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ATMOSPHERIC CUT-OFFS IN THE GENERALIZED MODEL OF IONIZATION PROFILES DUE TO THE COSMIC RAY CHARGED PARTICLES IN PLANETARY IONOSPHERES AND ATMOSPHERES WITH 5 ENERGY INTERVAL APPROXIMATION OF THE IONIZATION LOSSES FUNCTION

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Abstract

An analytical and numerical approach for penetration and ionization of cosmic ray nuclei with charge Z in planetary ionospheres and atmospheres is considered in this paper. 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 five interval function, which performs better approximation of the measurements and experimental data in comparison with previous results for four interval ionization losses function. The geomagnetic cut-off rigidities and the energy decrease laws for the different intervals are used to create an intermediate transition energy region, which performs the coupling of the five main intervals in the ionization losses function. A new sixth energy interval for charge decrease in lower energies is taken into account. The case of vertical cosmic ray penetration is considered. The atmospheric cut-offs are calculated for 6 basic cases of atmospheric depth values.

Key words: *cosmic rays, ionization model, planetary ionospheres and atmospheres, space weather*

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Introduction

Cosmic rays (CR) are an essential factor in Earth's environment affecting physics and chemistry of planetary atmospheres [1, 2]. 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 [3, 4, 5] is important for understanding the solar-terrestrial relationships and space weather.

CR ionisation, excitation and dissociation are basic processes in the atmospheres and ionospheres of the other planets, too. For example detailed calculations of ionization profiles are made for Venus [6, 7], Jupiter [8], and Saturn [9]. It takes place also in the atmospheres of their satellites, for instance Titan [10], which possesses a dense atmosphere, similar to the terrestrial atmosphere. There are numerous CR effects in planetary atmospheres. A few examples are shown here for such essential CR influences.

Cosmic rays and electric fields and currents

It is already proved that CR influence atmospheric electric fields and thunderstorms. The high energy cosmic particles determine the conductivities in the terrestrial environment. CR have also an effect on Earth's global charge and global electric circuit [2]. In [2] it is shown that main causes of thunderstorm discharges are EAS (external atmospheric showers) which are generated by primary CR particles with energy more than 10^{14} eV. In [2] are described EAS discharge mechanisms for descending lightning (from cloud to ground) and ascending lightning (from ground to cloud).

Cosmic rays, clouds and climate formation

Many papers concerning relationships between CR penetration in the atmosphere, cloudiness and climate formation are presented in the monograph [2]. According to works [11, 12], CR ionization is the basis of clouds formation. CR determine the low cloud properties [2, 13]. The latitudinal dependence of low cloud amount on cosmic ray induced ionization is established in [14].

Several possible causes of global climate change have been discussed in scientific literature [2, 15, 16, 17, 18]: 1) internal variability in the climate system, e.g., changes of atmospheric and ocean circulation; 2) large volcanic eruptions, which are known to cause a sudden cooling lasting several years; 3) change of concentration of greenhouse gases (the increase of atmospheric CO_2 concentration during the last 100 years by about 30% has led to an increase of approximately 0.7°C in the global surface temperature); 4) orbital change of the Earth's motion around the Sun; 5) changes in solar activity and CR intensity. The last possible cause is investigated in details in [2].

Some relationships between galactic cosmic rays and El Niño-Southern Oscillation trends are found in the International Satellite Cloud Climatology Project D2. These relationships are investigated in details in [19]. These relationships between cosmic rays in the atmosphere, cloud formation and their influence on climate are also treated in the review papers [20, 21, 22].

Some observations tending to investigate the nature of our Sun, in order to find causes or symptoms of its variable emission of light and heat are presented in the pioneer work of the famous astronomer William Herschel [23] yet in 1801, i.e. more than two hundred years ago. A strong coherence between solar variability and the monsoon phenomenon is established [24]. The altitude variations of cosmic ray induced production of aerosols and some implications for global cloudiness and climate are treated in [25].

A relationship exists between CR penetration and paleoclimate formation. A cosmic ray diffusion from the galactic spiral arms is observed in [26]. CR propagation reveals the spiral structure of the Milky Way and characterizes the ice age epochs on Earth [27]. Cosmic ray influence is also in a possible relationship with the celestial driver of phanerozoic climate [28]. A persistent solar influence on North Atlantic climate during the Holocene is found also in [29].

Analytical models for CR ionization in planetary ionospheres and atmospheres

All above mentioned processes and effects require the development of quantitative models for CR influence on the atmosphere and the ionosphere. For this purpose, a model of ionization profiles due to cosmic ray particles with charge Z in planetary ionospheres and atmospheres with multi-step energy interval approximation of the ionization losses function is created [2, 30, 31]. The energy decrease laws for different energy intervals of the ionization losses function are formulated. The corresponding electron production rate formulas are derived [32, 33]. 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 located in the chosen energy interval. This model is developed for CR protons, Helium nuclei (alpha particles) [34] and nuclei with charge $Z > 2$. Two interval [35, 36], three interval [37, 38] and four interval [39, 40] approximations of the ionization losses function dE/dh [1, 2, 40, 41] are taken into account. The corresponding electron production rate profiles for p, α - particles (He nuclei), L, M, H, VH groups of nuclei in the middle atmosphere and the lower ionosphere are calculated [42, 43].

The energy transformation laws were derived for the corresponding 5 interval approximation in the case of proton penetration [44, 45]. An intermediate transition region between neighbouring energy intervals was introduced [40]. But for more detailed calculations, a better approximation with 5 energy intervals for cosmic ray particles with charge Z can be applied. This new generalized model will be described in the present work. The model will contribute to the better accuracy of the problem solution [46, 47]. This 5 interval approximation is very close to the basic formula of Bohr-Bethe-Bloch for the ionization losses. A 6-th charge decrease energy interval is taken into account [2, 40]. The lower energy part of the ionization losses function is included in the new approximation [2, 40]. Vertical penetration of cosmic rays will be considered. It is the base for the full 3D electron production rate model.

Ionization Losses Formula (approximation of the Bohr-Bethe-Bloch function) for 5 energy interval model and nuclei with charge *Z*

The Bohr-Bethe-Bloch function is approximated in 5 energy intervals [1, 2]. One additional interval of charge decrease for cosmic ray (CR) particles from Z to 1 is included in (1) as interval 2.

(1)

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

E is the kinetic energy of charged particles, $\rho(h)$ is the neutral density of atmosphere, h is the altitude of the point, which is considered. The low energy part is taken into account. The ionization losses value is proportional to the square of the charge Z^2. They increase in interval 1 with increase of the kinetic energy E, in interval 2 they increase with increase of the particle charge. That means, the particles decrease their energy below the value $E_a = 0.15\times Z^2 < 200$ MeV during their penetration through the atmosphere. During this energy decrease the effective charge Z^* [2, 40] decreases and at the energy 0.15 MeV the particles become singly charged [2]. This is the energy at which the cosmic ray (CR) proton velocity equals the orbital electron velocity in hydrogen atom [2]. The charge decrease of CR nuclei which begins at energy E_a is due to the electron capturing in the nuclei shells. In intervals 3 and 4 there is a steep decrease of the ionization losses with the increase of kinetic energy. In interval 5 they are constant and in interval 6 they increase slowly with the increase of kinetic energy. This complex structure [1, 2, 46] of the ionization losses curve forms the basis of approximation (1).

Atmospheric cut-offs for 5 interval ionization losses function

The atmospheric cut-offs will be derived for those values of the travelling substance path, which correspond to the actual energy interval of the ionization losses function. For this purpose, the reverse value of the ionization losses function is integrated over the energy variable in the respective energy intervals [1]. The obtained value corresponds to the lowest energy of the particles which contribute to atmosphere ionization (with the assumption that the geomagnetic cut-off rigidity and the electric threshold for the actual height have smaller values [1, 2]).

Energy interval 1. We assume that the value of the travelling substance path $\widetilde{h}$ following the CIRA model [48] is located in interval 1 from (1):

$$(2)\qquad \widetilde{h} = \int_{kT}^{E_{A1}(h)} \frac{AdE}{2570\times E^{0.5}} = \frac{A}{0.5\times 2570} E^{0.5}\Big|_{kT}^{E_{A1}(h)} =$$

$$\frac{A}{1285}\left(E_{A1}^{0.5}(h) - (kT)^{0.5}\right)$$

The solution of equation (2) towards $E_{A1}(h)$ is the atmospheric threshold in interval 1. A is the atomic weight of particles. The integration is performed down to the energy of the thermal plasma of the solar wind.

(3) $$E_{A1}(h)=\left[\frac{1285}{A}\tilde{h}+(kT)^{0.5}\right]^2$$

The particle charge in this interval is equal to 1.

Energy interval 2 (charge decrease energy interval): The atmospheric cut-off in the second interval is calculated by means of the corresponding ionization path. In this case it is assumed that $E_{A1}(h) > 0.15$ MeV/n in (3). It is composed of two terms. In the first term the charge $Z = 1$. The charge in the second term decreases from Z^* to 1 with the energy decrease [40]. $\tilde{h}_i, i = 1,2$ is the travelling substance path in the corresponsing energy interval.

(4) $$\tilde{h}=\tilde{h}_1+\tilde{h}_2=\int_{kT}^{0.15}\frac{AdE}{2570E^{0.5}}+\int_{0.15}^{E_{A2}(h)}\frac{AdE}{1540E^{0.23}}=$$

$$\frac{A}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)+\frac{A}{1540\times 0.77}\left(E_{A2}^{0.77}(h)-0.15^{0.77}\right)$$

The atmospheric cut-off is obtained as solution of equation (4) towards $E_{A2}(h)$:

(5) $$E_{A2}(h)=\left[0.15^{0.77}-\frac{1540\times 0.77}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)+\right.$$

$$\left.+\frac{1540\times 0.77}{A}\tilde{h}\right]^{1/0.77}$$

Energy interval 3: If the value $E_{A2}(h) > E_a$, then the ionization path corresponding to interval 3 is composed of 3 terms with respect to the first 3 energy intervals of the ionization losses function. The charge in interval 1 $Z = 1$. The charge in interval 2 decreases from Z to 1. The charge value in energy interval 3 is equal to Z. A is the atomic weight of cosmic ray particles.

$$(6) \qquad \widetilde{h} = \widetilde{h}_1 + \widetilde{h}_2 + \widetilde{h}_3 = \int_{kT}^{0.15} \frac{A}{2570E^{0.5}} + \int_{0.15}^{E_a} \frac{AdE}{1540E^{0.23}} +$$

$$+ \int_{E_a}^{E_{A3}(h)} \frac{dE}{231\frac{Z^2}{A}E^{-0.77}} =$$

$$\frac{A}{1285}\left(0.15^{0.5} - (kT)^{0.5}\right) + \frac{A}{0.77 \times 1540}\left(E_a^{0.77} - 0.15^{0.77}\right) +$$

$$+ \frac{A}{1.77 \times 231 \times Z^2}\left(E_{A3}^{1.77}(h) - E_a^{1.77}\right)$$

After integration of equation (6), $E_{A3}(h)$ becomes its solution towards the unknown variable:

$$(7) \qquad E_{A3}(h) = \left[E_a^{1.77} - \frac{1.77 \times 231 \times Z^2}{1285}\left(0.15^{0.5} - (kT)^{0.5}\right) - \right.$$

$$- \frac{1.77 \times 231 \times Z^2}{0.77 \times 1540}\left(E_a^{0.77} - 0.15^{0.77}\right) +$$

$$\left. + 231 \times 1.77 \frac{Z^2}{A}\widetilde{h} \right]^{1/1.77}$$

Energy interval 4: If the condition $E_{A3}(h) > 200$ MeV/n is fulfilled, the ionization path is composed of the following 4 terms:

$$(8) \qquad \widetilde{h} = \widetilde{h}_1 + \widetilde{h}_2 + \widetilde{h}_3 + \widetilde{h}_4 = \int_{kT}^{0.15} \frac{AdE}{2570E^{0.5}} + \int_{0.15}^{E_a} \frac{AdE}{1540E^{0.23}} +$$

$$\int_{E_a}^{200} \frac{dE}{231\frac{Z^2}{A}E^{-0.77}} + \int_{200}^{E_{A4}(h)} \frac{dE}{68\frac{Z^2}{A}E^{-0.53}} =$$

$$\frac{A}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)+\frac{A}{1540\times 0.77}\left(E_{a}^{0.77}-0.15^{0.77}\right)+$$

$$\frac{A}{231\times 1.77\times Z^{2}}\left(200^{1.77}-E_{a}^{1.77}\right)+\frac{A}{68\times 1.53\times Z^{2}}\left(E_{A4}^{1.53}(h)-200^{1.53}\right)$$

The charge Z values in the corresponding energy intervals 1 and 2 are formed as in the previous case of the atmospheric cut-off $E_{A3}(h)$. The solution of equation (8) yields the atmospheric cut-off $E_{A4}(h)$:

$$E_{A4}(h)=\left[200^{1.53}+68\times 1.53\frac{Z^{2}}{A}\tilde{h}-\frac{68\times 1.53\times Z^{2}}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)-\right.$$

$$\left.-\frac{68\times 1.53\times Z^{2}}{1540\times 0.77}\left(E_{a}^{0.77}-0.15^{0.77}\right)-\frac{68\times 1.53}{231\times 1.77}\left(200^{1.77}-E_{a}^{1.77}\right)\right]^{1/1.53} \tag{9}$$

Energy interval 5: The condition $E_{A4}(h) > 850$ MeV/n determines the following ionization path calculation [1,2]:

$$\tilde{h}=\tilde{h}_{1}+\tilde{h}_{2}+\tilde{h}_{3}+\tilde{h}_{4}+\tilde{h}_{5}=\int_{kT}^{0.15}\frac{AdE}{2570E^{0.5}}+\int_{0.15}^{E_{a}}\frac{AdE}{1540E^{0.23}}+ \tag{10}$$

$$\int_{E_{a}}^{200}\frac{dE}{231\frac{Z^{2}}{A}E^{-0.77}}+\int_{200}^{850}\frac{dE}{68\frac{Z^{2}}{A}E^{-0.53}}+\int_{850}^{E_{A5}(h)}\frac{dE}{1.91\frac{Z^{2}}{A}}=$$

$$\frac{A}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)+\frac{A}{1540\times 0.77}\left(E_{a}^{0.77}-0.15^{0.77}\right)+$$

$$\frac{A}{231\times 1.77\times Z^{2}}\left(200^{1.77}-E_{a}^{1.77}\right)+\frac{A}{68\times 1.53\times Z^{2}}\left(850^{1.53}-200^{1.53}\right)+$$

$$\frac{A}{1.91\times Z^{2}}\left(E_{A5}(h)-850\right)$$

The following transformation of equation (10) is done with the purpose to find the atmospheric cut-off $E_{A5}(h)$:

$$(11)\qquad \frac{1.91\times Z^2}{A}\widetilde{h}+850=E_{A5}(h)+\frac{1.91\times Z^2}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)+$$
$$\frac{1.91\times Z^2}{1540\times 0.77}\left(E_a^{0.77}-0.15^{0.77}\right)+\frac{1.91}{231\times 1.77}\left(200^{1.77}-E_a^{1.77}\right)+$$
$$\frac{1.91}{68\times 1.53}\left(850^{1.53}-200^{1.53}\right)$$

The solution of equation (11) towards $E_{A5}(h)$ is the following:

$$(12)\qquad E_{A5}(h)=\frac{1.91\times Z^2}{A}\widetilde{h}+850-\frac{1.91\times Z^2}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)-$$
$$\frac{1.91\times Z^2}{1540\times 0.77}\left(E_a^{0.77}-0.15^{0.77}\right)-\frac{1.91}{231\times 1.77}\left(200^{1.77}-E_a^{1.77}\right)-$$
$$\frac{1.91}{68\times 1.53}\left(850^{1.53}-200^{1.53}\right)$$

Energy interval 6: The condition $E_{A5}(h) > 5000$ MeV/n determines the calculation of the atmospheric cut-off $E_{A6}(h)$ from the following expression for the ionization path which is equal to the travelling substance path $\widetilde{h}$ for kinetic energy decrease until absorption of the cosmic ray particles:

$$(13)\qquad \widetilde{h}=\widetilde{h}_1+\widetilde{h}_2+\widetilde{h}_3+\widetilde{h}_4+\widetilde{h}_5+\widetilde{h}_6=\int_{kT}^{0.15}\frac{AdE}{2570E^{0.5}}+\int_{0.15}^{E_a}\frac{AdE}{1540\times E^{0.23}}+$$
$$\int_{E_a}^{200}\frac{dE}{231\frac{Z^2}{A}E^{-0.77}}+\int_{200}^{850}\frac{dE}{68\frac{Z^2}{A}E^{-0.53}}+\int_{850}^{5000}\frac{dE}{1.91\frac{Z^2}{A}}+$$

$$\int_{5000}^{E_{A6}(h)} \frac{dE}{0.66\frac{Z^2}{A}E^{0.123}} = \frac{A}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)+$$

$$\frac{A}{1540\times 0.77}\left(E_a^{0.77}-0.15^{0.77}\right)+\frac{A}{231\times Z^2\times 1.77}\left(200^{1.77}-E_a^{1.77}\right)+$$

$$\frac{A}{68\times Z^2\times 1.53}\left(850^{1.53}-200^{1.53}\right)+\frac{A}{1.91\times Z^2}(5000-850)+$$

$$\frac{A}{0.66\times Z^2\times 0.877}\left(E_{A6}^{0.877}(h)-5000^{0.877}\right)$$

The corresponding transformation of (13) is the following:

$$(14)\qquad 0.66\times 0.877\frac{Z^2}{A}\widetilde{h}+5000^{0.877}=\frac{0.66\times Z^2\times 0.877}{1285}\left(0.15^{0.5}-(kT)^{0.5}\right)+$$

$$\frac{0.66\times Z^2\times 0.877}{1540\times 0.77}\left(E_a^{0.77}-0.15^{0.77}\right)+\frac{0.66\times 0.877}{231\times 1.77}\left(200^{1.77}-E_a^{1.77}\right)+$$

$$\frac{0.66\times 0.877}{68\times 1.53}\left(850^{1.53}-200^{1.53}\right)+\frac{0.66\times 0.877}{1.91}(5000-850)+E_{A6}^{0.877}(h)$$

The solution of (13) - (14) presents the atmospheric cut-off $E_{A6}(h)$ in energy interval 6:

$$(15)\qquad E_{A6}(h)=\Bigg[5000^{0.877}+0.66\times 0.877\frac{Z^2}{A}\widetilde{h}-\frac{0.66\times 0.877\times Z^2}{1285}\times$$

$$\left(0.15^{0.5}-(kT)^{0.5}\right)-\frac{0.66\times 0.877\times Z^2}{1540\times 0.77}\left(E_a^{0.77}-0.15^{0.77}\right)-$$

$$\frac{0.66\times 0.877}{231\times 1.77}\left(200^{1.77}-E_a^{1.77}\right)-\frac{0.66\times 0.877}{68\times 1.53}\left(850^{1.53}-200^{1.53}\right)-$$

$$\frac{0.66\times 0.877}{1.91}(5000-850)\Bigg]^{1/0.877}$$

The calculation of atmospheric cut-offs is important for evaluation of the lower boundary of integration in the corresponding ionization model [1, 2]. It determines the energy interval combinations between the initial cosmic ray kinetic energy intervals and the respective final ionization losses function energy intervals. These combinations create the different integral terms of the electron production rate model for the current valid values of altitude, zenith angle and azimuth angle.

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АТМОСФЕРНИ ПРАГОВЕ НА ОТРЯЗВАНЕ В ОБОБЩЕНИЯ МОДЕЛ НА ЙОНИЗАЦИОННИ ПРОФИЛИ ОТ ЗАРЕДЕНИТЕ ЧАСТИЦИ НА КОСМИЧЕСКИТЕ ЛЪЧИ В ПЛАНЕТНИТЕ ЙОНОСФЕРИ И АТМОСФЕРИ С АПРОКСИМАЦИЯ НА ФУНКЦИЯТА НА ЙОНИЗАЦИОННИТЕ ЗАГУБИ ВЪРХУ 5 ЕНЕРГИЙНИ ИНТЕРВАЛА

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Резюме

В настоящата статия е разгледан един аналитично-числен метод за описание на проникването и йонизацията от ядра на космическите лъчи със заряд Z в планетните йоносфери и атмосфери. Скоростта на електронната продукция се изчислява с нови формули, които съчетават петте основни енергийни интервала на функцията на йонизационните загуби (dE/dh). Тя е 5-интервална функция, която осъществява по-добра апроксимация на измерванията и експерименталните данни в сравнение с предходни резултати за 4–интервална функция на йонизационните загуби. Геомагнитните прагове на отрязване и законите за намаление на енергията за различните интервали се използват за създаване на междинна преходна област на енергията, която осъществява съчетаване на петте основни интервала на функцията на йонизационните загуби. Въвежда се един нов шести енергиен интервал за намаление на заряда в ниските енергии. Разглежда се вертикално проникване на космическите лъчи. Атмосферните прагове на отрязване са изчислени за 6 основни случая на стойностите на дълбочината на атмосферата.