S E S 2 0 1 0
Sixth Scientific Conference with International Participation
SPACE, ECOLOGY, SAFETY
2–4 November 2010, Sofia, Bulgaria

MODEL OF COSMIC RAY IONIZATION IN THE IONOSPHERE TAKING INTO ACCOUNT THE ENERGY INTERVALS FOR PARTICLE PENETRATION

Peter Velinov, Lachezar Mateev, Alexander Mishev

Space and Solar-Terrestrial Research Institute – Bulgarian Academy of Sciences
e-mail: pvelinov@bas.bg

Key words: *planetary ionospheres, solar radiation and cosmic ray effects, ionization mechanisms*

Abstract : *A model for galactic cosmic ray (CR) ionization in the ionosphere is presented in this report. A new analytical approach for CR ionization by protons and nuclei with charge Z in the lower ionosphere and the middle atmosphere is developed. For this purpose, the ionization losses for the energetic charged particles according to the Bohr-Bethe-Bloch formula are approximated in three different energy intervals – two main intervals and an intermediate coupling interval. More accurate expressions for CR energy decrease E(h) and electron production rate profiles q(h) are derived. q(h) is determined by the solution of a 3D integral with account of geomagnetic cut-off rigidity. The integrand in q(h) gives the possibility for application of adequate numerical methods - in this case, Gauss quadrature and Romberg extrapolation, for the solution of the mathematical problem. Computations for CR ionization are made. The contributions of the different approximation energy intervals are presented. The full CR composition is taken into account. The computations are made for different geomagnetic cut-off rigidities R in the altitude interval 30-70 km. The proposed improved CR ionization model will contribute to the quantitative understanding of solar-atmosphere relationships. The computer algebra program system Mathematica 5.2 is applied for calculation of the electron production rate values in characteristic energy intervals of the ionization losses function.*

1. Introduction

At present different possible drivers of solar-terrestrial relationships are investigated (Velinov et al., 1974; Dorman, 2004). Velinov (2000, 2006) proposed a combined hypothesis for cosmic rays (CR) - XUV influence on the solar-atmosphere relationships. The cosmic rays and XUV determine to a great extent the chemistry and electrical parameters in the atmosphere. They create ozonosphere and influence actively the ozone O_3 processes. The cosmic rays transmit to the ozonosphere their solar modulation. But the ozonosphere controls the meteorological solar constant and the thermal regime and dynamics (including the dynamics of the cloud system) of the lower atmosphere, i.e. the weather and climate. The XUV influence dominates during the day (in particular around noon) and CR influence dominates during the night and sunrise-sunset periods, because galactic CR are always bombarding the Earth atmosphere. The CR flux varies during the solar cycle in an opposite face to that of sunspots (Velinov et al., 1974; Dorman, 2004). This hypothesis of the solar-terrestrial relationships shows the way to a non-contradictory solution of the key problems of the solar-terrestrial physics.

Thus the galactic and solar cosmic rays are drivers of solar - atmosphere changes. They cause ionization and excitation of the middle atmosphere and lower ionosphere and also electromagnetic and nuclear interactions (Velinov et al., 2009) in the lower atmospheric layers (Velinov et al., 1974). In fact CR determine also the electric conductivity in the middle atmosphere and influence on this way the global electric circuit (Dorman, 2004; Velinov and Mateev, 1990). CR introduce the solar variability in the middle atmosphere and ozonosphere - because they are modulated by solar wind. As a continuation of our studies of CR ionization in the atmospheres of the planets in the Solar system (Velinov et al., 2004) we will present an improved method for calculation of the electron production rate *q(h)* profiles due to particles of all energy intervals: galactic and solar CR, anomalous CR component and other types of high energy particles (Velinov and Mateev, 2008). The proposed improved CR ionization model will contribute to the quantitative understanding of solar-atmosphere relationships (Velinov et al., 2008; Velinov et al., 2010).

2. Model

The analytical and numerical approaches for penetration of cosmic rays in the system ionosphere - atmosphere are important for determination of the ionization state in the Earth environment. These investigations are based on particle ionization theory developed by Bohr, Bethe and Bloch (Velinov et al., 1974).

Moreover, for the altitude above 50 km, one can further neglect changes of the energy of energetic particles, thus reducing the cosmic rays induced ionization (CRII) computation to an analytical ***thin target*** model, where the electron production rate per g/cm^2 is computed as

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

Here 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. The summation in the ionization integral (1) is made on the groups of nuclei: protons p, Helium (α-particles), light L (3 ≤ Z ≤ 5), medium M (6 ≤ Z ≤ 9), heavy H (Z ≥ 10) and very heavy VH (Z ≥ 20) nuclei in the composition of cosmic rays. Z is the charge of the nuclei. Q = 35 eV is the energy required for the formation of an electron-ion pair, $D(E)$ is the differential CR spectrum, $(dE/dh)_i$ are the ionization losses of a particle of type i.

In the altitude range from 25-30 to 50 km, an ***intermediate target*** model needs to be used, that accounts also for the particle's deceleration due to ionization losses. This model was applied for calculation of atmospheric electrical conductivities [Velinov and Mateev, 1990)] in the middle atmosphere for different cases: galactic CR (GCR), solar CR (SCR), Forbush decreases, day and night conditions, etc. (Mateev, 2010).

The structure of the model (1) allows its decomposition in submodels. In this case we take into account the physical meaning of the undependent variables subintervals. The integrand variables are: azimuth angle, zenith angle and kinetic energy of charged particles. Each combination of three characteristic subintervals and the corresponding altitude in the integrand variables defines its own electron production rate submodel, which is included in the general ionization rate model (1) with coupling intermediate energy subintervals. In this way the accordance with the experimental data is improved (Mateev, 2010). Each combination of *D(E)*, *dE/dh* and intermediate energy intervals defines its own contribution in the electron production rate value with corresponding analytical expression in the model (Velinov et al. 2008).

In this paper we compute the contribution of the ionization rate of some energy subintervals of particles, including the intermediate subinterval, in the general electron production rate value for the case of vertical CR protons penetration and two interval approximation of ionization losses function (Velinov et al,, 1974; Ruder et al., 2006).

3. Computational results

The model for two interval approximation (2) of the ionization losses function (of Bohr-Bethe-Bloch) with coupling intermediate energy interval is composed by 3 main terms (3) with corresponding initial energy value (4) – cut off rigidity $E_{km}(h)$, which forms the lower integral boundary in (1):

(2) $$-\frac{1}{\rho}\frac{dE}{dh} = \begin{cases} 242E^{-3/4} & E = 0.15-600\ \text{MeV} \quad \text{Interval 1} \\ 2 & E = 600-5\times10^{6}\ \text{MeV} \quad \text{Interval 2} \end{cases}$$

(3) $$q(h) = \frac{\rho(h)}{Q}\left(\int_{E_{km}}^{600} D(E)\left(\frac{dE}{dh}\right)_1 dE + \int_{600}^{E_\infty(h)} D(E)\left(\frac{dE}{dh}\right)_2 dE + \int_{E_\infty(h)}^{\infty} D(E)\left(\frac{dE}{dh}\right)_3 dE\right)$$

(4) $$E_{km} = \max\{E_{km,1}, E_{km,2}\} = \max\{E_R, E_A(h)\} = \max\left\{\left(\sqrt{R^2+0.88}-0.938\right)10^3; E_R(h)\right\}$$

The intermediate energy interval contribution is expressed by the second term in (3). This particular case of the general model (1) is derived in (Ruder et al., 2006).

The GCR protons spectrum for minimal solar activity is taken from (Buchvarova, 2002). The SCR protons spectrum, which is introduced in the computer code, is measured at the GLE05 event on

23 February 1956 (Velinov et al., 1974). The GCR electron production rate profiles are computed for altitudes between 30 and 60 km and geomagnetic cut-off rigidities E_R=10 MeV and 60 MeV. The SCR electron production rate profiles are computed for altitudes between 30 and 70 km.

The graphical presentation of the electron production rate profiles is given on Figs. 1 and 2. On Fig. 1 the values for E_R=10 MeV are higher because of the smaller lower integration boundary $E_{km}(h)$ (4). The total ionization rate is higher because of the contribution of all types of CR nuclei (Velinov et al., 1974). The change of the maximum value $E_{km}(h)$ in (4) with height decrease causes the coincidence of both profiles for E_R=10 MeV and 60 MeV (Fig. 1).

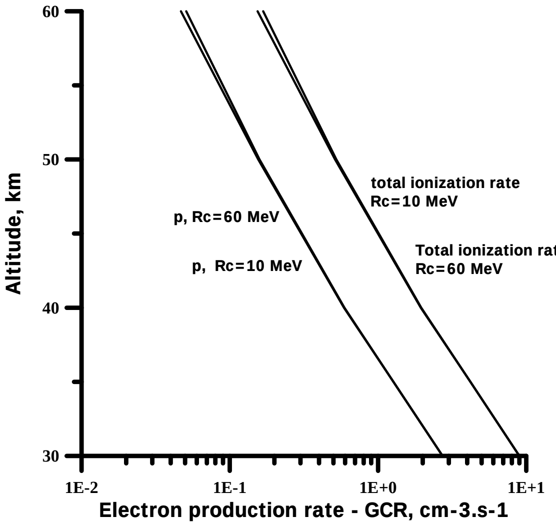

Figure 1

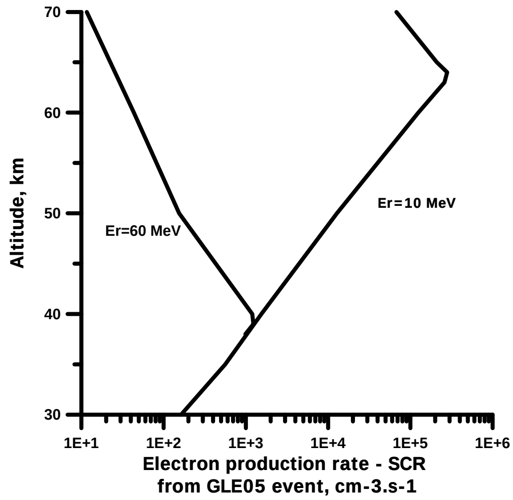

Figure 2

The same phenomenon occurs in the case of SCR. It is shown on Fig.2. Both curves are identical under the altitude of 38 km. Both maxima for E_R=10 MeV at altitude of 64 km and for E_R=60 MeV at altitude of 39 km are due to the switching of values in formula (4). The powerful SCR spectrum causes a great increase of the profiles values in comparison with these from GCR spectrum.

Table 1. Atmosphere parameters for GCR ionization calculation – vertical GCR penetration

Altitude *h*, km	Atmospheric density $\rho(h)$, g.cm^{-3}	Traveling substance path $\tilde{h}$, g.cm^{-2}	Cut-off rigidity E_A' at E_R'=10 MeV	Cut-off rigidity E_A'' at E_R''=60 MeV	Intermediate Interval Boundary E_B, MeV
60	3.21E-7	0.239	13.99	60	600.46
50	1.057E-6	0.855	29	60	601.71
40	3.97E-6	3.01	59.55	60	606.02
35	8.28E-6	5.93	87.7	87.72	611.86
30	1.77E-5	12.12	131.95	131.94	624.24

The bigger difference between both SCR profiles values than that between the GCR profiles values is proportional to the differential spectrum *D(E)* in the corresponding energy intervals.

Table 2. Electron production rate from GCR in characteristic energy intervals of differential GCR spectrum *D*(*E*) for minimal solar activity – vertical GCR penetration

Height *h*, km	*q*(*h*) in [E_A', 300], MeV	*q*(*h*) in [E_A'', 300], MeV	*q*(*h*) in [300, 600], MeV	*q*(*h*) in [600, E_B], MeV	*q*(*h*) in [E_B, 20000], MeV	*q*(*h*) in [20, 100], GeV	$q'_{GCR}(h)$	$q''_{GCR}(h)$
60	0.016	0.012	0.008	8.7×10^{-6}	0.0262	6.4×10^{-4}	0.168	0,154
50	0.044	0.04	0.027	10^{-4}	0.086	0.0021	0.5234	0,513
40	0.1652	0.1652	0.1	0.0014	0.32	0.008	1.96	1.95
35	0.366	0.366	0.214	0.0056	0.67	0.016	4.2	4.2
30	0.773	0.773	0.47	0.025	1.42	0.035	8.99	8.99

The parameters which form the energy interval boundaries and the ionization profiles for GCR and SCR penetration are shown in Tables 1 and 4. The numerical values of the electron production rate for different altitudes and angles of CR penetration are presented in Tables 2, 3, 3* for GCR and in Tables 5 and 6 for SCR.

Table 3. Electron production rate from inclined GCR penetration in characteristic kinetic energy E_k intervals of differential spectrum $D(E)$ for minimal solar activity and altitude of 50 km

θ^*	$Ch(X,\theta)$	$\tilde{h}$	E_A, MeV	E_B, MeV	(E_A-300) MeV	(300-600) MeV	(600-E_B) MeV	(E_B-20) GeV	(20-100) GeV	q_{CR} cm^{-3}s^{-1}	II** %
87°	14.73	12.59	134.84	625.18	0.058	0.028	0.002	0.085	0.0021	0.5778	1
90°	35.46	30.32	222.82	660.64	0.033	0.032	0.0049	0.083	0.0021	0.5115	3.2
93°	197.5	168.9	594.5	937.8	-	0.004***	0.03	0.069	0.0021	0.347	28.5
95°	1476	1262	2781.2	3124.3	-	-	0.0071***	0.024	0.0021	0.11	21.4

*Zenith angle; **Intermediate energy interval contribution: $q(600\text{-}E_B)/q_{protons}$;
***Energy interval boundaries: (E_A- E_k)

Table 3*. Contribution of intermediate interval (II) in % for GCR ionization and E_R=10 MeV

Altitude , km	60	50	40	35	30
Contribution II	1.7×10^{-2}	6.3×10^{-2}	0.2	0.44	0.9

Table 4. Atmospheric and geomagnetic cut off rigidities and intermediate energy interval boundaries (IEIB) which are used in the SCR electron production rate model – vertical SCR penetration

Altitude h, km	Cut-off rigidity $E_A(h)$	$E_A'(h)$ for geomagnetic cut-off E_R=10 MeV	$E_A''(h)$ for geomagnetic cut-off E_R=60 MeV	IEIB, MeV
70	6.16	10	60	600.11
65	9.43	10	60	600.24
64	10.22	10.22	60	600.27
60	13.99	13.99	60	600.48
50	29	29	60	601.71
40	59.55	59.55	60	606.02
39	64.21	64.21	64.21	-
35	87.7	87.7	87.7	611.85
30	131.95	131.95	131.95	624.23

Table 5. Electron production rate from SCR in characteristic energy intervals of differential GCR spectrum $D(E)$ for GLE05 event from 23 February 1956 – vertical SCR penetration

Altitude h, km	(E_A'-300) MeV	(E_A''-300) MeV	(300-600) MeV	(600-E_B) MeV	(E_B-20) GeV	(20-100) GeV	$q_p'(h)$ cm^{-3}s^{-1}
70	6.79×10^{4}	11.65	5.3×10^{-3}	2.4×10^{-7}	2.4×10^{-4}	1.97×10^{-10}	6.79×10^{4}
65	2.1×10^{5}	-	0.01	10^{-6}	4.78×10^{-4}	3.87×10^{-10}	2.1×10^{5}
64	2.8×10^{5}	-	0.012	1.31×10^{-6}	5.42×10^{-4}	4.39×10^{-10}	3.4×10^{5}
60	1.25×10^{5}	43.43	0.0194	3.73×10^{-6}	8.9×10^{-4}	7.22×10^{-10}	1.25×10^{5}
50	1.28×10^{4}	154.5	0.064	4.4×10^{-5}	2.9×10^{-3}	2.38×10^{-9}	1.28×10^{4}
40	1.54×10^{3}	1194	0.24	5.7×10^{-4}	0.011	8.9×10^{-9}	1540
39	-	1234	-	-	-	-	-
35	560.91	560.91	0.519	2.3×10^{-3}	0.021	1.9×10^{-8}	561.45
30	161.7	161.7	1.16	8.6×10^{-3}	0.042	3.99×10^{-8}	162.91

Table 6. Electron production rate at inclined SCR penetration in characteristic kinetic energy E_k intervals of differential spectrum $D(E)$ for GLE05 event from 23 February 1956 and altitude of 50 km

Θ*	E_A, MeV	E_B, MeV	(E_A-300) MeV	(300-600) MeV	(600-E_B) MeV	(E_B-20) GeV	(20-100) GeV	q_{CR} $cm^{-3}s^{-1}$	II** %
87°	134.84	625.18	8.64	0.0697	5.3×10^{-4}	2.49×10^{-3}	2.38×10^{-9}	8.713	6.1×10^{-3}
90°	222.82	660.64	0.698	0.083	0.00117	0.002	2.38×10^{-9}	0.784	0.15
93°	594.5	937.8	-	0.0013***	6.1×10^{-3}	4.97×10^{-4}	2.38×10^{-9}	0.0079	77.1
95°	2781.2	3124.3	-	-	5.4×10^{-6}***	4.05×10^{-6}	2.38×10^{-9}	9.4×10^{-6}	57

*Zenith angle; **Intermediate energy interval contribution: $q(600\text{-}E_B)/q_{protons}$;
***Energy interval boundaries: (E_A- E_k);
The corresponding parameters $Ch(X,\theta)$ and $\tilde{h}$ are given in Table 3

The nonlinearity of the problem corresponds to the computational values of the solutions. They are determined by the magnitude of the differential spectrum $D(E)$, the ionization losses function dE/dh and also by the energy interval values (Tables 2 and 5). The traveling substance path $\tilde{h}$ which determines the atmospheric cut-off $E_A(h)$ and the ionization losses function influences also the ionization rate values (Tables 3 and 6). For some bigger angles of CR penetration (θ > 90°, in spherical Earth model (Velinov et al., 2004)) the intermediate coupling interval has important contribution in the ionization rate value (Table 3, GCR penetration) and even dominates in it (Table 6, SCR penetration). Its contribution is proportional to the traveling substance path increase (with the zenith angle θ increase and the altitude h decrease).

The most important contribution for the GCR ionization rate is in the energy intervals [$E_A(h)$-300] MeV and [$E_B(h)$-20] GeV. It follows from the energy interval width, the differential spectrum and the ionization losses function values (Table 2). The SCR ionization rate value is determined by the energy interval [$E_A(h)$-300] MeV where the $D(E)$ and the dE/dh values are higher in comparison with the other energy intervals. The obtained ionization rate profiles are in accordance with experimental data and measurements (Velinov et al., 1974; Mateev, 2010).

4. Solution methods

The numerical algorithm which is applied realizes the Romberg integration method with Richardson extrapolation to the limit (Press et al., 2002). The numerical results are obtained for input accuracy ε = 0.004. They are in accordance with the output values of the *Mathematica* 5.2 computer system (Wolfram, 2003). The relative errors are calculated under 2%. Only in one case the relative error reaches 4.5% and for two other cases it is 2.5%.

5. Monte Carlo simulation of CR ionization

The CR ionization in the middle atmosphere was calculated with the CORSIKA programme system (Heck, 2004). The ionization profiles were obtained with Monte Carlo simulation. They are in accordance with the results of the analytical - numerical model (Velinov et al., 2009). On this way is obtained ***the full target model***.

Obviously to build an appropriate model for atmospheric ionization due to cosmic rays it is necessary to follow the evolution and properties of the cascade process in the atmosphere, especially the energy and location with corresponding arrival time of the produced secondary particles at given selected observation level. In the full target model we use the following relations with ionization yield function formalism (5):

(5) $$Y(x,E) = \Delta E(x,E)\frac{1}{\Delta x}\cdot\frac{1}{E_{ion}}\cdot\Omega$$

where ΔE is the deposited energy in layer Δx in the atmosphere and Ω is a geometry factor, integration over the solid angle with given zenith angle. Therefore the cosmic ray induced ionization is estimated according (6)

(6) $$q(h,\lambda_m) = \int_{E_0}^{\infty} D(E,\lambda_m)Y(h,E)\cdot\rho(h)dE$$

where $D(E,\lambda_m)$ is the differential primary cosmic ray spectrum at given geomagnetic latitude λ_m, Y is the yield function, $\rho(h)$ is the atmospheric density ($g.cm^{-3}$).

6. Conclusions

This improved analytical - numerical electron production rate model can be applied for calibration of the computer system CORSIKA (COsmic Rays Simulation for KAskade) (Heck, 2004) output results at altitudes 30-35 km. There the nuclear interactions begin to dominate over the electromagnetic interactions which are most important at the altitudes above 35 km. The electron production rate model can be applied for CR ozone production calculation (Tassev et al., 2006) and for electrical conductivities modeling in the middle atmosphere. The calculated intermediate energy interval can have dominating contribution in *q(h)* for greater traveling substance path in lower altitudes *h* and bigger zenith angle θ in the spherical Earth electron production rate model. The calculated interval contributions in *q(h)* are caused by the characteristic values of *D(E)*, *dE/dh* and the energy interval widths.

The presented improved model can be used for detailed investigation of the characteristics and contributions of the different energy intervals in the CR differential spectra and the ionization losses function. On this way the multi-interval computations can be defined in the input data of the model (1). They include also the charge decrease interval (Dorman, 2004; Velinov et al., 2008), the intermediate coupling intervals and the number (from 2 to 6) and types of the approximation intervals of the ionization losses function. The CR ozone production rate evaluation is made just using the energy interval measurements by the GOES satellites and their data bases in the Internet network (Tassev et al., 2006). The energy intervals investigation takes place according to the goal of the user of the model with respect to accuracy and interval types.

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