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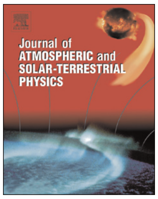

Influence of hadron and atmospheric models on computation of cosmic ray ionization in the atmosphere—Extension to heavy nuclei

A.L. Mishev [a,c,*], P.I.Y. Velinov [b]

[a] Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 Tzarigradsko chaussee, 1784 Sofia, Bulgaria
[b] Institute for Space Research and Technology, Bulgarian Academy of Sciences, Bl. 1 Acad. G. Bonchev str., 1113 Sofia, Bulgaria
[c] Sodankylä Geophysical Observatory (Oulu unit), University of Oulu, Finland

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ABSTRACT

In the last few years an essential progress in development of physical models for cosmic ray induced ionization in the atmosphere is achieved. The majority of these models are full target, i.e. based on Monte Carlo simulation of an electromagnetic-muon-nucleon cascade in the atmosphere. Basically, the contribution of proton nuclei is highlighted, i.e. the contribution of primary cosmic ray α-particles and heavy nuclei to the atmospheric ionization is neglected or scaled to protons. The development of cosmic ray induced atmospheric cascade is sensitive to the energy and mass of the primary cosmic ray particle. The largest uncertainties in Monte Carlo simulations of a cascade in the Earth atmosphere are due to assumed hadron interaction models, the so-called hadron generators. In the work presented here we compare the ionization yield functions Y for primary cosmic ray nuclei, such as α-particles, Oxygen and Iron nuclei, assuming different hadron interaction models. The computations are fulfilled with the CORSIKA 6.9 code using GHEISHA 2002, FLUKA 2011, UrQMD hadron generators for energy below 80 GeV/nucleon and QGSJET II for energy above 80 GeV/nucleon. The observed difference between hadron generators is widely discussed. The influence of different atmospheric parametrizations, namely US standard atmosphere, US standard atmosphere winter and summer profiles on ion production rate is studied. Assuming realistic primary cosmic ray mass composition, the ion production rate is obtained at several rigidity cut-offs – from 1 GV (high latitudes) to 15 GV (equatorial latitudes) using various hadron generators. The computations are compared with experimental data. A conclusion concerning the consistency of the hadron generators is stated.

1. Introduction

Subatomic particles of galactic and extra-galactic origin: cosmic rays (CR)s constantly impinge the Earth's atmosphere. They govern the ionization in the middle atmosphere and troposphere (Velinov et al., 1974; Dorman, 2004; Bazilevskaya et al., 2008; Usoskin et al., 2009). Primary CR particles initiate nuclear-electromagnetic-muon cascade resulting in an ionization of the ambient air. In this cascade only a fraction of the energy of the primary CR is transfer to high energy secondary particles reaching the ground. Most of the primary energy is released in the atmosphere by ionization and excitation of the molecules of air (Bazilevskaya et al., 2008; Usoskin et al., 2009).

The ion pair production is related to various atmospheric processes (de Jager and Usoskin, 2006; Bazilevskaya et al., 2008; Dorman, 2009), influence on electric circuit and on chemistry compositions, aerosols, etc. in the middle atmosphere, specifically during major solar proton events (Vitt and Jackman, 1996; Damiani et al., 2008; Jackman et al., 2008; Velinov and Tonev, 2008; Calisto et al., 2011; Jackman et al., 2011; Mironova et al., 2012; Kilifarska et al., 2013; Tonev and Velinov, 2013; Tassev et al., 2014). While the atmospheric effect of cosmic ray of galactic or solar origin is highly debated, the role of cosmic ray induced ionization is apparent (Usoskin and Kovaltsov, 2006; Bazilevskaya et al., 2008; Dorman, 2009). At present an essential progress in development of physical models for cosmic ray induced ionization in the atmosphere is achieved (Usoskin and Kovaltsov, 2006; Bazilevskaya et al., 2008; Usoskin et al., 2009; Velinov et al., 2009). The estimation of cosmic ray induced ionization is possible on the basis of semi-empirical models (O'Brien, 1970), simplified analytical models (O'Brien, 2005) or on a Monte Carlo simulation of the atmospheric cascade (Desorgher et al., 2005; Usoskin et al., 2004; Usoskin and Kovaltsov, 2006; Velinov et al., 2009). The analytical models are constrained to a given atmospheric region and/or cascade

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[*] Corresponding author at: Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 Tzarigradsko chaussee, 1784 Sofia, Bulgaria. Tel.: +359 2 9746310; fax: +359 2 9753619.
E-mail address: mishev@inrne.bas.bg (A.L. Mishev).

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component or primary particles (Velinov et al., 2012; Asenovski et al., 2013).

The largest uncertainties in numerical simulations of an atmospheric cascade are due to the assumed models for hadron interactions i.e. the so-called hadron generators. The stochastic nature of the individual particle production leads to large shower-to-shower fluctuations, which depend on the particle mass number. The probability for interaction of a primary CR particle depends only on its traversed amount of matter (atmospheric air). The atmospheric depth associated with a given height above sea level plays a key role in cascade simulation (Risse and Heck, 2004; Engel et al., 2011). In addition, the development of the cascade process in the atmosphere depends on the properties of the medium (Bernlöhr, 2000). As it was recently demonstrated, the seasonal variations of the atmospheric profiles assumed in CORSIKA code seem to be rather large and they play an important role in cascade development simulation (Keilhauer et al., 2004, 2006).

Moreover, the contribution of proton nuclei in recent studies of cosmic ray induced ionization is highlighted (Ondraskova et al., 2008; Mishev et al., 2010, 2011a; Calisto et al., 2011; Usoskin et al., 2011). Basically, the contribution of CR nuclei to the atmospheric ionization is neglected or scaled to protons (Desorgher et al., 2005; Usoskin and Kovaltsov, 2006; Mishev et al., 2010; Usoskin et al., 2011). In this connection, the influence of assumed low energy hadron interaction models and atmosphere seasonal variations in CORSIKA (COsmic Ray SImulations for KAscade) code on the energy deposit, respectively ionization is of a big interest. In the paper presented here, we study the effect of assumed hadron generators on computations of cosmic ray induced ionization in the atmosphere, specifically the contribution of heavy nuclei, as well as the influence of different atmospheric parametrizations assumed in CORSIKA code, namely US standard atmosphere, US standard atmosphere winter and summer profiles (for details see Appendix D in Heck et al. (1998) and references therein).

2. Model for cosmic ray induced ionization

In the paper presented here we apply a full target model similar to Oulu model for cosmic ray induced ionization (Usoskin and Kovaltsov, 2006). We use the ionization yield function Y formalism:

$$Y(h,E)=\frac{\triangle E(h,E)\Omega}{\triangle h E_{ion}} \tag{1}$$

where $\triangle E$ is the deposited energy in an atmospheric layer $\triangle h$, Ω is the geometry factor – a solid angle and $E_{ion}=35$ eV is the energy necessary for creation of an ion pair in air (Velinov et al., 1974; Porter et al., 1976), h represents the air overburden above a given altitude in the atmosphere expressed in g/cm^2. The ion production rate is obtained on the basis of Eq. (2) following procedure described by Mishev and Velinov (2007a), Velinov and Mishev (2007), Velinov et al. (2009)

$$Q(h,\lambda_m)=\sum_i\int_E^\infty D_i(E)Y_i(E,h)\rho(h)dE \tag{2}$$

where $D_i(E)$ is the differential cosmic ray spectrum for a given component i: protons p, Helium (α-particles), Light nuclei L ($3\le Z\le 5$), Medium nuclei M ($6\le Z\le 9$), Heavy nuclei H ($Z\ge 10$) and Very Heavy nuclei VH ($Z\ge 20$) in the composition of primary cosmic rays (Z is the atomic number); Y_i is the ionization yield function defined according to Eq. (1) for various i, ρ is the atmospheric density, λ_m is the geomagnetic latitude, E is the initial energy of the incoming primary nuclei on the top of the atmosphere.

The simulation of the atmospheric cascade is performed with the CORSIKA 6.990 code (Heck et al., 1998). The assumed in this study hadron generators are: FLUKA (a German acronym for Fluctuating Cascade) 2011 (Fasso et al., 2005; Battistoni et al., 2007), GHEISHA (Gamma-Hadron-Electron-Interaction SH(A) ower) 2002 (Fesefeldt, 1985), UrQMD (Ultrarelativistic Quantum Molecular Dynamics) (Bass et al., 1998; Bleicher et al., 1999) for hadron interactions below 80 GeV/nucleon and QGSJET (Quark Gluon String with JETs) II (Ostapchenko, 2006) for high energy range above 80 GeV/nucleon.

3. Results for atmospheric cascade simulations

The atmospheric cascade simulations are performed with CORSIKA 6.990 code. As was mentioned above, various hadron generators for hadron interactions below 80 GeV/nucleon are assumed: FLUKA 2011 , GHEISHA 2002, UrQMD. For high energy range above 80 GeV/nucleon the QGSJET II hadron generator is applied. As it was demonstrated the number of charged particles, respectively energy deposition in an atmospheric cascade as a function of atmospheric depth is sensitive to the atmospheric density profile (Bernlöhr, 2000; Keilhauer et al., 2004, 2006). In order to study the influence of several atmospheric density profiles on cosmic ray induced ionization we assume different atmospheric parametrizations used in CORSIKA code (Mishev and Velinov, 2008, 2010). The atmospheric profiles used in this study are: US standard atmosphere profile parametrized by Keilhauer et al. (2004), US standard atmosphere winter and summer profiles (for details see Appendix D in Heck et al., 1998 and references therein), based on various measurements over Middle and North Europe, Argentina, South Pole, etc. In all cases the density variation of the atmosphere with altitude is modelled by 5 layers (layer one: 0–4 km above sea level (a.s.l.), layer two: 4–10 km a.s.l., layer three: 10–40 km a.s.l., layer four: 40–100 km a.s.l, layer five: >100 km a.s.l). In the four lower layers (altitude till 100 km a.s.l.) the density, accordingly mass overburden follows an exponential dependence on the altitude, while in the last layer (above 100 km a.s.l.) the mass overburden decreases linearly. The boundary of the US standard atmosphere assumed in CORSIKA code is at the height where the mass overburden vanishes i.e. at $h=112.8$ km above sea level. We simulate up to 100,000 events per energy point per nuclei and compare the ionization yield function Y. For the computations presented in Figs. 1–3 we assume US standard atmosphere parametrized according to Keilhauer et al. (2004).

The simulation results for primary α-particles are presented in Fig. 1a–d for 1 GeV, 10 GeV, 100 GeV and 1 TeV kinetic energy of the primary nuclei. In the case of 1 GeV/nucleon the relative difference between yield functions computed with different hadron generators is irregular as a function of the altitude. A significant difference above about 16 km a.s.l. with excess of ionization capacity assuming FLUKA hadron generator is seen (Fig. 1a). The relative difference between FLUKA and GHEISHA is in the order of 15–18% at altitude of 15 km a.s.l., while below and above this level it increases significantly up to 50–80% or even to 120–125% (at altitude about 11 km a.s.l.). Accordingly, the difference between FLUKA and UrQMD is about 30% in the region in and above the Pfotzer maximum (a secondary particle intensity maximum at the altitude of 15–26 km, which depends on latitude and solar activity) (Fig. 1a). Below this level the relative difference is quasi-constant in the order of 20%. Several example values are given in Tables 1 and 2. The relative difference between UrQMD and GHEISHA is significant in the region of the Pfotzer maximum and diminish below this altitude. In the troposphere at altitude of about 5 km a.s.l., where the intrinsic cascade fluctuations takes