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New Improved Operational Models for Cosmic Ray Effects in Space Physics

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Abstract. An analytical and numerical approach for penetration and ionization of cosmic ray nuclei with charge Z in the planetary ionospheres and atmospheres is considered. The electron production rates are calculated using new formulas, which couple the five main energy intervals in the ionization losses function (dE/dh). This is a 5-interval function, which performs a better approximation of the measurements and the experimental data in comparison with previous results. The geomagnetic cut-off rigidities and the energy decrease laws for the different intervals are used for creating of an intermediate transition energy region, which performs the coupling of the 5 intervals in the ionization losses function. A new 6-th energy interval for charge decrease in lower energies is taken into account.

Ionization profiles in the Earth atmosphere due to a large solar energetic particle event on 20 January 2005, produced by various nuclei, namely Helium, Oxygen and Iron are presented also. The spectra of the nuclei are explicitly considered. A full Monte Carlo simulation of the cosmic ray atmospheric cascade with CORSIKA 6.52 code using FLUKA 2006 and QGSJET II hadronic interaction models is carried out. The energy deposit in the atmosphere is obtained. The atmosphere is divided per 10 g/cm^2, which permits good precision. The ionization rate is compared for different latitudes, namely for 40°N, 60°N and 80°N. The contribution of various nuclei as a function of the latitude is widely discussed.

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1 Introduction

Cosmic rays (CR) are an essential factor in the Earth environment affecting physics and chemistry of the planetary atmospheres [1]. They are the main ionizing agent for the lower and middle atmosphere. That is why the study of the influence of cosmic ray penetration in the Earth's atmosphere and ionosphere is important for understanding of the solar-terrestrial relationships and space weather. These processes and effects require the development of quantitative models for CR influence on the atmosphere. For this purpose a model of ionization profiles due to CR particles with charge Z in planetary atmospheres with multi-step energy interval approximation of the ionization losses function is created [2, 3]. The energy decrease laws for different energy intervals of the ionization losses function are formulated. The corresponding electron production rate formulas are derived. It is assumed that the calculated energies are positive for the given atmospheric depth $\tilde{h}$ and the projections (energy transformations) of the interval boundaries are situated in the chosen energy interval. This model is developed for CR protons, Helium nuclei (alpha particles) and nuclei with charge $Z > 2$. The corresponding electron production rate profiles for protons (p), alpha particles (He), light (L), middle (M), heavy (H) and very heavy (VH) groups of nuclei in the middle atmosphere and the lower ionosphere are calculated.

In the present work the energy transformation laws will be derived for the 5 interval approximation. An intermediate transition region between neighboring energy intervals will be introduced. This new generalized model will contribute to the better accuracy of the problem solution. This 5 interval approximation is very close to the formula of Bohr-Bethe-Bloch for the ionization losses as also to the experimental measurements [1, 2]. A 6th charge decrease energy interval is taken into account [2]. The lower energy part of the ionization losses function is included in the new approximation. Vertical penetration of cosmic rays will be considered. It is the base for the full 3D electron production rate model.

2 Electron Production Rate in 5 Energy Intervals with Charge Decrease in the Ionization Losses Function

The improved CR ionization model includes the electron production rate terms in 6 energy intervals of the ionization losses function and 5 intermediate transition region terms between the basic intervals. The lower bound of integration E_{min} is chosen as the maximum between the atmospheric cut-off and the geomagnetic cut-off rigidity [1]. The case of vertical penetration of cosmic rays is considered. This improved model can be extended to the 3-dimensional case in the Earth environment with introduction of the Chapman function [1], which takes into account the Earth sphericity. Then all possible combinations of initial and final energy intervals of CR penetration must be included.

The final energy $E_6(h)$ can be calculated by the equation [4]

$$E_6(h) = \left[E_k^{0,877} - 0,579 \frac{Z^2 \tilde{h}}{A} \right]^{1/0,877} \tag{1}$$

The following case of lower integration boundary is assumed [4]: $kT \leq E_{A1}(h) \leq E_{\min} \leq 0.15 < E_a$ MeV/n. The next equation presents the corresponding electron production rate [4]:

$$
\begin{aligned}
Q(h) = & \frac{2570\rho(h)}{\varepsilon} \int_{E_{min}}^{0,15} D(E)[E_1(h)]^{0,5} dE \\
& + \frac{2570\rho(h)}{\varepsilon} \int_{0,15}^{E_{0,15;2}(h)} D(E)[E_{21}(h)]^{0,5} dE \\
& + \frac{1540\rho(h)}{\varepsilon} \int_{E_{0,15;2}(h)}^{E_a} D(E)[E_2(h)]^{0,23} dE \\
& + \frac{1540\rho(h)}{\varepsilon} \int_{E_a}^{E_{a;3}(h)} D(E)[E_{32}(h)]^{0,23} dE \\
& + \frac{231Z^2\rho(h)}{\varepsilon} \int_{E_{a;3}(h)}^{200} D(E)[E_3(h)]^{-0,77} dE \\
& + \frac{231Z^2\rho(h)}{\varepsilon} \int_{200}^{E_{200;4}(h)} D(E)[E_{43}(h)]^{-0,77} dE \\
& + \frac{68Z^2\rho(h)}{\varepsilon} \int_{E_{200;4}(h)}^{850} D(E)[E_4(h)]^{-0,53} dE \\
& + \frac{68Z^2\rho(h)}{\varepsilon} \int_{850}^{E_{850;5}(h)} D(E)[E_{54}(h)]^{-0,53} dE \\
& + \frac{\rho(h)}{\varepsilon} \int_{E_{850;5}(h)}^{5000} D(E)\frac{dE}{dh}[E_5(h)] dE \\
& + \frac{\rho(h)}{\varepsilon} \int_{5000}^{E_{5000;6}} D(E)\frac{dE}{dh}[E_{65}(h)] dE \\
& + \frac{0,66Z^2\rho(h)}{\varepsilon} \int_{E_{5000;6}}^{\infty} D(E)[E_6(h)] dE,
\end{aligned}
\tag{2}
$$

where $\rho(h)$ is the neutral density [5], $\varepsilon = 35$ eV is the energy for formation of one electron-ion pair [1], $D(E)$ is the primary spectrum of the galactic cosmic rays which penetrate at the top of the atmosphere, E_i is the final energy of the corresponding interval i, $E_{i,i-1}$ is the energy after boundary crossing between energy intervals i and $i-1$ and dE/dh is the ionization losses function in interval 5 with final energies $E_5(h)$ and $E_{65}(h)$, which is calculated with the following formula:

$$
-\frac{1}{\rho}\frac{dE}{dh}[E_5(h)] = -\frac{1}{\rho}\frac{dE}{dh}[E_{65}(h)] = 1,91Z^2. \tag{3}
$$

In the general case different types of energies $E_{ij}(h)$ can appear. These energies $E_{ij}(h)$ are calculated for $6 \leq i \leq 2$ and $j < i$. These combinations of values of the indices i, j include all possible cases of such energy types. The case

$i-j>1$ occurs for greater values of the travelling substance path and for greater zenith angles of particle penetration in the 3D model formula expressions. These expressions can include angle and height interval areas with equivalent formulations but generally they are specific for every considered altitude and penetration angle. This fact must be taken into account in the final realization of the highest version of our operational model.

The integrand in $Q(h)$ gives the possibility for application of adequate numerical methods. We use Wolfram Mathematica 7 [6] and Maple 14 [7] interactive procedures for numerical calculation of the electron production rate. In this way the intervals and CR groups contributions can be computed. On the basis of expression (2) a new operational model CRIMA (Cosmic Ray Ionization Model for the Atmosphere) is developed. CRIMA is a physical space weather model with fully operational implementations. CRIMA is able to produce values of electron production rate by CR ionization in the Earth's atmosphere for different altitudes (30 - 120 km), solar activities (low, moderate and high), geomagnetic and atmospheric cut-offs. This model is better than the previous models [8] and can determine the energy intervals contributions for all groups of CR nuclei. In Figure 1 the interface of CRIMA operational model is shown.

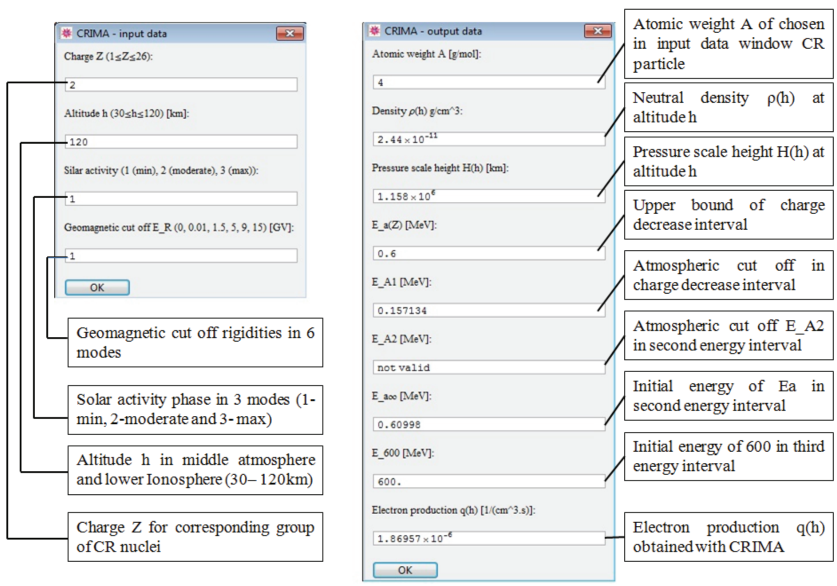

Figure 1. Interface of CRIMA operational model – input and output data windows.

In Figure 2 some of the first results computed by our operational model are shown. The three solid curves represent the total electron production rate through different solar activity, when the effect of anomalous CR can be seen in high altitudes - above 80 km. The ionization profiles are calculated for solar

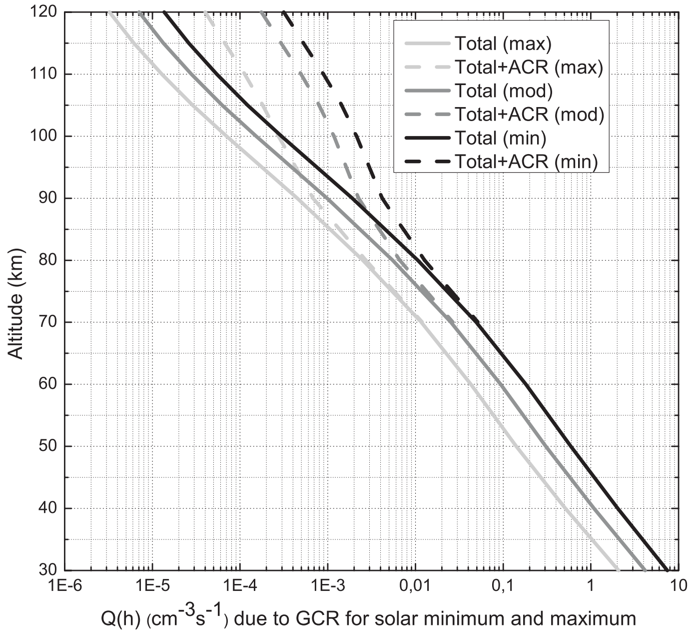

Figure 2. Ionization profiles by galactic and anomalous CR during solar minimum ($\Phi = 400$ MV), moderate and maximum ($\Phi = 1300$ MV) activity.

minimum ($\Phi = 400$ MV), moderate and maximum ($\Phi = 1300$ MV) activity. Φ is the modulation potential in the interplanetary space at the orbit of the Earth, *i.e.* 1 AU. The electron production rate values are proportional to the square of the charge (Z^2), flux intensity in the different energies and the neutral density in middle atmosphere. The variations of threshold values in the profiles reflect also the general nonlinearity of the problem.

The proposed CRIMA model can be used for every altitude, azimuth and zenith angle in the middle atmosphere and the lower ionosphere. Some combinations of energy intervals will arise which will cause the derivation of corresponding new formulas for energy integration in the model of the electron production rate with multi-interval ionization losses function, which was presented in this paper. The charge decrease Z of particles in the additional energy interval is taken into account [3, 4]. The full 3D integration with introduction of the Chapman function [1] can then be done which will provide higher accuracy of the CRIMA model. The coupling of the energy intervals of the ionization losses function is done.

The integration over the full altitude-zenith-azimuth surface will be performed with account to the local Chapman function value which corresponds to the travelling substance path for the point which is calculated. These values differ from one another which will increase the number of interval combinations and the complexity of the CRIMA model. The analytical and numerical results in this work are important for the space weather investigations and applications.

3 Contribution of Helium, Oxygen and Iron Nuclei to Atmospheric Ionization during SEP Event on 20 January 2005

Among the solar particle events, the solar eruptive fire event of 20 January 2005 is of big attention of the solar and solar-terrestrial community due to its outstanding characteristics. It was characterized by a fast coronal mass ejection (CME). The most important, it was accompanied by an unusually hard-spectrum solar energetic particle (SEP) flux near the Earth including major ground-level enhancement (GLE) of the cosmic rays, the second largest in the observational history of neutron and superneutron monitors.

SEP are high-energy particles coming from the Sun. They consist of protons, electrons and heavy ions. Generally the energy of SEPs range is from a few tens of keV, occasionally to GeV. Solar energetic particles originate from two processes: energetization at a solar flare site or by shock associated with coronal mass ejection. In several rare occasions a solar flare accelerates protons to sufficiently high energies for these particles to be propagated along the heliomagnetic field to the Earth and to be detected as an increase in the counting rate of the ground based cosmic ray detectors, causing GLE event. GLE is defined as a sharp increase of small duration in the counting rate of ground-based cosmic ray detectors caused by the accelerated charged particles.

The major SEP event of 20th January 2005 occurred into the descending phase of the 23th solar cycle near to its minimum. Several hard X-ray flares accompanied by series of coronal mass ejections took place in January 2005, the first from 14th of January. At 20th January 2005 the X7.1 solar flare from the active region NOAA AR10720 produced a strong X ray burst, which started at 06:36 UT. The peak of the emission was at 07:01 UT. During the first hour the particle spectrum parameters were dramatically changing. The changes of the spectra can be connected with the particle acceleration mechanism preceding the CME launch. In the next 10 hours acceleration produces spectra with very stable parameters, most likely formed at CME driven shock site. In addition the SEP event of 20 January 2005 is clearly anisotropic and with high amount of heavy ions [9]. This is the reason to consider in this study the spectra after 08:00 UT.

It is possible to fit the spectra, extending from < 0.1 to > 100 MeV/nucl with double-power-law function [9]. Afterwards it is a matter of algorithm to estimate the induced ionization in the atmosphere.

Primary cosmic ray particles penetrate into the Earth's atmosphere and release energy via nuclear interaction and ionization losses. When a particle from primary CR penetrates the Earth's atmosphere, it produces nuclear-electromagnetic-muon cascade. The high-energy primary solar cosmic ray collides with an atmospheric nucleus and produces new energetic particles. Those also collide with air nuclei and each collision adds a large number of particles to the developing cascade. The electrons and positrons re-generate gamma rays via Bremsstrahlung in the frame of the electromagnetic cascade. In practice the totality of these particles depose energy in the Earth's atmosphere and ionize the medium. For a given energy protons produce showers that develop deeper in the atmosphere than showers from nuclei.

While the direct energy input of CRs into the atmosphere is minor, they form the main source of ionization [1]. In this study we apply the formalism of ionization yield function Y which is defined according to Oulu model [10] following the procedure described in [11]. In fact the ionization yield function represents the number of ion pairs produced at a given altitude h in the atmosphere by given primary cosmic ray nuclei with kinetic energy E at the top of the atmosphere.

The estimation of atmospheric ionization rates is based on the following equation:

$$Q(h, \lambda_m) = \int_{E_0}^{\infty} D(E, \lambda_m) Y(h, E) \rho(h) dE, \tag{4}$$

where $D(E, \lambda_m)$ is the differential primary cosmic ray spectrum at given geomagnetic latitude λ_m for a given component of primary cosmic ray, Y is the yield function, $\rho(h)$ is the atmospheric density (g/cm^3) [12].

In general the cosmic rays follow a steep spectrum with a small deviation from the power law. Therefore the spectrum is expressed in part.cm^{-2}s^{-1}sr^{-1} MeV^{-1} as:

$$D(E) = KE^{-\gamma}, \tag{5}$$

where γ is the spectrum index. In this study we consider He, O and Fe as primary nuclei according to the experimentally obtained spectra [9]. The characteristics of the corresponding fluence spectra are presented in Table 1.

Table 1. Characteristics of Helium, Oxygen and Iron fluence spectra on 20 January 2005 SEP event.

Particle	Helium	Oxygen	Iron
K	$2,519.10^7$	$9,2696.10^5$	$7,94.10^4$
γ	2,18	2,61	2,45

In this study the evolution of atmospheric cascade is carried out with CORSIKA 6.52 code [13] with corresponding hadronic interaction models FLUKA 2006 [14] and QGSJET II [15]. The FLUKA 2006 is used for simulation of the hadronic interactions below 80 GeV/nucleon and QGSJET II for hadronic interactions above 80 GeV/nucleon, respectively. The CORSIKA is widely used atmospheric cascade simulation tool. It permits to perform a detailed analysis of the cascade evolution in the atmosphere. In this code the interactions and decays of various nuclei, hadrons, muons, electrons and photons in the atmosphere up to extreme energies are realistically performed. The result of the simulations is detailed information about the type, energy, momenta, location and arrival time of the produced secondary particles at a given selected altitude above the sea level. It is possible to obtain the energy deposit by different shower components and particles from ground till the very upper atmosphere for various solar particles considering explicitly the secondary components.

4 Atmospheric Ionization Rate from He, O and Fe Nuclei

The purpose of this paper is to estimate the ionization rate and to obtain ionization profiles during the SEP event on 20 January 2005. In our previous work [16] the contribution of proton nuclei is highlighted, as well as in the recent work [17]. The energy loss per distance, respectively ionization, travelled by charged particles (protons, alpha particles, nuclei traversing matter) depends on the square of the particle charge Z according to Bohr-Bethe-Bloch equation.

Therefore the ionization caused by light, middle and heavy cosmic ray nuclei should be considered separately from protons. Moreover the capacity for ionization of the ambient air by heavy ions in the upper atmosphere is greater [11]. In this connection the ionization rate in the Earth's atmosphere due to various nuclei, namely light, middle and heavy nuclei during SEP event on 20 January 2005 is of a big interest.

We consider He, O and Fe as primary nuclei according to the experimentally obtained spectra [9, 18] and parameters shown in Table 1. The ionization rates are estimated for 40^o N, 60°N and 80°N at Greenwich meridian taking into account the corresponding rigidity cut-offs. We simulate 50 000 events per energy spectrum assuming US Standard Atmosphere model [12]. The atmosphere is divided per 10 g/cm^2. This permits a detailed description of ionization profiles. In our study we express x in g/cm^2, the residual atmospheric depth, *i.e.* the amount of matter (air) overburden above a given altitude in the atmosphere. This is naturally related to the development of the cascade. Subsequently the mass overburden is transformed in an altitude above the sea level (a.s.l). The contribution of the different cascade components is explicitly taken into account, namely the electromagnetic, muon and hadron component.

Hence after obtaining the energy deposit from all secondary cosmic ray components, respectively ionization yield function Y on the basis of (3), the ionization profiles as ion pairs per second in cm^3 are obtained. The ion rates are presented as ion pairs per second, per cm^3, per nucleon, per atmosphere.

The results are presented in Figure 3 for various conditions. In Figure 3 the ion rates due to various nuclei (Helium, Oxygen and Iron) at 40 °N, 60°N and 80°N

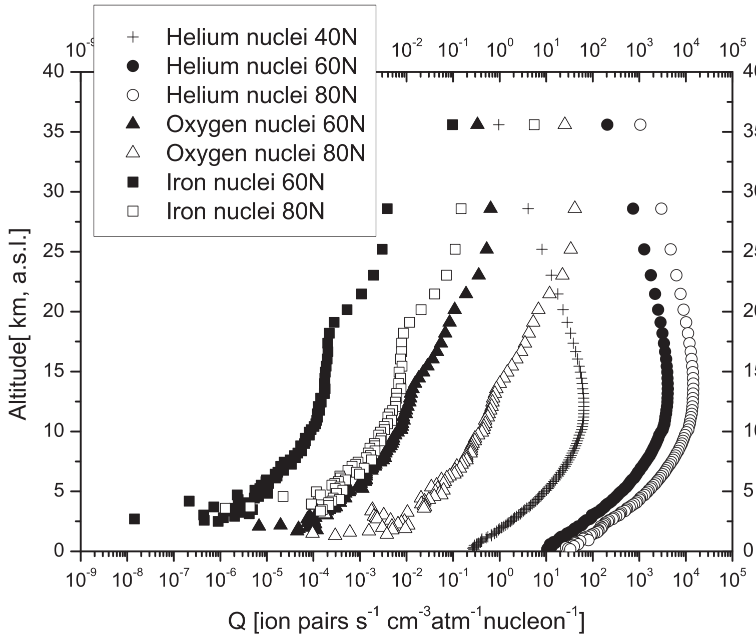

Figure 3. Ionization profiles at 40^o N, 60^o N and 80^o N due to Helium, Oxygen and Iron nuclei of solar CR during SPE on 20 January, 2005.

latitude are presented. The contribution from Helium nuclei dominates as expected. The contribution of a nuclei even in the upper atmosphere is negligible. Actually in Figure 3 the various ion rates from different nuclei are compared. In all cases the contribution from Helium nuclei dominates. The contribution of Oxygen and Iron nuclei is in practice negligible, specifically in the middle and the low atmosphere. However for 80 °N latitude in the upper atmosphere the contribution from Oxygen nuclei is comparable with the contribution from Helium nuclei.

5 Conclusions

In this study the possibility for estimations of the induced by galactic, anomalous and solar CR including the major SEP event of 20 January 2005 ionization in the atmosphere on the basis of CRIMA model and CORSIKA code simulations is demonstrated. CR effects are important in the entire atmosphere, from ground level to upper atmosphere in various latitudes, especially in the polar regions. The obtained ionization profiles are applicable to atmospheric physics and chemistry, environment, dosimetry and space weather research.

Cosmic rays play an important role for the electric conductivity profiles in the atmosphere. A statistical relation between sporadic solar energetic particle events associated with solar flares, coronal mass ejections and atmospheric properties [19] was widely discussed. As an example, as it recently has been shown, the chemistry of the minor atmospheric components, namely nitrogen (NO_x) and odd hydrogen (HO_x) production causing ozone variations is related to such type of events [20, 21]. In this connection the quantitative study of cosmic ray ionization in the troposphere-stratosphere is of a great interest.

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