The induced Ionization by Solar Cosmic Rays in the Earth Atmosphere-CORSIKA code simulations

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Abstract—. **In this work we propose physical model for estimation of solar cosmic ray induced ionization in the upper atmosphere of the Earth on the basis of recent simulations. The contribution of the electromagnetic, muon and hadronic components to total ionization is computed. Atmospheric cascade processes are simulated using CORSIKA code. The Fluka and QGSJET hadronic interaction subroutines are applied. The simulations are carried out according US Standard Atmosphere, taking into account Earth curvature. The atmosphere is divided in 1036 layers per 1g/cm^2, allowing good precision for longitudinal energy deposit estimation, respectively ion pair production. Different energies of primary solar protons are considered. The energy deposit of different cascade components is obtained. As a result the ionization yield function Y is computed. This permitted to obtain explicitly the profiles of ion production rates q(h) by solar cosmic rays in the upper atmosphere.**

1. INTRODUCTION

THE cosmic rays are the dominant source of ionization of the troposphere. The galactic cosmic rays create the ionization in the stratosphere and troposphere and also in the independent ionosphere layer at altitudes 50-80 km in the D region [1]. First Van Allen (1952) [2] received cosmic ray produced ionization in the atmosphere on the basis of V2 rocket sounding measurements. The study of cosmic ray induced ionization is very important, because it is connected with cloud formation and atmospheric chemistry.

The primary galactic cosmic rays extend over twelve decades of energy with the corresponding decline in the intensity. The flux goes down from 10^4 m^{-2} s^{-1} at energies ~ 10^9 eV to 10^{-2} km^{-2} yr^{-1} at energies ~10^{20} eV.

The solar cosmic rays originate mostly from solar flares. Coronal mass ejections and shocks in the interplanetary medium also produce energetic particles. Usually solar cosmic ray particles have energy of up to several hundred MeV/nucleon, rarely up to few GeV/nucleon. Their composition is similar to galactic cosmic rays: mostly protons, about 10% of He and <1% heavier elements. During strong solar flares, the flux of particles at the Earth largely increases leading in some case to a ground level enhancements.

A solar flare is a violent explosion of the surface of the Sun's. Solar flares take place in the solar corona and chromosphere. In solar flare different particles, such as, electrons, protons and even heavy ions are accelerated. Usually the flares occur in active regions around sunspots.

As was mentioned above the solar flares are associated with coronal mass ejections, which represents an ejection of material from the solar corona. The ejected material is a plasma consisting of electrons, protons and small quantities of heavier nuclei such as Helium, Oxygen and Iron.

The particles from primary cosmic ray radiation produce cascade processes in the Earth atmosphere. The high energy particle from primary cosmic ray collides with an atmospheric nucleus and produces new, very energetic particles. Those also collide with air nuclei. Each collision adds a large number of particles to the cascade. Some of the produced particles are neutral pions. The neutral pions immediately decay to a pair of high energy gamma quanta. The gamma quanta produce electron positron pairs passing near air nuclei. The electrons and positrons regenerate gamma rays via Bremsstrahlung, building the electromagnetic cascade. The charged pions decay into muons. In addition different hadrons, strange particles, are produced in strong interactions. As a result we observe nucleonic-electromagnetic cascade. The secondary particles depose energy in the atmosphere. As a result they ionize the medium i.e. this is cosmic ray induced ionization.

Obviously the ionization profiles are connected with energy deposit of the EAS particles. To estimate the cosmic ray induced ionization it is possible to use a model based on an analytical approximation of the atmospheric cascade [3] or on a Monte Carlo simulation of the atmospheric cascade [4, 5].

2. MODEL

Our model is based on full Monte Carlo simulation of the atmospheric cascade processes. The majority of Monte Carlo codes for cascade simulations give detailed information for type, energy, momentum, direction and arrival time of secondary particles ate given location. The CORSIKA code [6] gives the possibility to obtain information about the characteristics of large diversity of particles at given location

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(observation depth) in the atmosphere. In addition, very important for our aims, it is possible to sample the longitudinal shower development and obtain fluxes (for electromagnetic, hadronic, muon particles, as well as neutrinos and Cherenkov photons), and deposited energy of secondary particles.

In this work we apply the formalism for ionization yield function *Y* which is defined according Oulu model [7]

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

where ΔE is the deposited energy in layer Δx in the atmosphere and Ω is a geometry factor, integration over the solid angle.

In *Y* we use E_{ion}=35 eV [8], which is the energy needed for production of one ion pair and Ω is geometrical factor (integration over the solid angle with zenith of 70 degrees). Basically the ionization yield function *Y* gives an average of produced ion pairs at given observation level and at given energy of the primary particle. In addition ionization yield function *Y* gives the possibility to estimate the ion pair production in the case when one deal with mean spectrum.

Therefore the ion pair production *q* by cosmic rays following steep spectrum is calculated according the formula:

$$q(h,\lambda_m) = \int_{E_0}^{\infty} D(E,\lambda_m)Y(h,E)\cdot\rho(h)dE \qquad (2)$$

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

The simulation of atmospheric cascade processes is carried out with CORSIKA 6.52 code [6]. The hadronic interactions below 80GeV/nucleon are simulated with FLUKA 2006 [9] and above 80GeV/nucleon with QGSJET II [10] subroutines. The electromagnetic interactions in CORSIKA are simulated with EGS4 [11]. The SLANT version of the code is applied [12] with realistic curved atmospheric model [13]. This permits to follow the longitudinal shower development in vertical bins, counting all particles crossing horizontal layers and summing the deposited energy between two consecutive horizontal layers. The atmospheric depth is parameterized according to J. Linsley US Standard Atmosphere model [14]. The atmosphere is divided in layers per 1g/cm^2. This gives the possibility for detailed description of deposited energy, respectively ion pairs production.

The contribution of the different cascade components is taken into account, namely the electromagnetic, muon and hadron component [15, 16] and their contribution as a function of the altitude and energy is analyzed.

3. IONIZATION RATES FROM PRIMARY SOLAR PROTONS

The energy deposit in the Earth atmosphere is obtained on the basis of full Monte Carlo simulation of the atmospheric cascade processes due to solar protons using CORSIKA 6.52 code [6] and hadronic interaction models FLUKA 2006 [9] and QGSJET II [10]. Therefore the ionization rates are obtained using ionization yield function Y (1) taking into account proton step spectrum with index 5.0.

In Fig. 1 and Fig.2 are presented the obtained ionization rates for solar protons with different energies, namely 10MeV, 20 MeV, 40 MeV and 60 MeV.

The used statistics varies between 10 000 and 50 000 events per energy point. As was expected the shape of ioniozation profiles and the position of the Pfotzer maximum are very similar [17]. However we observe several differences. As was expected the position of Pfotzer maximum is deeper in the atmosphere for 60 MeV incoming protons. The observed differences in ionization rates (Fig.3) are due essentially on the different particle fluxes, because the steepness of the spectrum.

The observed large fluctuations below 600 g/cm^2 level are due essentially of low particle fluxes at this atmospheric region and low statistics. The can be considered as systematic errors. Obviously it is necessary to study the processes in low atmosphere separately.

Obviously the solar energetic particles effects are important in the upper atmosphere of the Earth, namely in stratosphere, mesosphere and lower thermosphere as well in the polar regions. It is known that cosmic rays plays important role for electric conductivity processes in the middle atmosphere. Therefore they influence the atmospheric electric processes. The solar cosmic rays, appeared during sporadic solar energetic particle events associated with solar flares, coronal mass ejections. In this connection the quantitative study of solar cosmic rays ionization in the troposphere-stratosphere is of a big interest as well the contribution of the different components to total ionization in attempt to investigate previously proposed analytical models.

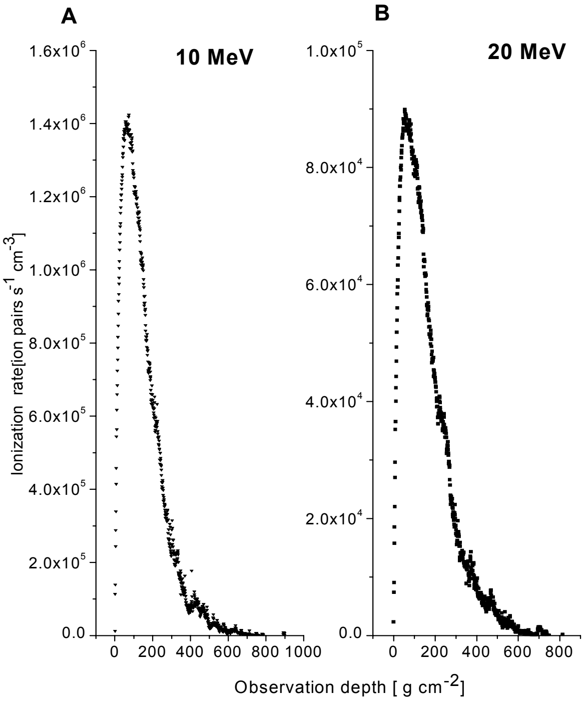

Fig. 1 The ionization rates for 10 and 20 MeV solar protons

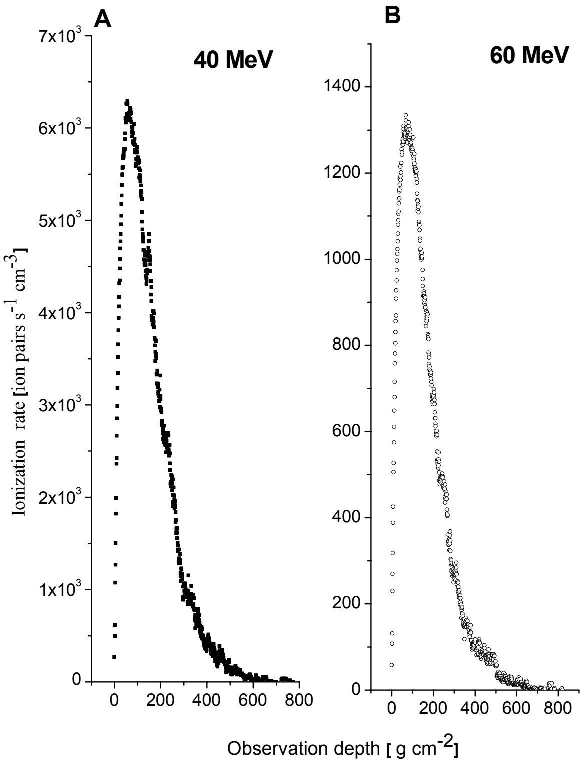

Fig. 2 The ionization rates for 40 MeV and 60 MeV solar protons

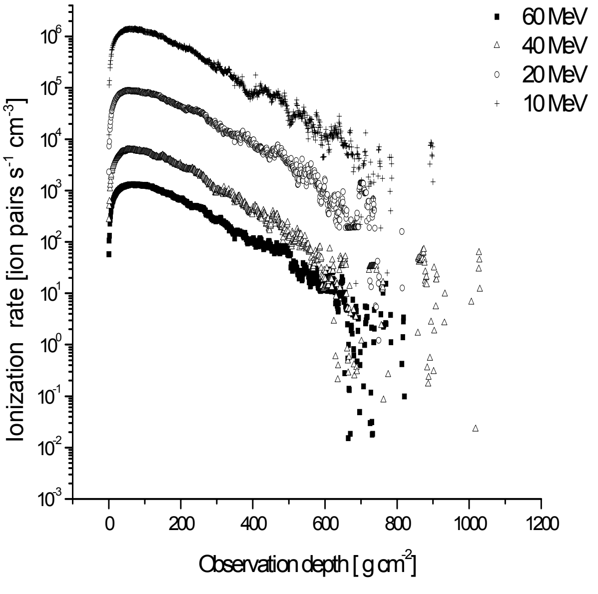

Fig. 3 Comparison of ionization profiles due to solar protons with different energies

4. CONTRIBUTION OF DIFFERENT COMPONENTS

On the basis of formalism described in section 2 of the paper using the obtained ionization yield function Y (1), which gives the number of ion pairs, produced in 1 g of the ambient air at a given atmospheric depth by 1 proton of the primary cosmic ray particles with the given energy per nucleon and convenient parameterization of cosmic ray spectrum we obtain the ionization rates according formula (2) due to primary solar protons.

The results are plotted as ion pairs per second in cm^3 function of the observation depth. In Fig. 4-7 are plotted the ionization profiles for 10 MeV, 20 MeV, 40 MeV and 60 MeV protons respectively. With solid black squares is shown the total ionization. The electromagnetic component is presented with open circles. The hadron and muon components are shown with up and dawn triangles.

The contribution of hadron component to total ionization in all cases is significant [18]. At the other hand the contribution of muon component is in practice negligible. The ionization due to energy deposit from hadron particles, in the case of 10 MeV (Fig. 4) solar protons, dominates till 250 g/cm^2 observation level. Below this altitude the contribution of hadron and electromagnetic components is in practice equal. Similar behavior of component contribution is observed in the case of 20 MeV solar protons as incoming particles (Fig.5). In this case the hadron contribution dominates till altitudes corresponding to 280 g/cm^2. In the case of 40 and 60 MeV solar protons as initiating atmospheric cascade particles the electromagnetic and hadron particles render energy equally deeper in the atmosphere (Fig.6 and Fig.7). In all cases the contribution from hadron particles dominates till observation depths of some 300 g/cm^2.

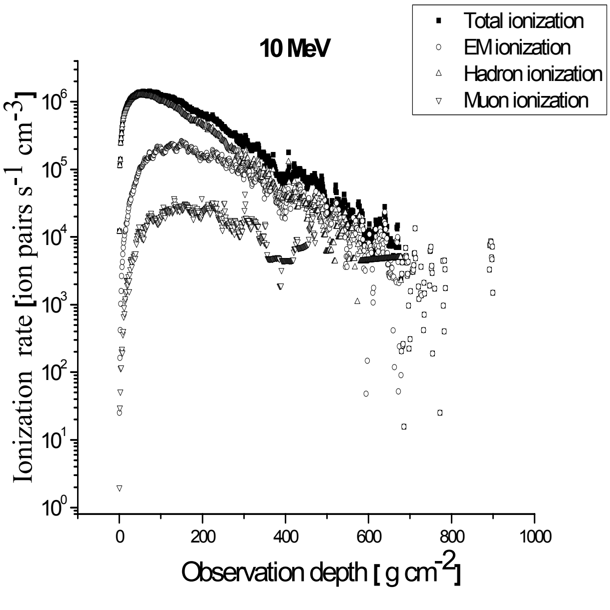

Fig. 4 Ionization rate for 10 MeV solar protons with contribution of EM, hadron and muon components

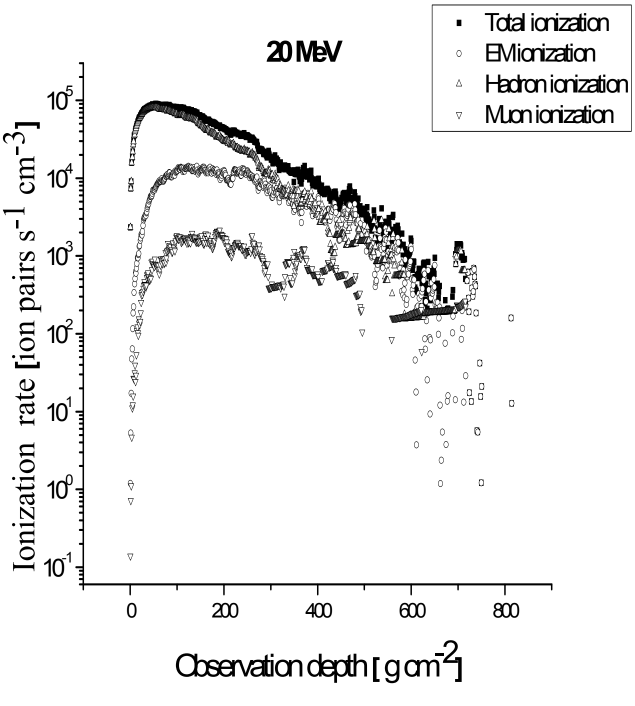

Fig. 5 Ionization rate for 20 MeV solar protons with contribution of EM, hadron and muon components

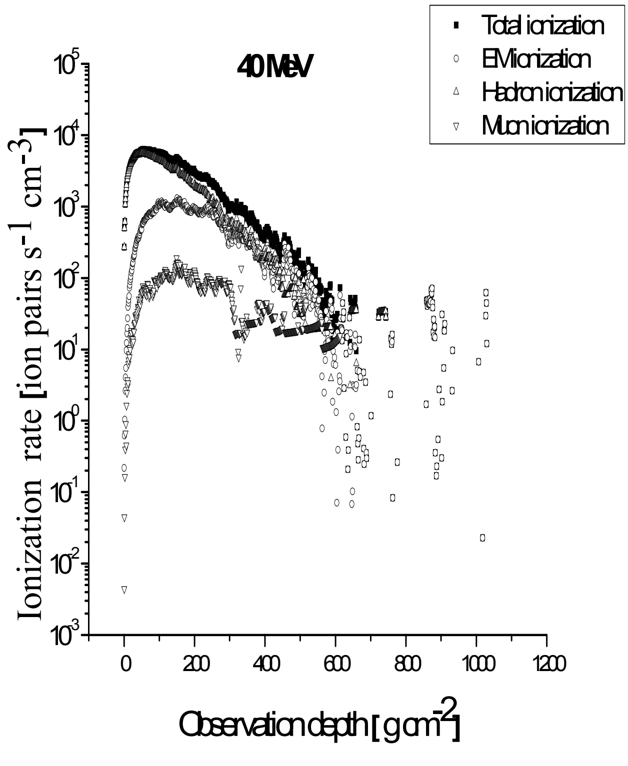

Fig. 6 Ionization rate for 40 MeV solar protons with contribution of EM, hadron and muon components

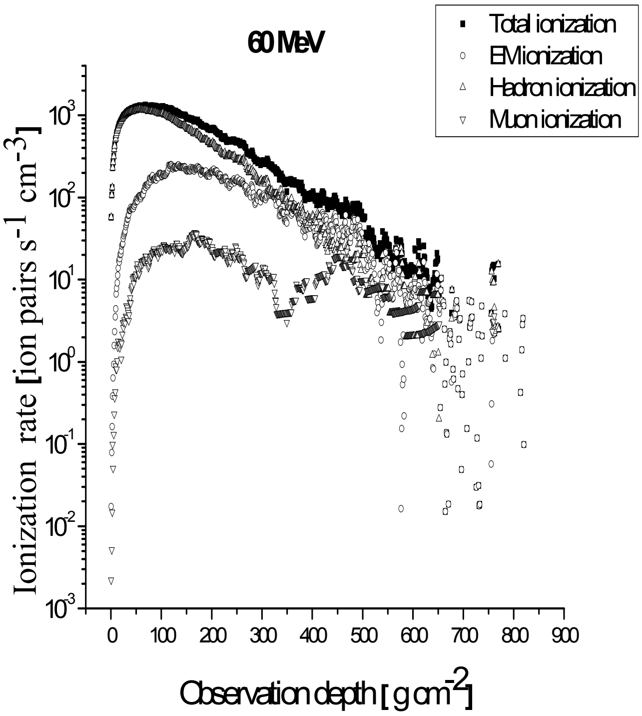

Fig. 7 Ionization rate for 60 MeV solar protons with contribution of EM, hadron and muon components

5. DISCUSSION

In all plots large fluctuations of the energy deposit, respectively ion pair production are observed at altitudes below 600-700 g/cm^2 (below 4000 m above seal level). They are due essentially to low secondary particle flux in this atmospheric region and may be considered as systematic errors. The contribution of hadron component to total ionization is significant especially at observation levels above 300 g/cm^2 (9300 m above sea level). Therefore the present work gives the possibility to improve several previously proposed models, which take into account only electromagnetic component.

The solar energetic particles effects are important in the upper atmosphere of the Earth, namely in stratosphere, mesosphere and lower thermosphere. The adequate model of cosmic ray induced ionization is a first step for electric conductivity processes in the middle atmosphere understanding. The solar cosmic rays, appeared during sporadic solar energetic particle events associated with solar flares, coronal mass ejections. It exist several studies showing a statistical relation between such events and atmospheric properties [19, 20].

Obviously on the basis of recent CORSIKA code [6] simulations with corresponding hadron interaction subroutines FLUKA 2006 [9] QGSJET II [10] the energy deposit by different secondary particles for solar proton primaries can be estimated. To obtain q as ion pair produced per second in cm^3 it is necessary to multiply the results per atmospheric density ρ. The cosmic ray differential spectrum $D(E)$ is approximated according convenient parameterization. Obviously the described formalism gives the possibility to estimate the ion rate due to solar proton in different regions of the Earth, heliospheric conditions [21] assuming in addition convenient parameterizations [22].

6. CONCLUSION

In this work is presented new model for calculation of the ionization of primary cosmic rays into the Earth atmosphere on the basis of Monte Carlo simulations on the basis of CORSIKA code version 6.52. The obtained results allow estimate of the ion pair production in different regions of the Earth in the whole atmosphere starting from ground level.

In the presented study was demonstrate the possibility to estimate the induced by solar cosmic rays ionization in the Earth atmosphere explicitly. The ionization profiles are applicable to the entire atmosphere, from ground level to upper atmosphere. In the proposed model all components of the atmospheric cascade are taken into account. The future work is related with comparison with analytical approaches and study of cascades produced by heavier particles. In addition taking into account the performance of CORSIKA code to sample the longitudinal development of cascade process in the atmosphere, we intend to estimate the dose exposure at high mountain and flight altitudes. The presented results are very important for studies related with influence of cosmic rays on atmospheric processes, small particles in the atmosphere and space weather.

The obtained results in this work give a good basis for study of ozone production in Pfotzer maximum and solar-terrestrial influences and space weather. The future work is related with comparison of the proposed results with analytical approaches and detailed study of the impact of the different components.

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