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Cosmic ray induced ionization model CRAC:CRII: An extension to the upper atmosphere

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[1] A new version of the CRAC:CRII model computing ionization induced by cosmic rays in the atmosphere is presented, which is extended to the upper atmosphere and can be now applied to the entire atmosphere. The model is able to compute the ionization rate in the atmosphere at any given location and time provided the energy spectrum of incoming cosmic rays is known. It is discussed that the use of earlier models, either analytical or Monte Carlo, with the limited upper energy of 500 MeV, is well validated for the upper atmosphere (above a few g/cm^2 atmospheric depth, which corresponds to the altitude about 40 km) to study the effect of solar energetic particles but may lead to a significant underestimate of the background ionization due to galactic cosmic rays. The use of a full model accounting for the atmospheric cascade and full energy range of incoming cosmic rays, rather than earlier simplified models, is recommended to study the ionization effects of galactic cosmic rays in the upper atmosphere. On the other hand, transient strong effects of solar energetic particle events can be studied using truncated models.

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1. Introduction

[2] Cosmic rays form the main source of ionization of the Earth's atmosphere leading to substantial physical-chemical changes in the ambient air (see, e.g., reviews by *Dorman* [2004] and *Harrison and Tammet* [2008]). Since direct measurements of the ionization, called cosmic ray induced ionization (CRII), are difficult, research in this field is largely based upon models, which need to be reliable and verified. Different models exist which are often used to study CRII effect in the atmosphere. Earlier models were based upon analytical approximations and were not very well suited for the lower atmosphere. Models of the new generation consider the nucleonic-electromagnetic-muon cascade, initiated by cosmic rays in the atmosphere, to its full extent using a Monte Carlo numerical simulation approach. First model of this kind was developed by *Usoskin et al.* [2004] and greatly upgraded recently [*Usoskin and Kovaltsov*, 2006]. This is the CRAC (Cosmic Ray Atmospheric Cascade) model based on CORSIKA and FLUKA Monte Carlo tools. This approach was followed by other groups, leading to a variety of independent models [e.g., *Desorgher et al.*, 2005; *Velinov and Mishev*, 2007; *Vasilyev et al.*, 2008] which made it possible to perform a full mutual test of the models [*Bazilevskaya et al.*, 2008]. Different Monte Carlo based models appear to agree within about 10% with each other and fragmentary direct measurements in the troposphere [*Usoskin et al.*, 2009a], thus providing a useful and reliable tool to study CRII in the lower atmosphere.

[3] Ionization of the upper atmosphere is crucially important for the atmospheric chemistry and dynamics [e.g., *Krivolutsky et al.*, 2005; *Laštovička and Križan*, 2005] and requires a careful modeling. This ionization is usually computed using an analytical approximation of the so-called thin target [*Vitt and Jackman*, 1996]. Such models are typically focused upon the energy range of primary cosmic rays below 500 MeV which corresponds to experimental data from satellite-based detectors. A new Monte Carlo model of the upper atmosphere ionization has appeared recently [*Wissing and Kallenrode*, 2009], which is however also limited to below 500 MeV particles. These models are primarily focused on the effect of solar energetic particles and are less suitable to study galactic cosmic rays. We note that the upper atmosphere's ionization effect, caused by solar energetic or magnetospheric particles, is sporadic and highly temporarily variable by orders of magnitude, while galactic cosmic rays form a slowly changing ionization background which becomes important mostly during quiet periods.

[4] In this paper we extend the recent model CRAC:CRII [*Usoskin and Kovaltsov*, 2006], validated for the troposphere/stratosphere, toward upper atmosphere and discuss validity of different assumptions and approximations. We consider only cosmic rays, of galactic or solar origin, which consist predominantly of protons and α particles. The updated

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Table 1. Ionization Yield Function $Y_p(h, E_o)$ for Primary Cosmic Protons as a Function of the Atmospheric Depth h and Kinetic Energy E_o[a]

	E_o (GeV/nuc)								
h (g/cm^2)	0.1	0.3	1	3	10	30	100	300	1000
0	1.1E+6	5.5E+5	3.5E+5	3.2E+5	3.6E+5	4.1E+5	4.6E+5	5.0E+5	5.5E+5
0.01	1.1E+6	5.6E+5	3.5E+5	3.3E+5	3.7E+5	4.2E+5	4.7E+5	5.1E+5	5.6E+5
0.02	1.1E+6	5.6E+5	3.6E+5	3.4E+5	3.8E+5	4.3E+5	4.7E+5	5.2E+5	5.7E+5
0.03	1.1E+6	5.6E+5	3.6E+5	3.4E+5	3.8E+5	4.3E+5	4.8E+5	5.3E+5	5.8E+5
0.04	1.1E+6	5.6E+5	3.6E+5	3.4E+5	3.9E+5	4.4E+5	4.8E+5	5.3E+5	5.9E+5
0.05	1.1E+6	5.6E+5	3.6E+5	3.4E+5	3.9E+5	4.4E+5	4.9E+5	5.4E+5	5.9E+5
0.06	1.2E+6	5.7E+5	3.6E+5	3.4E+5	3.9E+5	4.4E+5	4.9E+5	5.4E+5	6.0E+5
0.07	1.2E+6	5.7E+5	3.7E+5	3.5E+5	3.9E+5	4.5E+5	5.0E+5	5.4E+5	6.0E+5
0.08	1.2E+6	5.7E+5	3.7E+5	3.5E+5	3.9E+5	4.5E+5	5.0E+5	5.5E+5	6.1E+5
0.09	1.1E+6	5.7E+5	3.7E+5	3.5E+5	4.0E+5	4.5E+5	5.0E+5	5.5E+5	6.1E+5
0.1	1.1E+6	5.7E+5	3.7E+5	3.5E+5	4.0E+5	4.5E+5	5.1E+5	5.6E+5	6.2E+5
0.2	1.2E+6	5.8E+5	3.8E+5	3.6E+5	4.1E+5	4.7E+5	5.3E+5	5.9E+5	6.6E+5
0.3	1.2E+6	5.8E+5	3.8E+5	3.7E+5	4.3E+5	4.9E+5	5.6E+5	6.1E+5	7.0E+5
0.4	1.2E+6	5.9E+5	3.9E+5	3.7E+5	4.4E+5	5.1E+5	5.8E+5	6.4E+5	7.3E+5
0.5	1.2E+6	5.9E+5	3.9E+5	3.8E+5	4.4E+5	5.2E+5	6.0E+5	6.6E+5	7.6E+5
0.6	1.2E+6	5.9E+5	3.9E+5	3.8E+5	4.5E+5	5.4E+5	6.1E+5	6.9E+5	7.9E+5
0.7	1.2E+6	6.0E+5	3.9E+5	3.8E+5	4.6E+5	5.5E+5	6.3E+5	7.1E+5	8.2E+5
0.8	1.2E+6	6.0E+5	4.0E+5	3.9E+5	4.7E+5	5.6E+5	6.5E+5	7.3E+5	8.5E+5
0.9	1.1E+6	6.0E+5	4.0E+5	3.9E+5	4.8E+5	5.7E+5	6.7E+5	7.5E+5	8.8E+5
1	1.1E+6	6.0E+5	4.0E+5	4.0E+5	4.8E+5	5.8E+5	6.8E+5	7.8E+5	9.1E+5
2	1.0E+6	6.1E+5	4.2E+5	4.2E+5	5.4E+5	6.8E+5	8.4E+5	9.9E+5	1.2E+6
3	9.5E+5	6.2E+5	4.3E+5	4.4E+5	5.9E+5	7.6E+5	9.8E+5	1.2E+6	1.5E+6
4	8.5E+5	6.3E+5	4.3E+5	4.5E+5	6.3E+5	8.4E+5	1.1E+6	1.4E+6	1.8E+6
5	7.7E+5	6.3E+5	4.4E+5	4.6E+5	6.8E+5	9.2E+5	1.3E+6	1.7E+6	2.2E+6
6	6.5E+5	6.3E+5	4.5E+5	4.8E+5	7.1E+5	1.0E+6	1.4E+6	1.9E+6	2.6E+6
7	4.5E+5	6.3E+5	4.5E+5	4.9E+5	7.5E+5	1.1E+6	1.6E+6	2.2E+6	3.1E+6
8	3.0E+5	6.3E+5	4.5E+5	4.9E+5	7.9E+5	1.2E+6	1.8E+6	2.5E+6	3.6E+6
9	2.0E+5	6.2E+5	4.5E+5	5.1E+5	8.2E+5	1.2E+6	2.0E+6	2.9E+6	4.1E+6
10	1.5E+5	6.0E+5	4.6E+5	5.1E+5	8.6E+5	1.3E+6	2.1E+6	3.2E+6	4.8E+6
15	3.2E+4	5.3E+5	4.6E+5	5.5E+5	1.0E+6	1.6E+6	3.1E+6	4.8E+6	7.5E+6

[a]Ion pairs are given in sr cm^2 g^{-1}.

model is aimed to simulate the atmospheric ionization from the ground up to the top of the atmosphere and covers the energy range of primary cosmic ray nuclei from several tens of MeV up to TeV (kinetic energy per nucleon). Thus, less energetic particles of magnetospheric origin (e.g., auroral electrons or quasi-trapped particles) are left beyond this model. However, since their energy is low and they cannot initiate a cascade and penetrate deep into the atmosphere, they do not require Monte Carlo simulations and can be adequately modeled by the existing analytics-based models.

2. Cosmic Ray Induced Ionization: Extension of the Model

[5] Here we extended our recent CRAC:CRII model of the CRII toward upper atmosphere. Full details of the model are given elsewhere [*Usoskin and Kovaltsov*, 2006], but we repeat them here in brief. The model uses CORSIKA Monte Carlo tool (v.6.617 August 2007) [*Heck et al.*, 1998] with lower-energy nuclear processes being simulated using FLUKA (v.2006.3b March 2007) [*Fassò et al.*, 2001] tool. The model has been successfully verified against other models and available fragmentary direct data [*Bazilevskaya et al.*, 2008; *Usoskin et al.*, 2009a] and recommended for practical use by COST-724 (http://cost724.obs.ujf-grenoble.fr) and CAWSES/SCOSTEP (http://www.bu.edu/cawses) international programs. Originally, CRII has been computed in equal layers of 10 g/cm^2 atmospheric depth, which provides good enough resolution for lower atmosphere. (The concept of the atmospheric depth refers to the amount of matter (in grams) in an atmospheric column of unit area (1 cm^2) above the given point. This concept is linearly related to the static barometric pressure with the coefficient of 1.0195. For example, the sea level with its 1013.25 hPa barometric pressure corresponds to 1033 g/cm^2 atmospheric depth.) However, this mesh appears too rough to be used for the upper part of the atmosphere. Therefore, inspired by requests from different groups, we have redone the simulations for the upper part of the atmosphere with a finer spatial resolution as required to study ionization there. The newly computed values of the ionization yield function, Y, are given in Tables 1 and 2 for protons and α particles, respectively, for the upper 15 g/cm^2 of the atmosphere (above approximately 28 km).

[6] The function Y is related to the ionization rate Q at a given depth h as:

$$Q(h) = \sum_{\mathrm{A}} \int_{E_{\mathrm{c,A}}}^{\infty} J_{\mathrm{A}}(E_o) \cdot Y_{\mathrm{A}}(E_o, h) dE_o, \qquad (1)$$

where J_{A} is the intensity (in number of nucleons per second · cm^2 · sr · GeV/nuc) of primary cosmic rays of sort A with energy per nucleon E_o. Summation is over the sort of primary particles (protons, α particles and heavier species). Integration is over the kinetic energy of primary particles per nucleon above the energy corresponding to the local geo-

Table 2. Ionization Yield Function $Y_\alpha(h, E_o)$ for Primary Cosmic α Particles as a Function of the Atmospheric Depth h and Kinetic Energy E_o[a]

	E_o (GeV/nuc)								
h (g/cm^2)	0.1	0.3	1	3	10	30	100	300	1000
0	1.1E+6	5.5E+5	3.5E+5	3.2E+5	3.6E+5	4.1E+5	4.6E+5	5.0E+5	5.5E+5
0.01	1.1E+6	5.5E+5	3.5E+5	3.3E+5	3.7E+5	4.2E+5	4.7E+5	5.2E+5	5.8E+5
0.02	1.1E+6	5.6E+5	3.5E+5	3.3E+5	3.8E+5	4.3E+5	4.8E+5	5.3E+5	5.9E+5
0.03	1.2E+6	5.6E+5	3.6E+5	3.3E+5	3.8E+5	4.3E+5	4.8E+5	5.4E+5	6.0E+5
0.04	1.2E+6	5.6E+5	3.6E+5	3.4E+5	3.8E+5	4.4E+5	4.9E+5	5.4E+5	6.1E+5
0.05	1.2E+6	5.6E+5	3.6E+5	3.4E+5	3.9E+5	4.4E+5	4.9E+5	5.5E+5	6.2E+5
0.06	1.2E+6	5.6E+5	3.6E+5	3.4E+5	3.9E+5	4.4E+5	5.0E+5	5.5E+5	6.3E+5
0.07	1.2E+6	5.6E+5	3.6E+5	3.4E+5	3.9E+5	4.4E+5	5.0E+5	5.6E+5	6.4E+5
0.08	1.2E+6	5.6E+5	3.6E+5	3.4E+5	3.9E+5	4.5E+5	5.1E+5	5.6E+5	6.5E+5
0.09	1.2E+6	5.6E+5	3.6E+5	3.4E+5	3.9E+5	4.5E+5	5.1E+5	5.7E+5	6.6E+5
0.1	1.2E+6	5.7E+5	3.6E+5	3.4E+5	4.0E+5	4.5E+5	5.1E+5	5.7E+5	6.6E+5
0.2	1.2E+6	5.7E+5	3.7E+5	3.5E+5	4.1E+5	4.7E+5	5.4E+5	6.1E+5	7.3E+5
0.3	1.2E+6	5.8E+5	3.7E+5	3.6E+5	4.2E+5	4.9E+5	5.7E+5	6.4E+5	7.8E+5
0.4	1.2E+6	5.8E+5	3.8E+5	3.6E+5	4.3E+5	5.0E+5	5.9E+5	6.7E+5	8.3E+5
0.5	1.2E+6	5.8E+5	3.8E+5	3.7E+5	4.4E+5	5.2E+5	6.1E+5	6.9E+5	8.8E+5
0.6	1.2E+6	5.8E+5	3.8E+5	3.7E+5	4.5E+5	5.3E+5	6.4E+5	7.2E+5	9.2E+5
0.7	1.2E+6	5.9E+5	3.8E+5	3.7E+5	4.6E+5	5.4E+5	6.5E+5	7.4E+5	9.7E+5
0.8	1.2E+6	5.9E+5	3.8E+5	3.8E+5	4.6E+5	5.5E+5	6.7E+5	7.7E+5	1.0E+6
0.9	1.2E+6	5.9E+5	3.8E+5	3.8E+5	4.7E+5	5.6E+5	6.9E+5	7.9E+5	1.1E+6
1	1.2E+6	5.9E+5	3.9E+5	3.8E+5	4.8E+5	5.7E+5	7.1E+5	8.1E+5	1.1E+6
2	1.1E+6	6.0E+5	4.0E+5	4.0E+5	5.3E+5	6.5E+5	8.8E+5	1.0E+6	1.5E+6
3	1.1E+6	6.0E+5	4.0E+5	4.2E+5	5.8E+5	7.2E+5	1.0E+6	1.2E+6	2.0E+6
4	9.8E+5	6.0E+5	4.1E+5	4.3E+5	6.3E+5	7.9E+5	1.2E+6	1.4E+6	2.5E+6
5	8.5E+5	6.0E+5	4.1E+5	4.5E+5	6.7E+5	8.5E+5	1.4E+6	1.7E+6	3.0E+6
6	7.1E+5	6.0E+5	4.1E+5	4.6E+5	7.1E+5	9.1E+5	1.5E+6	1.9E+6	3.7E+6
7	5.0E+5	6.0E+5	4.1E+5	4.7E+5	7.5E+5	9.7E+5	1.7E+6	2.1E+6	4.4E+6
8	2.7E+5	5.9E+5	4.1E+5	4.8E+5	7.8E+5	1.0E+6	1.9E+6	2.4E+6	5.1E+6
9	1.5E+5	5.9E+5	4.2E+5	4.9E+5	8.2E+5	1.1E+6	2.1E+6	2.7E+6	6.0E+6
10	7.9E+4	5.7E+5	4.2E+5	5.0E+5	8.6E+5	1.1E+6	2.3E+6	2.9E+6	6.9E+6
15	1.1E+4	4.8E+5	4.2E+5	5.3E+5	1.0E+6	1.6E+6	3.4E+6	4.6E+6	1.1E+7

[a]Ion pairs are given in sr cm^2 g^{-1}.

magnetic cutoff for the particles of sort A. If the yield function Y is expressed in units of (cm^2 g^{-1}), the ionization rate is obtained as the number of ion pairs produced in one gram of air per second. Full details are given by *Usoskin and Kovaltsov* [2006]. Thus, the ionization yield function gives the number of ion pairs produced in one gram of the ambient air at a given atmospheric depth by one nucleon of the primary cosmic ray particle with the given energy per nucleon, i.e., for $J_A = 1$ (cm^2 s sr GeV/nuc)$^{-1}$. Throughout the paper we consider kinetic energy per nucleon. The values of Y for the lower part of the atmosphere remain the same as given by *Usoskin and Kovaltsov* [2006] and thus are not shown here. The practical use of Tables 1 and 2 is identical to the recipe described in section 2.5 of *Usoskin and Kovaltsov* [2006]. Precomputed data tables and a full instruction of the use is available at http://cosmicrays.oulu.fi/CRII/CRII.html.

[7] The uppermost layer of the atmosphere (denoted as 0 g/cm^2 in Tables 1 and 2) can be resolved analytically (see section 3), which is totally independent of the numerical approach applied to the main part of the atmosphere. (We explicitly assume here that the chemical composition is constant in the entire atmosphere. This assumption is well validated for the homosphere (altitude below about 100 km or the atmospheric depth $h > 10^{-3}$ g/cm^2) but may be violated in the heterosphere. Accordingly, the uppermost point in Tables 1 and 2 which formally corresponds to 0 g/cm^2 may be somewhat uncertain.) A smooth transition between the computed ionization functions using the two approaches (analytical and numerical) confirms the validity of the latter.

3. Analytical Approach

[8] Here we performed an analytical calculation of the ionization rate in the upper atmospheric layer, using a thin target approximation similar to, e.g., that by *Vitt and Jackman* [1996]. Within this approach, secondaries produced in the atmospheric cascade can be neglected. Let us consider a primary cosmic rays particle (proton or α particle) with the kinetic energy per nucleon E_o penetrating to the atmosphere at the zenith angle θ. We neglect elastic scattering and assume that the particle moves straight, but loses its energy due to ionization of the ambient air or is lost due to nuclear inelastic processes. The probability of a particle of type A with initial kinetic energy E_o to survive, against inelastic process, until its kinetic energy becomes E' is given as

$$W(E_o, E', A) = \exp\left(-\int_{E'}^{E_o} \frac{dE}{\frac{dE}{dx}(E, A)\cdot\lambda_{\rm in}(E, A)}\right), \qquad (2)$$

where $\frac{dE}{dx}(E, A)$ and $\lambda_{\rm in}(E, A)$ are the stopping power due to ionization losses and the path length for inelastic nuclear collisions, respectively, as tabulated by *Janni* [1982]. The

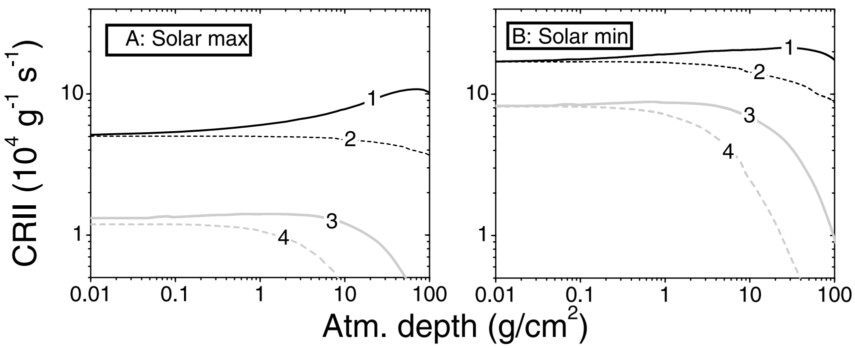

Figure 1. Ionization rate in the polar upper atmosphere induced by galactic cosmic ray protons for (a) solar maximum and (b) solar minimum conditions, computed by different models. The curves are denoted as (1) full Monte Carlo model, (2) full analytical thin-target model, (3) Monte Carlo model considering only primary cosmic rays with energy below 500 MeV, and (4) analytical thin-target model considering only primary cosmic rays with energy below 500 MeV.

energy E' is related to the thickness x (in g/cm^2) traversed by the particle along its trajectory as

$$x = R(E_o) - R(E'), \tag{3}$$

where $R(E)$ is the path length of a particle with energy E due to ionization losses [*Janni*, 1982]. Then, assuming that, on average, one ion-electron pair is produced per each 35 eV of deposited energy [*Porter et al.*, 1976], one can write the ionization rate at a thickness x as

$$\frac{dq}{dx}(x, E_o, A) = \frac{1}{35\,\text{eV}} \cdot \frac{dE}{dx}(E', A) \cdot W(E_o, E', A), \tag{4}$$

where E' is defined from the equation (3).

[9] For a particle with the incident zenith angle θ, the relation between the thickness x traversed by the particle and the atmospheric depth h, assuming the locally flat atmosphere, is

$$x = \frac{h}{\cos\theta} \tag{5}$$

[10] Then the ionization rate at the atmospheric depth h is defined as

$$\frac{dq}{dh}(h, E_o, A) = \frac{1}{\cos\theta} \cdot \frac{dq}{dx}(x, E_o, A). \tag{6}$$

The above consideration was derived for a single nucleon of the primary particle with energy E_o entering the atmosphere at the zenith angle θ.

[11] For the isotropic unit intensity of primary cosmic rays, i.e., $J = 1$ (cm^2 s sr Gev/nuc)$^{-1}$, the flux of particles impinging on the top of the atmosphere from the solid angle Ω is $dF/d\Omega = \cos\theta$. Then the ionization yield function Y is defined as

$$Y_{\text{A}}(E_o, h) = \int \frac{dq}{dh} \cdot \frac{dF}{d\Omega}\, d\Omega = 2\pi \int_0^1 \frac{dq}{dx}(x, E_o, A)\, d\cos\theta, \tag{7}$$

where argument x of function dq/dx is defined by equation (5). Note that at the top of the atmosphere ($h = 0$) this integral is reduced to

$$Y_{\text{A}}(E_o, h = 0) = \frac{2\pi}{35\,\text{eV}} \cdot \frac{dE}{dx}(E_o, A) \tag{8}$$

4. Comparison of Different Approaches

[12] An energetic cosmic ray particle moving through rarefied air of the upper atmosphere directly ionizes the ambient air. Losing energy in this process, the particle gradually decelerates. Low-energy particles can be completely stopped in the upper atmosphere due to these ionization loses. This process can be simply modeled using an analytical approach [see, e.g., *Vitt and Jackman*, 1996]. If, however, a particle possesses high enough energy, it can traverse sufficient amount of matter (of the order of 100 g/cm^2) to accidentally collide with a nucleus of ambient matter and produce a number of secondaries, each of them can also ionize ambient air and subsequently collide with nuclei, etc., leading to the development of an atmospheric cascade. This process is well understood but cannot be modeled analytically and requires a Monte Carlo approach [*Usoskin et al.*, 2004; *Desorgher et al.*, 2005; *Usoskin and Kovaltsov*, 2006]. It dominates CRII in the lower and middle atmosphere (troposphere/stratosphere) but plays also a role in the upper atmosphere as discussed below. Here we compare the results of different models for the upper part of the atmosphere above 100 g/cm^2 (approximately 16 km).

[13] Figure 1 presents a comparison of the CRII in the upper 100 g/cm^2 of the atmosphere due to galactic cosmic ray protons as computed for solar maximum and minimum conditions using the full model described here and an analytical model (section 3), and applying the full energy spectrum of galactic cosmic rays (black curves) or only particles with energy below 500 MeV (grey curves). It is clear from Figure 1 that considering only low-energy protons (<500 MeV, grey curves), one underestimates the ionization rate quite dramatically, by a factor of 2 for the solar minimum and a factor of 5 for the solar maximum

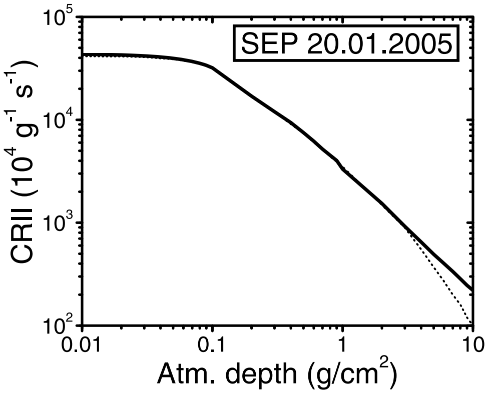

Figure 2. Ionization rate (averaged over the whole day) in the polar upper atmosphere induced by an extreme solar energetic particles event of 20 January 2005. Solid and dashed curves denote the results obtained from the present full Monte Carlo and analytical models, respectively.

conditions, even in the uppermost part of the atmosphere. The difference is larger for the solar maximum because of the harder energy spectrum of GCR [e.g., *Usoskin et al.*, 2005]. When using a simplified analytical model instead of a full solution (solid versus dashed curves) one starts underestimating the ionization rate already at 0.1 g/cm^2 by 10%, by 20–25% at 1 g/cm^2 and by a factor of 2 at 10 g/cm^2. At the atmospheric depth greater than a few tens of g/cm^2 (altitude below $\approx$ 20 km) the analytical model does not work properly.

[14] Atmospheric ionization during solar energetic particle event is usually modeled using an analytical model with incident particles being less energetic than 500 MeV. In Figure 2 we compare the computed CRII in polar region caused by an extreme solar events of 20 January 2005, which was one of the strongest ever observed. The event-integrated energy spectrum of solar particles has been taken the same as that of *Usoskin et al.* [2009b]. First of all, the averaged level of ionization in the upper atmosphere during that day was orders of magnitude greater than that due to galactic cosmic rays only. The analytical model considering only protons with energy below 500 MeV corresponds pretty well to the full model computation in the upper few g/cm^2 (about 40 km altitude). Below that, the analytical model progressively underestimates the effect.

5. Conclusions

[15] We have presented an extended version of the CRAC:CRII model [*Usoskin and Kovaltsov*, 2006], which can be now applied to the entire atmosphere. The model is able to compute the ionization rate induced by solar or galactic cosmic rays in the atmosphere at every given location and time provided the energy spectrum of incoming cosmic rays is known. Other sources of the upper atmosphere ionization, such as solar electromagnetic radiation or precipitating particles of magnetospheric origin, are not considered in the framework of this study.

[16] It is shown that the use of earlier models, either analytical or Monte Carlo with the limited upper energy of 500 MeV, is well validated for the upper atmosphere (above a few g/cm^2 atmospheric depth or 40 km altitude) to study the effect of solar energetic particles but may lead to a significant underestimate of the background ionization due to galactic cosmic rays.

[17] Therefore, we recommend that a full model accounting for the atmospheric cascade and full energy range of incoming cosmic rays, the CRAC:CRII model presented here, or, e.g., the PLANETOCOSMIC [*Desorgher et al.*, 2005] model, is used to study the ionization effects in the upper atmosphere caused by galactic cosmic rays, while transient strong effects of solar energetic particle events can be studied using truncated models.

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