciation of the impact of Solar Cosmic Rays (SCRs) from the Solar Particle Events (SPEs) on the ionosphere and middle atmosphere (30 - 80 km). These altitudes are above the Regener-Pfotzer maximum. Unlike Galactic Cosmic Rays (GCR), the differential spectra of SCR essentially vary in time. The SCR fluxes also differ from each other during the different events. The spectrum and intensity behavior is explained considering the structure of the CORSIMA program. The calculation results are in agreement with the experimental data and show characteristic features of the propagation process for different altitudes and geomagnetic latitudes. The calculations are performed for geomagnetic latitudes 90^o (cusp region). The development of this research is important for the processes and mechanisms of space weather.

Introduction

The relativistic particles of cosmic rays (protons and heavier nuclei of galactic and/or solar origin) [1, 2] induce complicated nuclear-electromagnetic-lepton cascades in the atmospheres of the Earth, planets and their moons [3–11], which eventually lead to ionization and excitation of the planetary environment. The ionization of the atmosphere caused by cosmic rays determines the effects of the precipitating particles on the physics and chemistry of the atmosphere [12–14].

Solar cosmic rays are an important factor in the ionization and energetic state of the ionosphere and atmosphere [1–4, 6, 14]. The new model CORSIMA (COsmic

Ray Spectrum and Intensity in Middle Atmosphere) is presented in this paper. CORSIMA is a submodel of CORIMIA (COsmic Ray Ionization Model for Ionosphere and Atmosphere) [15–19].

This paper presents the results of the CORSIMA program with application to GLE (Ground Level Enhancement) 05 on February 23, 1956 and GLE69 on January 20, 2005. Similar analyzes for GLEs 59, 69 and 70 are given in [20–23].

Spectra and electromagnetic interactions of SCRs

The corresponding differential spectra for GLE 69 were taken from the available GOES satellite data [22]. We investigate the SCR effects in the polar cusp region at geomagnetic latitudes of 90^o during two of the strongest Solar Proton Events (SPEs) observed since the beginning of neutron monitor measurements of cosmic rays. In this way the extreme influence of solar activity on the ionization state of the ionosphere and middle atmosphere is calculated.

In contrast to the GCR cases, the SCR differential spectra essentially vary in time over the course of the event studied [24, 25]. It is difficult to generalize about the global impact of SCR on atmospheric chemistry and electrical conductivities for the entire time period. Therefore, it is useful to consider more than one-time point of the effects of SCR. In the case of GLE 69, we consider two characteristic time points – at 8:00UT and 23:00UT during SCR penetration. The corresponding differential spectrum in $cm^{-2}.s^{-1}.MeV^{-1}$ outside the atmosphere (according to GOES data) for the time at 8:00UT is:

(1) $$D(E) = 1{,}55 \times 10^{6} E^{-2{,}32},$$

and for the time point at 23:00UT is:

(2) $$D(E) = 10^{7} E^{-3{,}43}.$$

The differential spectrum for GLE 05 [3] is:

(3) $$D(E) = 2{,}4 \times 10^{10} E^{-5}.$$

These spectra are determined in the following way. For each spectrum (1) and (2), two data points are taken from the GOES data. They belong to different energy intervals of the measurement as indicated in these data lists. Then a system of equations is solved for the two unknown parameters of the spectrum: the magnitude K and the exponent γ [5].

The CORSIMA program is applied for the first time to the SEP and the results show that it is suitable for calculating the propagation of solar particles. The model embedded in this program includes the full approximation of the Bohr-Bethe-

Bloch ionization losses function [15–19] using 6 characteristic energy intervals for cosmic ray (CR) nuclei groups:

$$(4)\qquad -\frac{1}{\rho}\frac{dE}{dh}=\begin{cases}2.57\times10^{3}E^{0.5} & \text{if } kT\le E\le 0.15\,\text{MeV/n} & \text{, interval 1}\\ 1540E^{0.23} & \text{if } 0.15\le E\le E_a=0.15Z^2\ \text{MeV/n} & \text{, interval 2}\\ 231\times Z^2E^{-0.77} & \text{if } E_a\le E\le 200\,\text{MeV/n} & \text{, interval 3}\\ 68\times Z^2E^{-0.53} & \text{if } 200\le E\le 850\,\text{MeV/n} & \text{, interval 4}\\ 1.91\times Z^2 & \text{if } 850\le E\le 5\times10^{3}\ \text{MeV/n} & \text{, interval 5}\\ 0.66\times Z^2E^{0.123} & \text{if } 5\times10^{3}\le E\le 5\times10^{6}\ \text{MeV/n} & \text{, interval 6}\end{cases}$$

We investigate the case of solar protons penetration (charge Z = 1) into the Earth's atmosphere. That is, the interval 2 is not considered. On the other hand, we show that the last three high energy intervals (above 200 MeV) do not contribute to the ionization rate (GLE 69 at 23:00UT and GLE 05). The last two intervals (the energies above 2 GeV) for GLE 69 at 8:00UT are also without contribution (Fig. 1). Consequently, the dependence of the particle number on the characteristic energy intervals can be seen in Fig.1 (4). For comparison, we also show GCR spectra at solar minimum and maximum and anomalous CR (ACR) spectra for O^+ and He^+ with charge Z = 1, i.e. singly ionized. The ACR spectra are effective below 100 MeV and the GCR spectra - above 1 GeV (relativistic energies).

Model description

The operational model embedded in the CORIMIA program is developed in [15–19]. The mathematical expression for calculating the ionization rate in the atmosphere, including the full composition of CR, is as follows.

$$(5)\qquad q(h)=\sum_i q_i(h)=\frac{1}{Q}\sum_i \int_{E_i}^{\infty}\int_{A=0}^{2\pi}\int_{\theta=0}^{\pi/2+\Delta\theta} D_i(E)\left(\frac{dE}{dh}\right)_i \sin\theta\, d\theta\, dA\, dE,$$

where A is the azimuth angle, θ is the angle towards the vertical, $\Delta\theta$ takes into account that at a given height the particles can penetrate from the space angle (0°, θ_{max}=90°+$\Delta\theta$), 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($3\le Z\le 5$), Medium M ($6\le Z\le 9$), Heavy H ($Z\ge 10$) and Very Heavy VH ($Z\ge 20$) nuclei in the composition of cosmic rays [1-4]. Z is the charge of the nuclei, Q=35eV is the energy which is necessary for formation of one electron-ion pair [6].

$D_i(E)$ is the corresponding SCR differential spectrum for protons which is given in (1) – (3).

Energy cut-offs E_i, which are lower boundary of integration in (5), are calculated on the base of geomagnetic E_R and atmospheric cut-offs E_A for given geomagnetic latitude λ_m and atmospheric altitude (traveling substance path $\tilde{h}$) with the following expression:

$$(6)\qquad E_{\min} = \max\{E_R(\lambda_m), E_A(\tilde{h})\}$$

The geomagnetic cut-off [4] is evaluated in the equation (7):

$$(7)\qquad E_R(\lambda_m) = \left(14.9\left(\mathrm{Cos}\left[\frac{\pi\lambda_m}{180}\right]^4\right)^2 + 0.88\right)^{1/2} - 0.938\,.$$

The atmospheric cut-offs take into account the traveling substance path and for the case of SCR protons (because of the characteristic energy interval ranges [18] take the forms E_{A1} and E_{A2}:

$$(8)\qquad E_{A1}(h) = \left((kT)^{0.5} + 1285\tilde{h}\right)^2,$$

$$(9)\qquad E_{A2}(h) = \left[0.15^{1.77} - \frac{231\times1.77}{1285}\left(0.15^{0.5} - (kT)^{0.5}\right) + 231\times1.77\tilde{h}\right]^{1/1.77}$$

From (5) we obtain the concrete expressions for the electron production rate caused by SCR protons penetration in the atmosphere. From Figure 1, it can be seen that the first three intervals are effective for the contributions to the ionization rate values. They are intervals 1, 3 and 4 in (4) for Z = 1. The energy decrease laws [8] without boundary crossing for these intervals are:

$$(10)\qquad E_1(h) = \left[E_k^{0.5} - 1285\tilde{h}\right]^2,$$

$$(11)\qquad E_2(h) = \left[E_k^{1.77} - 231\times1.77\tilde{h}\right]^{1/1.77}$$

$$(12)\qquad E_3(h) = \left[E_k^{1.53} - 68\times1.53\tilde{h}\right]^{1/1.53}$$

The energy decrease laws with boundary crossing have the form:

(13) $$E_{21}(h)=\left[0.15^{0.5}-1285\tilde{h}+\frac{1285}{231\times1.77}\times\left(E_k^{1.77}-0.15^{1.77}\right)\right]^2$$

Expression (13) is valid if particles with initial energy in interval 2 cross the boundary due to ionization losses and cause ionization with energy in interval 1 at altitude h. Similar expression is derived when particles transfer the boundary between interval 3 and 2:

(14) $$E_{32}(h)=\left[200^{1.77}+\frac{231\times1.77}{68\times1.53}\left(E_k^{1.53}-200^{1.53}\right)-231\times1.77\tilde{h}\right]^{1/1.77}.$$

We also include two coupling intervals for upper boundaries of interval 1 and 3 ($E_{0.15}(h)$, $E_{200}(h)$) which have the form:

(15) $$E_{0.15}(h)=\left[0.15^{1.77}+231\times1.77\tilde{h}\right]^{1/1.77},$$

(16) $$E_{200}(h)=\left[200^{1.53}+1.53\times68\tilde{h}\right]^{1/1.53}.$$

The sub model for SCR protons penetration in the atmosphere is derived in equation (17):

(17) $$\begin{aligned}q(h)=\frac{\rho(h)}{Q}\Bigg\{&2.57\times10^3\int_{E_{\min}}^{0.15}D(E)\left[E_1(h)\right]^{0.5}dE+\\&2.57\times10^3\int_{0.15}^{E_{0.15}(h)}D(E)\left[E_{21}(h)\right]^{1/2}dE+\\&+231\int_{E_{0.15}(h)}^{200}D(E)\left[E_2(h)\right]^{-.077}dE+231\int_{200}^{E_{200}(h)}D(E)\left[E_{32}(h)\right]^{-0.77}dE+\\&+68\int_{E_{200}(h)}^{850}D(E)\left[E_3(h)\right]^{-0.53}dE\end{aligned}$$

This expression is characteristic of SCR differential spectra, because it is restricted to the lower energy intervals of the ionization losses function.

Results and conclusions

The CORSIMA submodel for calculating of SCR penetration in the atmosphere considering the first three characteristic energy intervals (17) is applied to the GLE05 and GLE 69 events. These are the most powerful and well-known

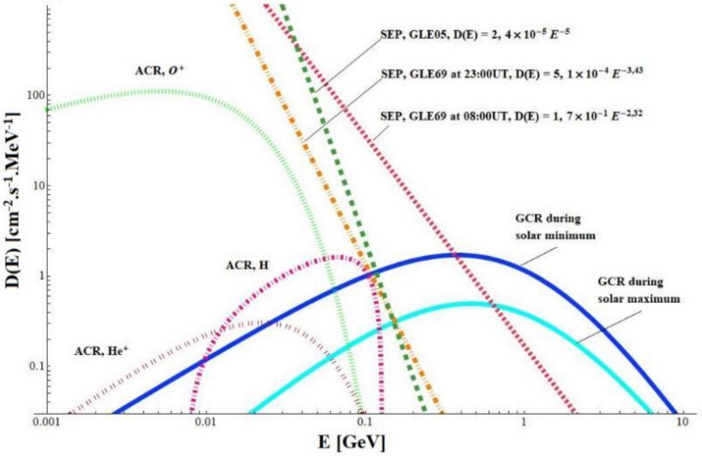

Fig. 1. Differential spectra of solar cosmic rays (SCRs) during GLE 05 and GLE 69 (8:00UT and 23:00UT). Here for comparison are presented also galactic cosmic ray (GCR) spectra during solar maximum (light blue) and solar minimum (dark blue) and anomalous cosmic ray (ACR) spectra for O^+, He^+ and H^+.

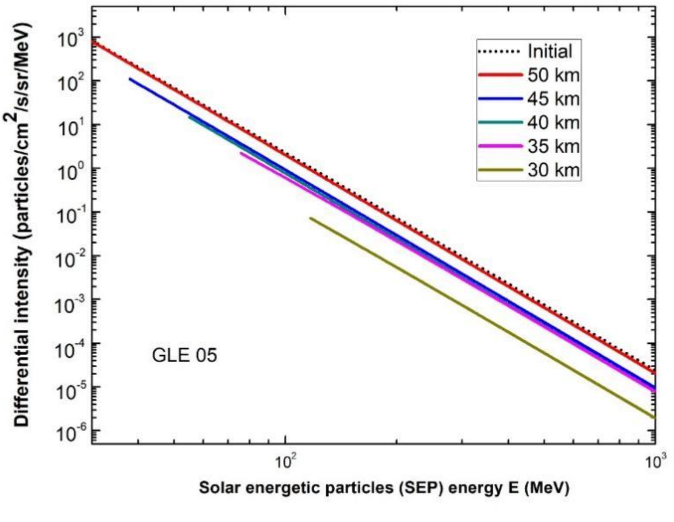

Fig. 2. Solar energetic particles (SCRs) spectrum from SPE event on 23 February 1956 at altitudes 30, 35, 40, 45, 50 km with initial spectrum outside of the atmosphere (dotted curve), this is the most powerful solar proton event in the history of space era

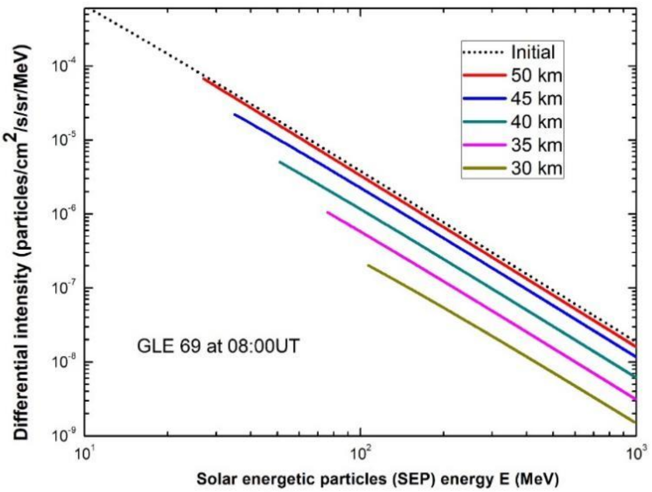

Fig. 3. Solar energetic particles (SCRs) spectrum from SPE event on 20 January 2005 at 8:00 UT for altitudes 30, 35, 40, 45, 50 km with initial spectrum outside of the atmosphere (dotted curve). This is the second powerful solar proton event in the space era.

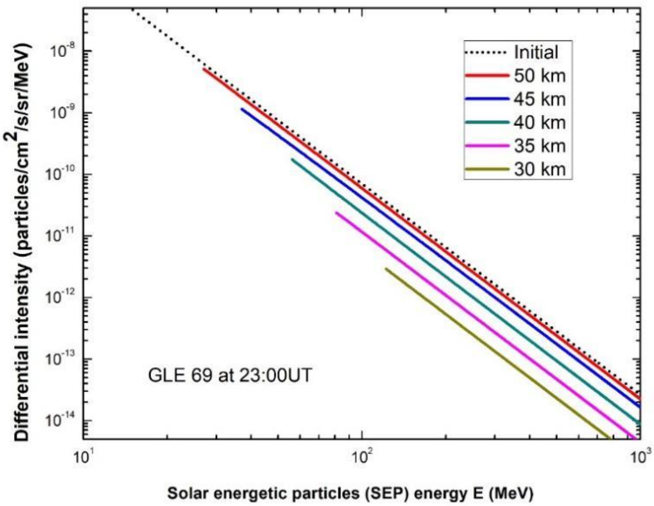

Fig. 4. Solar energetic particles (SCRs) spectrum from SPE event on 20 January 2005 at 23:00 UT for altitudes 30, 35, 40, 45, 50 km with initial spectrum outside of the atmosphere (dotted curve). This is the second powerful solar proton event in the space era.

events in the history of space exploration. Figures 2, 3 and 4 show the main results of the spectra calculated with the CORSIMA program.

The intensity of the spectrum of SCR depends on the trajectory of the substance (dependence on altitude, atmospheric cut-offs and ionization losses), geomagnetic cut-offs, neutral density (dependence on altitude), strength of the spectrum and exponent (number of charged particles).

Fig. 1 shows the GCR spectra for solar minimum and solar maximum with their characteristic maxima at 600 MeV. The SCR spectra for GLE05 and GLE69 at 8:00UT and 23:00UT are also shown. The ACR (Anomalous Cosmic Ray) spectra for O+ and He+ have lower energy values as shown in Fig. 1. On Fig. 1 are presented the main ionization sources in the upper atmosphere.

Fig. 2 shows the results of the spectra calculation of GLE 05, the strongest event observed in the history of solar cosmic ray research. This is the strongest solar proton event observed in the history of solar cosmic ray investigations. The characteristic behavior of the spectra for all altitudes is due to the wandering substance path and the corresponding atmospheric cut-offs for each altitude value. This is correct because we calculate the intensities for the polar cusp where the geomagnetic cut – off rigidity is nearly zero.

Figures 3 and 4 present the spectra of SCR during GLE 69 with spectra measured on 20.01.2005 at 8:00UT and 23:00UT. These curves reflect spectra in the polar cusp region for $\lambda_m \approx 90^o$ where the corresponding geomagnetic cut-offs are ≈ 0 GV. The altitude region covers the heights interval (30–80) km. As can be seen in Figures 2 and 3, the spectra increase with altitude.

The SCR spectra at latitude 90º cross due to the different energy power and magnitudes of the differential spectra for 8:00 and 23:00 UT (see Fig. 1). For lower altitudes (larger cut-off values) the spectrum with lower power dominates. For higher altitudes, the decreasing neutral density already dominates.

The differential spectrum with the smaller exponent (8:00 UT) causes larger values for lower altitudes. The reason is the strong atmospheric cut-off at these altitudes. At higher altitudes, the influence of the larger spectrum (23:00UT) dominates.

The CORSIMA and CORIMIA programs (which are based on the Mathematica program system) are able to calculate the SCR spectra and intensity stably and accurately for the effects of any solar CR impact on the lower ionosphere and middle atmosphere. The structure of the program is user–friendly, with detailed descriptions of input and output data in corresponding windows. In the future, we will further develop and improve the CORSIMA program as a directly applicable routine for the study of space weather and climate [26–29].

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СПЕКТЪР И ИНТЕНЗИТЕТ НА КОСМИЧЕСКИТЕ ЛЪЧИ ПО МОДЕЛА CORSIMA В СРЕДНАТА АТМОСФЕРА. ИЗПОЛЗВАНЕ И ПРИЛОЖЕНИЕ ЗА СЛЪНЧЕВИТЕ КОСМИЧЕСКИ ЛЪЧИ

П. Велинов, С. Асеновски, Л. Матеев

Резюме

Представен е новият модел CORSIMA (COsmic Ray Spectrum and Intensity in Middle Atmosphere). Изчислени са спектрите и интензитетите на слънчевите космически лъчи (SCR) от GLE (Ground Level Enhancement) 05 на 23 февруари 1956 г. и GLE 69 на 20 януари 2005 г. на различни височини. За целта се прилага операционният модел CORSIMA. В окончателната версия на програмата CORSIMA е използвана апроксимация в 6 характерни енергийни интервала на функцията на Бор-Бете-Блох, включително интервала за намаляване на заряда. Дадени са аналитични изрази за приносите на енергийните интервали. За първи път представяме количествена и качествена оценка на въздействието на слънчевите космически лъчи (SCR) от събитията със слънчеви частици (SPE) върху йоносферата и средната атмосфера (30–80 km). Тези височини са над максимума на Регенер-Пфотцер. За разлика от галактическите космически лъчи (GCR), диференциалните спектри на SCR значително варират във времето. SCR потоците също се различават един от друг по време на различните събития. Поведението на спектъра и интензитета е обяснено като се има предвид структурата на програмата CORSIMA. Резултатите от изчисленията са в съответствие с експерименталните данни и показват характерни особености на процеса на разпространение за различни височини и геомагнитни ширини. Изчисленията са извършени за геомагнитни ширини 90^o (касп-област). Развитието на това изследване е важно за процесите и механизмите на космическото време.