Recent Modeling of Galactic Cosmic Ray Induced Ionization in the Earth Atmosphere

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Abstract—. **In this work we describe recent physical model for evaluation of cosmic ray induced ionization in the atmosphere and ionosphere. Detailed simulations with CORSIKA 6.52 code using FLUKA 2006 and QGSJET II hadronic interaction models are carried out. The energy deposit of galactic cosmic ray induced air showers is obtained. On the basis of computational results the ionization yield function *Y*, respectively ion pair production *q* in the atmosphere are estimated. The impact of different shower components, namely electromagnetic, muon and hadronic components is estimated. The simulations are performed according realistic atmospheric model (US Standard Atmosphere) following steep energy spectrum of primary cosmic rays. The main result is the estimation of profiles for ion production rates q(h) by galactic cosmic rays in the ionosphere and atmosphere. The obtained ionization profiles are applicable to the entire atmosphere, from ground level to 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] measured the 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, atmospheric chemistry and is related to the global electric circuit.

The primary 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 shape of the spectrum is with small deviation from the power law function across this wide energy interval. The observed small change in the slope $\propto E^{-2.7}$ to $\propto E^{-3.0}$ around $1\text{-}3.10^{15}$ eV is well known as the "knee" of the spectrum. The "knee" is usually associated with an energy limit of acceleration mechanisms of supernova remnants and may be related to a loss of ability for galactic magnetic field to retain the cosmic ray flux. The second change, observed in the region of extremely high energies is known as "ankle". The "ankle" is usually associated with the onset of the dominant extra galactic cosmic ray spectrum. The peak of the energy distribution is at about 0.3 GeV.

When a particle from primary cosmic ray radiation penetrates the Earth's atmosphere it produces cascade processes. The high energy primary cosmic ray collides with an atmospheric nucleus and produces new, very energetic particles. Those also collide with air nuclei, and each collision adds a large number of particles to the developing cascade. Some of the produced particles are neutral pions, each one of which immediately decays to a pair of gamma rays.

The gamma rays produce electron positron pairs when passing near nuclei. The electrons and positrons regenerate gamma rays via Bremsstrahlung, building the electromagnetic cascade. This aggregate cascade process i.e. nuclear-electromagnetic cascade is known as an extensive air shower.

The cascade consists of billions of secondary particles. The majority of those particles are electrons and muons. They arrive at ground level over large areas of several square kilometers.

The predominant interactions are electromagnetic. The cross sections for the production of hadron and muon pairs are several orders of magnitude smaller than that for electron-pair production. In the electromagnetic shower, protons produce electron-positron pairs, and electrons and positrons produce photons via Bremsstrahlung (stopping radiation).

Generally in such type of cascade process only a small fraction of the initial primary particle energy can reach the ground (observation level) as high energy secondary particles. In fact the most of the primary energy is released in the atmosphere by ionization and excitation of the air molecules. For a given energy, protons produce showers that develop, deeper in the atmosphere than showers from nuclei. In our case we study only primary protons.

At the same time the stochastic nature of the individual particle production processes leads to large shower-to-shower fluctuations. On the other hand, the size of the fluctuations depends also on the mass number.

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].

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2. FORMALISM

Obviously the ionization profiles are connected with energy deposit of the EAS particles. In our work we use the ionization yield function Y which is defined according to Oulu model [6]

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

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 [7], 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 in our case). 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 ($g.cm^{-3}$).

3. IONIZATION YIELD FUNCTION Y FOR PRIMARY PROTONS

Obviously the cosmic ray induced ionization is related to energy deposit by secondary cosmic rays. A power full tool based on Monte Carlo simulation of the cascade process in the atmosphere, precisely the deposited energy, is CORSIKA code [8], which is the most widely used in the last years simulation code for cascade processes in the atmosphere.

The code simulates the interactions and decays of nuclei, hadrons, muons electrons and photons in the atmosphere up to energies of several 10^{20} eV. The output of the code gives information about the type, energy, direction, locations and arrival time of the produced secondary particles at the selected observation level. In addition, which is important for our aims, the possibility to obtain the energy deposit by different components and particles at given observation levels exists.

For the simulations the recent version CORSIKA 6.52 code [8] with corresponding hadronic interaction models FLUKA 2006 [9] and Quark Gluon String wit JETs QGSJET II [10] was used. For the simulations of hadronic interaction below 80 GeV/nucleon FLUKA 2006 was assumed and QGSJET II above 80 GeV/nucleon respectively. The hadronic event generator FLUKA 2006 is used for the description of inelastic interactions below energy of several 100 GeV. Within FLUKA 2006 these collisions are handled by different hadronic interaction models above, around and below the nuclear resonance energy range.

The ionization yield function Y is obtained for different energies of primary protons using expression (1). The used statistics varies between 10 000 and 3000 events per energy point. In Fig. 1-4 are presented the ionization yield functions with corresponding contributions of the different components for 1 GeV, 10 GeV, 100 GeV and 1 TeV energy of the primary proton. In Fig.1-4 with solid black squares is shown the total ionization, with open circles the contribution of electromagnetic component, with crosses the contribution of muon component and with open triangles the contribution of hadron component.

We observe the variation of the different components contribution to total ionization as a function of the energy of the primary proton. In low energy range around 1 GeV [6, 11] the dominant contribution to total ionization is due to hadronic component.

Increasing the energy as was expected the ionization increases Fig.2 and Fig. 3. At the same time the contribution of the different components changes as a function of the energy of the incident particle and the atmospheric depth.

Increasing the energy the role of the electromagnetic component increases and in practice dominates in the high energy range above several tens of GeV. Moreover in the middle and high atmosphere at observation levels above 600 g/cm^2, which are near to shower maximum, the contribution of the electromagnetic component is more important comparing to other components. At lower atmosphere the ionization is due essentially to muon component. In the range of very high energies, around TeV practically the electromagnetic component determines the ionization.

Similar behavior of the contribution of the different components is observed in the case of simulations according steep spectrum [12].

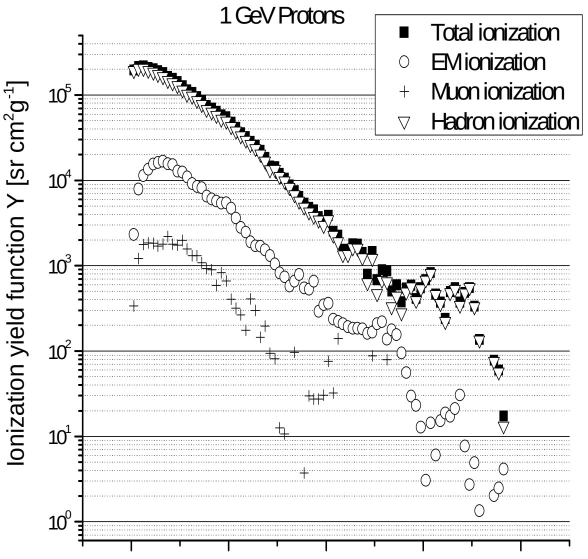

Fig. 1 The ionization yield function Y with contributions of the electromagnetic (EM), muon and hadron components for 1 GeV primary proton

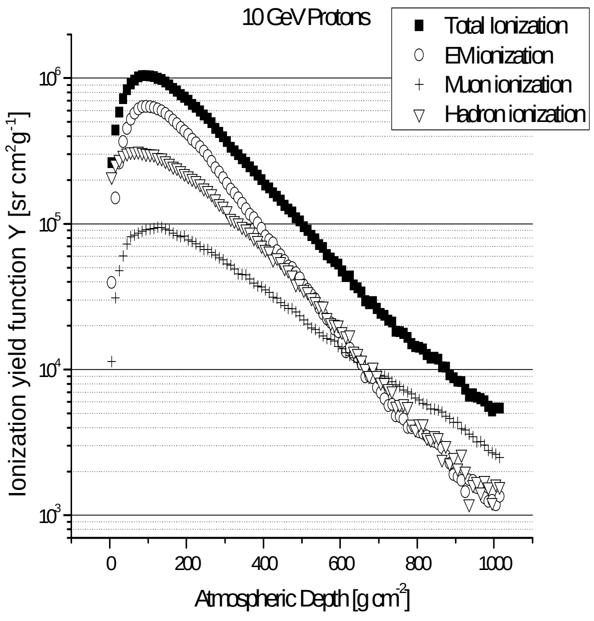

Fig. 2 The ionization yield function Y with contributions of the electromagnetic (EM), muon and hadron components for 10 GeV primary proton

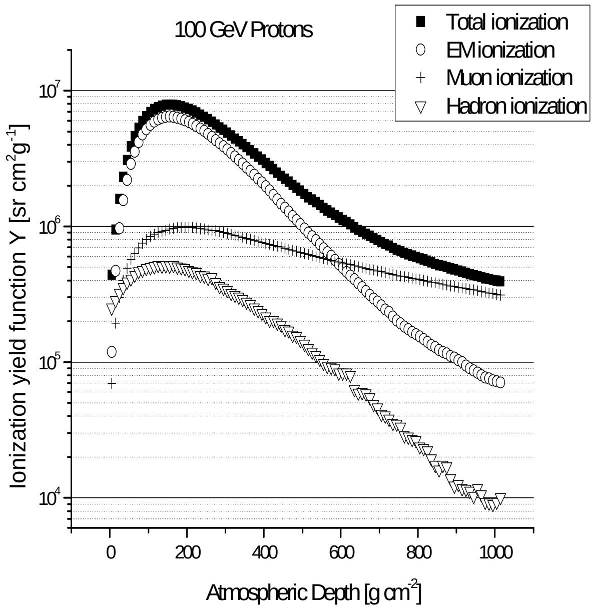

Fig. 3 The ionization yield function Y with contributions of the electromagnetic (EM), muon and hadron components for 100 GeV primary proton

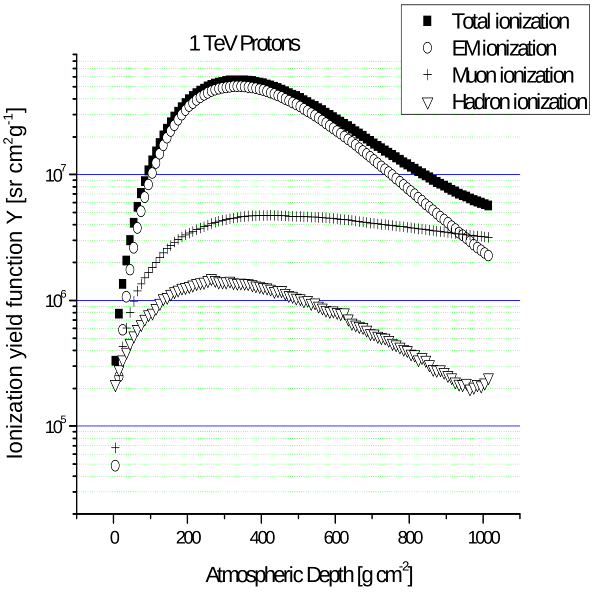

Fig. 4 The ionization yield function Y with contributions of the electromagnetic (EM), muon and hadron components for 1 TeV primary proton

Similar behavior of ionization yield function Y is observed in the case when we used CORSIKA [8] with GHEISHA [13] as hadronic interaction model in low energy range [14]. The differences are observed around Pfotzer maximum. However the application of FLUKA is recommended.

4. IONIZATION RATES IN THE ATMOSPHERE

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).

The parameterization of cosmic ray spectrum is taken from [15]. In Fig. 5-8 are presented the ionization rates for solar minimum and solar maximum for different rigidity cut-offs. As was expected the ionization rates differ with increase during solar minimum. The position of the Pfotzer maximum is in practice the same. Below some 800 g/cm^2 (2000 m above sea level) the rates in practice coincide.

The different cut-offs correspond to geomagnetic latitudes λ_m= 0°, 30°, 41° and 55°. As was expected the shape of the ionization profiles for given rigidity are quite similar with observed difference only in the magnitudes for solar minima and solar maxima. For polar region the Pfotzer maximum is not so clearly described and as was expected the ionization profile magnitude is more important.

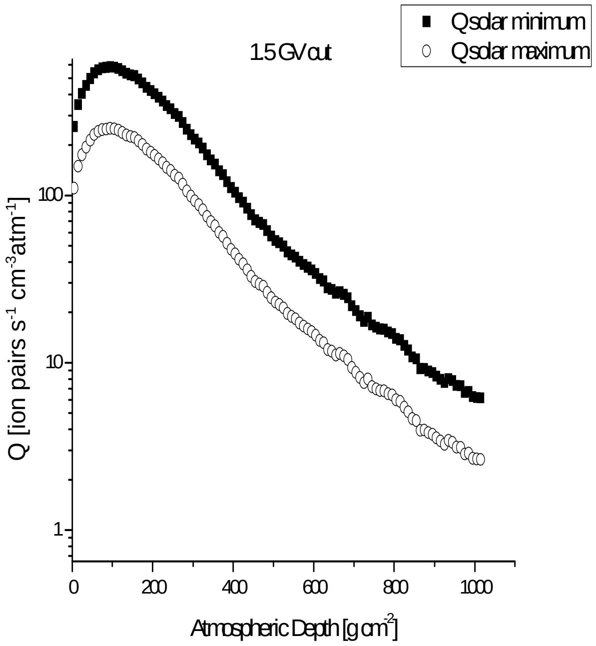

Fig. 5 Ionization profiles for solar minimum and solar maximum for 1.5 GV rigidity

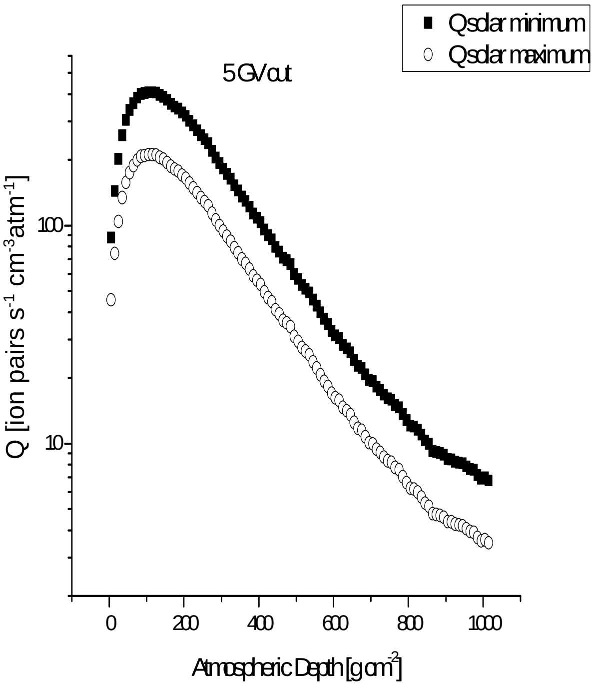

Fig. 6 Ionization profiles for solar minimum and solar maximum for 5 GV rigidity

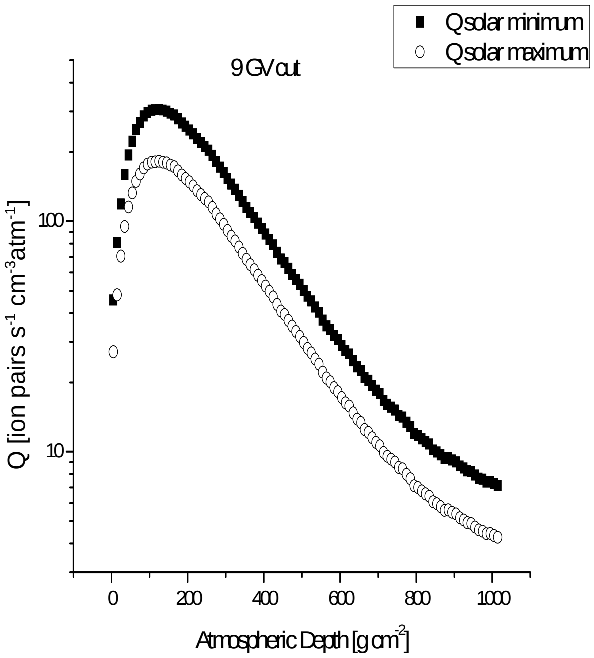

Fig. 7 Ionization profiles for solar minimum and solar maximum for 9 GV rigidity

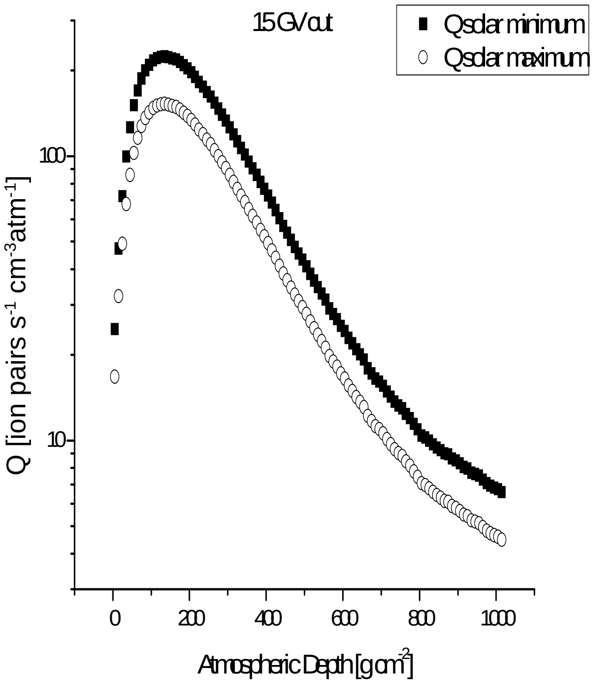

Fig. 8 Ionization profiles for solar minimum and solar maximum for 15 GV rigidity

5. APPLICATIONS

On the basis of CORSIKA code [8] simulations the energy deposit by different secondary particles for proton primaries is computed. To obtain *q* as ion pair produced per second in cm^3 it is necessary to multiply the ionization yield function Y per atmospheric density ρ. The cosmic ray differential spectrum *D(E)* is approximated according the parameterization given in [15] for solar minimum and solar maximum. Therefore it is possible using the mentioned above parameterization and using the mean ionization yield function *Y* to calculate the ionization profiles for given spectrum and given conditions. The integration of the spectra is carried out on the basis of numerical methods using Maple subroutines.

In addition normalization to one atmosphere is carried out. This permits in more realistic manner to estimate to cosmic ray induced ionization and ionization rate respectively. This permits to compare the ionization profiles at solar minimum (Fig.9) and solar maximum (Fig.10) at different regions of the Earth [6, 16].

The same formalism can be applied for fast estimations using ionization yield function Y parameterization [17] instead of a full Monte Carlo simulation of the cascade process.

In addition a comparison with experimental data is carried out (Fig.11). We observe good agreement between experimental data and simulated ionization rates. The observed difference is due mainly on the fact that we consider only primary protons.

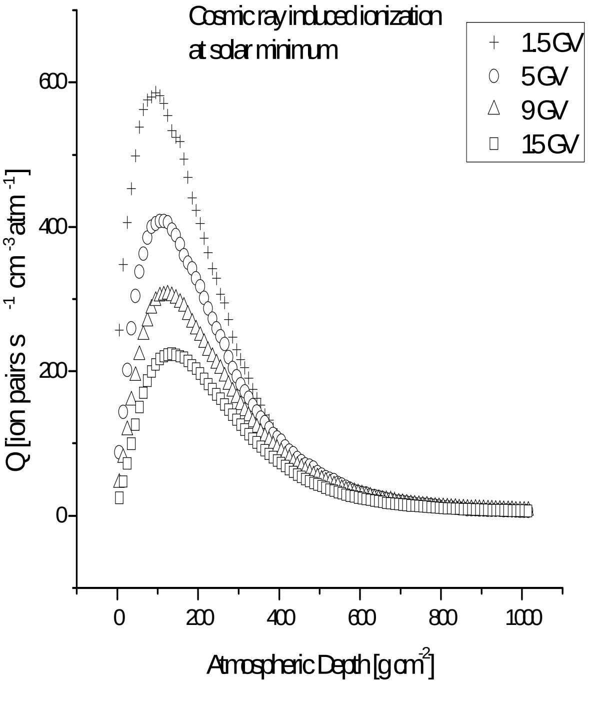

Fig. 9 Comparison between ionization profiles for solar minimum for 1.5, 5, 9 and 15 GV rigidity

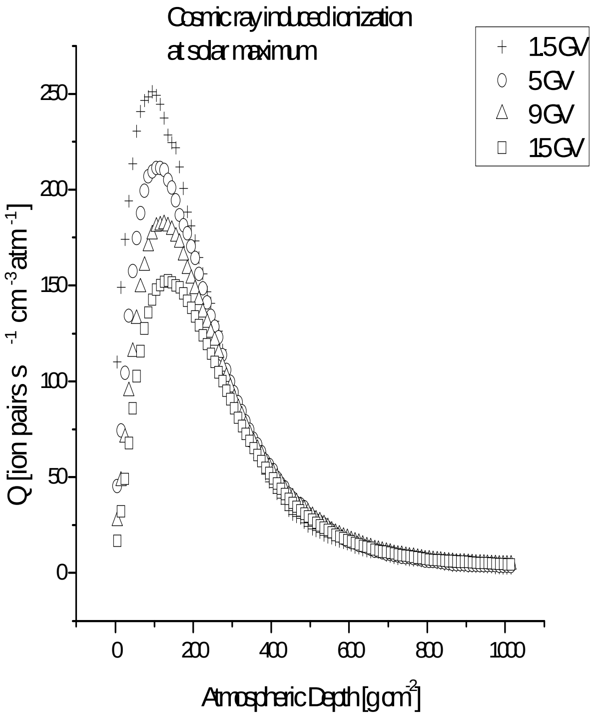

Fig. 10 Comparison between ionization profiles for solar maximum for 1.5, 5, 9 and 15 GV rigidity

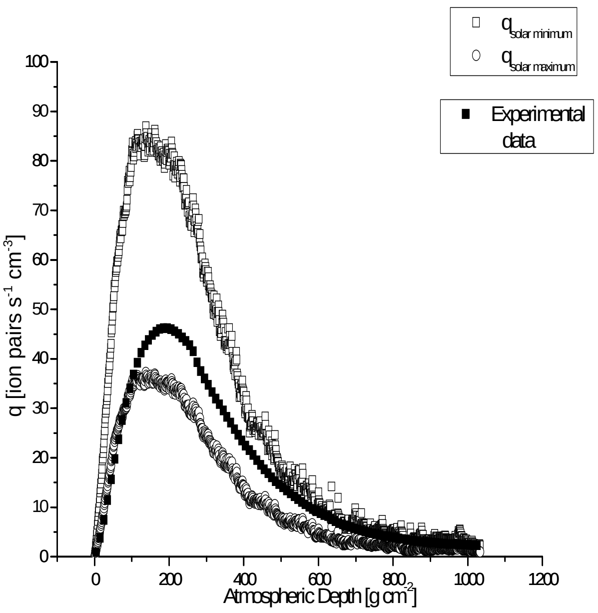

Fig. 11 Comparison between ionization profiles for solar maximum for 1.5, 5, 9 and 15 GV rigidity

6. CONCLUSION

In this work a new model is presented for calculation of the ionization of primary cosmic rays in the Earth atmosphere on the basis of Monte Carlo simulations using CORSIKA code version 6.52. The obtained results allow estimate of the ion pair production in different regions of the whole atmosphere starting from ground level. Only primary protons are considered in this study. The contribution of alpha particles as well as heavy nuclei is a topic of future study.

The obtained results in this work give a good basis for study of ozone production in the 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. In addition application for dose rate estimation at different altitudes will be of an utmost interest.

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