PROCEEDINGS OF SCIENCE

Computation of electron precipitation atmospheric ionization: updated model CRAC-EPII

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A new model of the CRAC family, CRAC:EPII (Cosmic Ray Atmospheric Cascade: Electron Precipitation Induced Ionization) is presented. The model allows one to calculate atmospheric ionization induced by precipitating electrons. The model is based on pre-computed with high-precision ionization yield functions, which are obtained using full Monte Carlo simulation of electron propagation and interaction in the Earth's atmosphere, explicitly considering all physical processes involved in ion production. The simulations were performed using GEANT 4 simulation tool PLANETOCOSMICS with NRLMSISE 00 atmospheric model. A quasi-analytical approach, which allows one to compute the ionization yields for events with arbitrary incidence is also presented. It is compared with Monte Carlo simulations and good agreement between Monte Carlo simulations and quasi-analytical approach is achieved.

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1. Introduction

Different types and populations of high energy particles are involved in the atmospheric ionization [1, 2]. The energetic particles (EPs) are the main sources of ionization below 100 km. At altitudes above 100 km dominate the contribution of solar UV and X-rays, which are absorbed below. Energetic precipitating particles include galactic cosmic rays (GCRs), solar energetic particles (SEPs), precipitating protons, relativistic electrons from radiation belts, auroral electrons. In this work we focus on relativistic electrons, while other sources are considered elsewhere.

The precipitating electrons ionize the atmosphere, specifically it's upper polar part. Effects due to electron precipitation are usually observed in the auroral zone [3]. However, occasionally relativistic electron precipitation can occur also in sub-auroral zone as well as in middle latitudes [4, 5]. In general, electrons precipitate into the atmosphere from different regions of the magnetosphere due to various mechanisms [6, 7, 8, 9, 10, 11]. There are several atmospheric processes affected by the impact ionization as well as processes related to global electric circuit and minor constituents in the Earth's atmosphere [12, 13, 14, 15]. In the upper part of the atmosphere the impact ionization is governed by the direct ionization, while in the lower part of the atmosphere dominates the secondary ionization mostly due to Bremsstrahlung radiation (henceforth Bremsstrahlung).

The majority of studies are focused at heights of about 60–80 km above the sea level (a.s.l.), which correspond to precipitating electrons of about 100–400 keV. However, the contribution of relativistic electron precipitation is not discussed nor the additional Bremsstrahlung ionization. Here, we present a model based on Monte Carlo simulations for computation of ionization induced by relativistic electron precipitation explicitly taking into account Bremsstrahlung.

2. CRAC:EPII model

In this study, the propagation and interaction of high energy protons with the atmosphere are simulated using the PLANETOCOSMICS code [16]. We employ the NRLMSISE 00 atmospheric model [17]. Here, we use a previously developed formalism of a yield function [18]. The ion production rate in the atmosphere is obtained as an integral of the product of the primary particle spectrum and the pre-computed yield function defined as:

$$Y(x,E) = \frac{\partial E(x,E)}{E_{ion}\partial x} \tag{2.1}$$

where ∂E is the energy deposition in atmospheric layer ∂x at depth x, averaged per primary particle with kinetic energy E, and E_{ion}=35 eV is the average energy necessary for production of an ion pair in air [19]. The computations were carried out in the energy range of precipitating electrons between 20 keV and 500 MeV. and at atmospheric depths from 6.5×10^{-9} g/cm^2 (about 200 km a.s.l.) to the sea level (1033 g/cm^2). An example of ionization yields for electrons is shown in Fig.1 (isotropic incidence) and Fig.2 (various incidence). The ionization yield function $Y(x,E)$ convoluted with a primary particle spectrum gives the ion production rate q(x) at a given depth x as

$$q(h) = \int J(K)Y(h,K)\rho(h)dK \tag{2.2}$$

where J(K) is the differential energy spectrum of the primary particles with energy K.

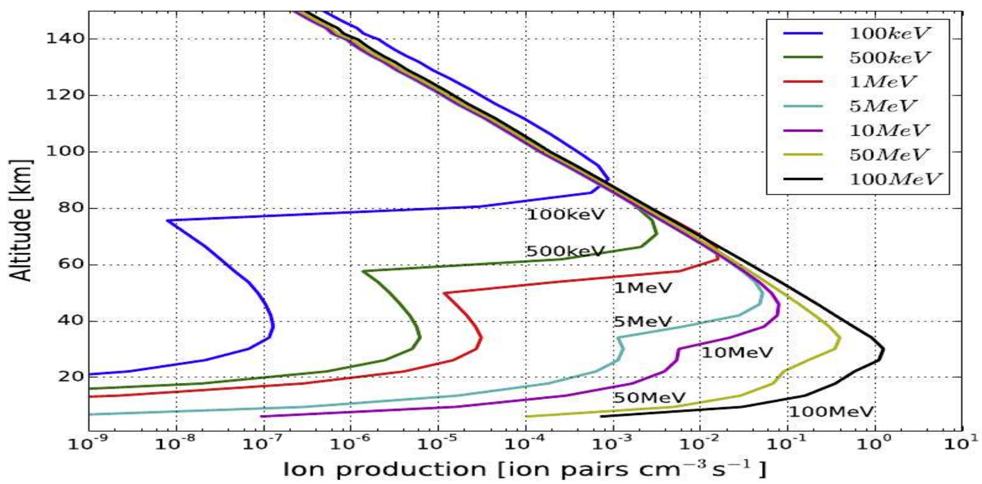

Figure 1: Ionization yields vs. altitude due to isotropic incidence of monoenergetic electrons in the energy range 100 keV–100 MeV, as denoted in the legend.

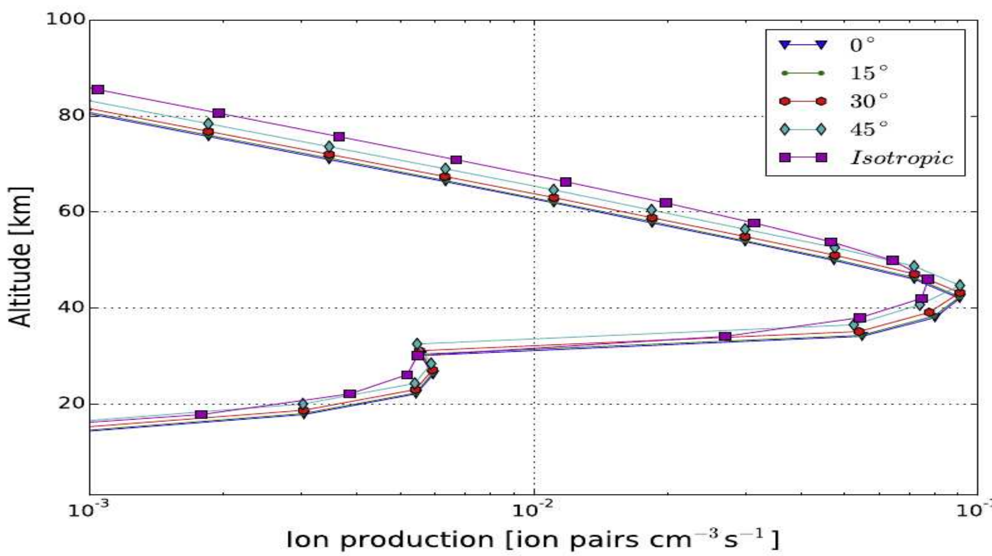

Figure 2: Ionization yelds vs. altitude [km] of electron with 10 MeV energy for isotropic and various angles of incidence as denoted in the legend.

3. Computation of ionization induced by EPs with arbitrary incidence

On the basis of a quasi-analytical approach, based on re-computation of vertically derived ionization yields, we can compute the ionization yields for events with arbitrary incidence, details are given elsewhere [20]. The ionization yields $Y_\alpha(x',K)$ for a monoenergetic electrons with energy K and with angle of incidence α is calculated:

$$Y_\alpha(x,K) = Y(x',K)/\cos\alpha, \tag{3.1}$$

where x' is the rescaled atmospheric depth, calculated as x'=$x/\cos\alpha$ and $Y(x,K)$ is the ionization yields for electrons with vertical incidence computed with the CRAC:EPII model at depth x, details given elsewhere[21, 22]. Let the intensity of electrons is $J(K,\alpha,\phi) = J_0 f(\alpha,\phi)$ where α and ϕ are the the zenith and azimuth angles of incident electrons and J_0 is unit flux and the angular distribution is normalized to 1 i.e. $\int_0^{2\pi}\int_{-\pi/2}^{\pi/2} \sin\alpha d\alpha d\phi = 1$. The flux of electrons within a solid angle $d\Omega = \sin\alpha d\alpha d\phi$ is

$$dF(K) = J_0(K) f(\alpha,\phi) \sin\alpha \cos\alpha d\alpha d\phi \tag{3.2}$$

Accordingly the total flux of electrons is $F(K) = A \cdot J_0(K)$, where $A = \int_0^{2\pi}\int_0^1 f(\alpha,\phi)\cos\alpha d\cos\alpha d\phi$. Hence the ion production rate at depth x is:

$$I(x,K) = \rho(h)\int_0^{2\pi}\int_0^1 J_0(K) Y_\alpha(x,K) f(\alpha,\phi)\cos\alpha d\cos\alpha d\phi \tag{3.3}$$

The corresponding ionization yield function $Y_f(x,K)$ for particles with arbitrary angular distribution $f(\alpha,\phi)$ in a way that $I(x,K) = Y_f(x,K)F(K)\rho(h)$, leads to:

$$Y_f(x,K) = \frac{1}{A}\int_0^{2\pi}\int_0^1 Y_\alpha(x,K) f(\alpha,\phi)\cos\alpha d\cos\alpha d\phi \tag{3.4}$$

In the case of axial symmetry $f(\alpha,\phi)$ is a function only on the zenith angle α. Therefore:

$$Y_f(x,K) = \frac{\int_0^1 Y_v(x',K) d\cos\alpha}{\int_0^1 f(\alpha)\cos\alpha d\cos\alpha} \tag{3.5}$$

where x' is the rescaled atmospheric depth, calculated as x'=$x/\cos\alpha$ and Y_v is the ionization yield function for electrons with vertical incidence. It is easy to see that:

$$f(\alpha) = \frac{n+1}{4\pi}\cos^n\alpha \tag{3.6}$$

which in case of isotropic incidence (distribution) n=0, hence f=$1/\pi$ leads to:

$$Y_{iso}(x,K) = 2\int_0^1 Y_v(x',K) d\cos\alpha \tag{3.7}$$

A good agreement between Monte Carlo simulations and the quasi-analytical approach is achieved (Fig.3)

The yield function $Y(x,K)$ is the response of the atmosphere, the ionization yields, to the mono-energetic unit flux of primary particles entering the Earth's atmosphere. One can see the essential contribution of Bremsstrahlung in the ionization yields, specifically at depths below 1 g/cm^2, which is explicitly considered in the yield function (Fig.4) The shapes of the ionization yield functions as a function of the altitude are similar to each other at depths greater than 5 g/cm^2, but different in the region of the upper atmosphere, where spikes exist due to large fluctuations of the computed energy deposit and the lack of secondary particles.

The differential ionization function F (the integrand of Eq. 2.2, but $\rho(h)$ term), defined as a product of the ionization yield function (Fig.4) and a given spectrum of primary electrons is shown in Figure 5 for several atmospheric depths. Here, we consider a hard electron spectrum from [23], the details of computation are given elsewhere [21]. The differential ionization function F allows

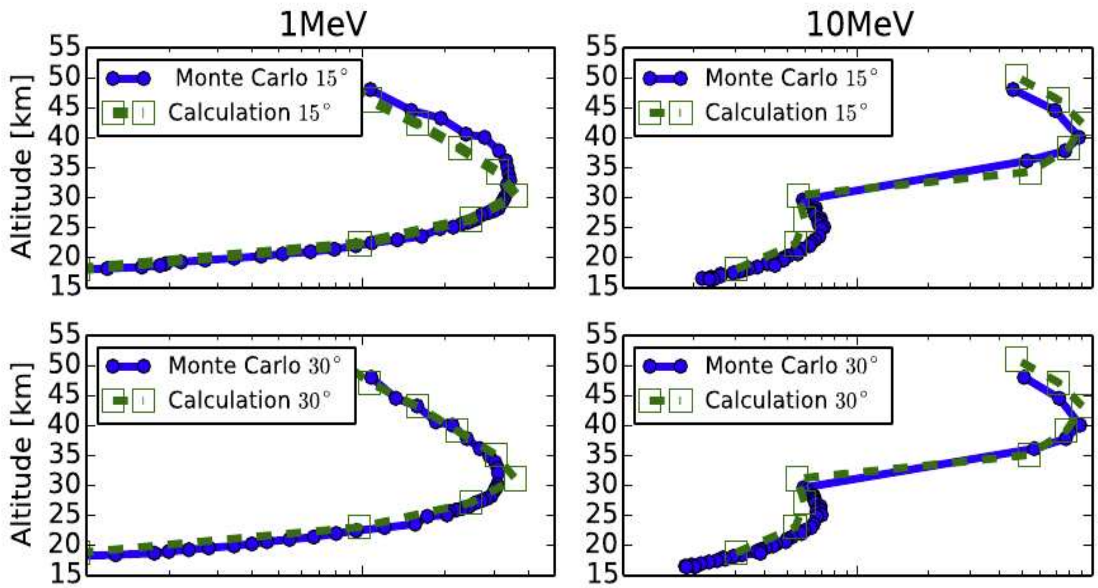

Figure 3: Comparison of ionization rates due to electrons with various angle of incidence and energy as denoted in the legend, computed with quasi-analytical approach Eq. (4) and PLANETOCOSMICS. The left hand panels denote electrons with energy 1 MeV, while right hand denote electrons with energy 10 MeV.

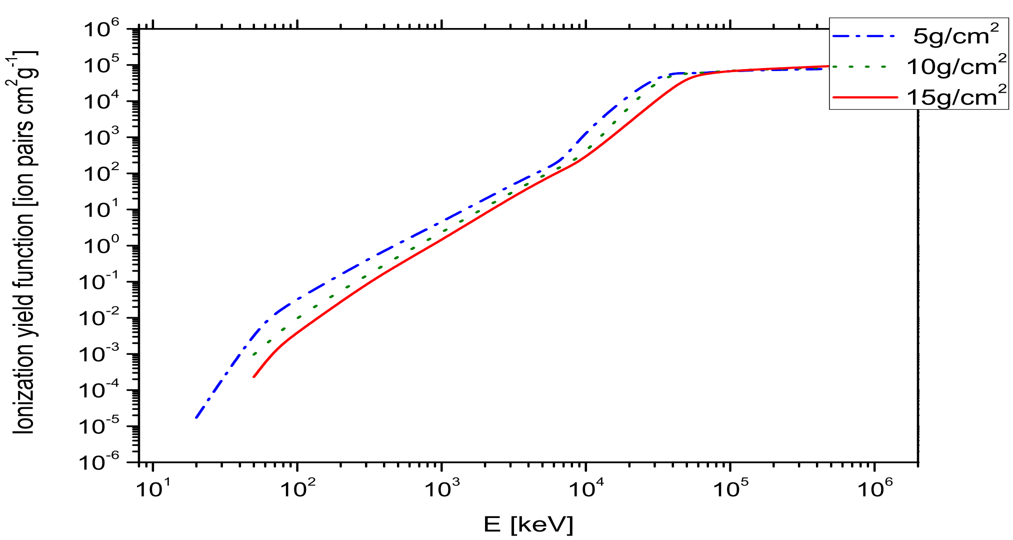

Figure 4: Ionization yield function for precipitating electrons with vertical incidence at several depths as denoted in the legend. The curves are smoothed over the computed data points.

one to estimate the most effective energy of primaries to induce ionization, which strongly depends on the atmospheric depth. Here, the integration is over the energy above 20 keV. One can see that the most effective energy of precipitating electrons to induce ionization strongly depends on the

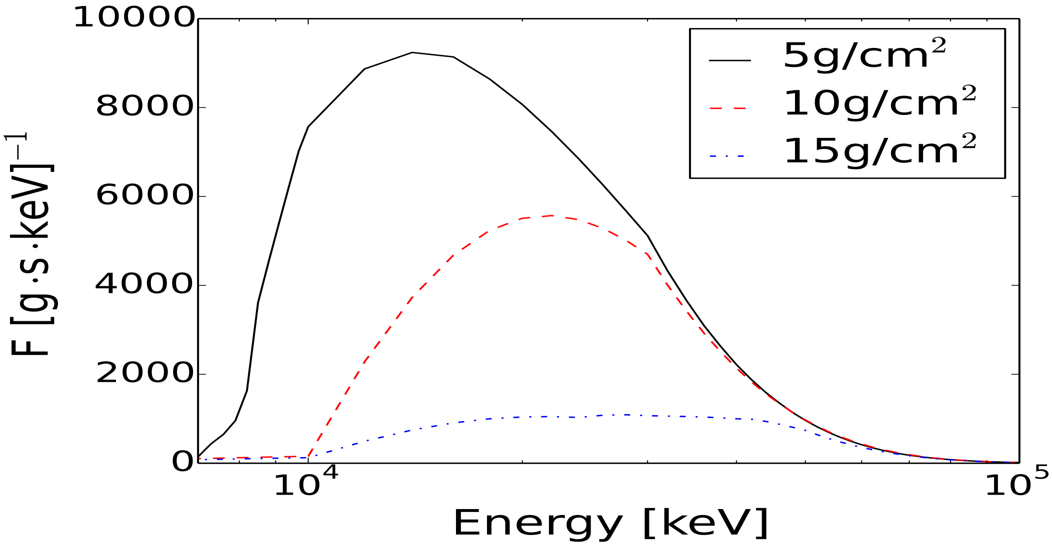

Figure 5: Differential ionization function F for precipitating electrons at several depths as denoted in the legend.

atmospheric depth. The ionization at depth of about 5 g/cm^2 is dominated by electrons with energy of about 10 MeV, accordingly at depth of about 10 g/cm^2 is governed by particles with energy of about 200 MeV. The maximum shifts to higher energies with decreasing the altitude (increasing the depth). At depths of about 15 g/cm^2 the differential ionization function F flattens, because of the diminishing number of high energy precipitating electrons.

4. Conclusion

Here, we have presented an upgraded full numerical model CRAC:EPII, which allows one to compute the ion production in the Earth's atmosphere due to relativistic and high energy precipitating electrons. The model is based on a full Monte Carlo simulations of propagation and interaction of precipitating electrons with the air using the PLANETOCOSMICS code. The model allows one to perform computations of ion production in the whole atmosphere, specifically in the stratosphere over the Globe. In fact, the model is an extension of cosmic ray ionization model CRAC. A convenient quasi-analytical approach for computation of the ionization yields for particles with arbitrary incidence, based on re-computation of vertically derived ionization yields is presented. A good agreement of the approach with direct simulations is achieved.

Acknowledgements

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