Effects of different atmospheric profiles on ionization in the Earth atmosphere

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***Abstract*. The longitudinal profile of atmospheric cascades is sensitive to the energy and mass of the primary particle. In this work are compared cosmic ray ionization yield functions Y for winter, summer and US standard profiles of atmosphere. The data are obtained on the basis of CORSIKA 6.52 code simulations using FLUKA 2006 and QGSJET II hadronic interaction subroutines. The energy deposit of proton induced cascade processes in the atmosphere is calculated for different types of atmospheres. The ion pair production in the atmosphere and the impact of the different shower components, precisely the electromagnetic, muon and hadronic is estimated according the used different atmospheric types. The observed differences are discussed.**

***Keywords*: cosmic rays, ionization model, hadronic models**

I. Introduction

In is known that 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 C-layer at altitudes 50-80 km in the D- region. The study of cosmic ray induced ionization is very important, because it is possibly connected with cloud formation [1], [2] and atmospheric chemistry [3]. Therefore a recent model for cosmic ray induced ionization is very important for investigation of such type of problems. One possible tool is based on Monte Carlo simulations of the cascade process in the atmosphere, precisely the energy deposit and afterwards the estimation of ion pair production.

When a particle from primary cosmic ray flux penetrates the Earth's atmosphere the results is the developemnt of cascade process in the atmosphere. The cascade consists of billions of secondary particles, the majority electrons and muons. They arrive at ground level over large areas of several square kilometers. The predominant interactions are electromagnetic.

The high energy particle 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.

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.

Obviously the development of the cascade process in the atmosphere depends of the properties of the medium. In addition for a given energy, protons produce showers that develop, deeper in the atmosphere than showers from nuclei. 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 atmospheric depth associated with a given height plays a central role in cascade simulation. The probability for interaction of a shower particle depends only on its traversed column depth. The latter can be expressed conveniently as difference between the atmospheric depths of the production and interaction points. Similarly the conversion of height to atmospheric depth is needed for mapping a reconstructed event geometry to the depth profile of a shower. The relation between atmospheric depth and height follows from the air density profile, whereas typically the density profile of the US Standard Atmosphere 1976. Since the seasonal variations of the atmospheric profiles seem to be rather large, it is important to check their influence on shower developement. In this connection the detailed study of the atmospheric cascade as a function of the atmosphere profile is very important.

II. Model and simulations

The cosmic ray induced ionization could be estimated using the Oulu model formalism [4] on the basis of ionization yield function Y (1).

$$Y(x,E) = \triangle E(x,E)\Omega/\triangle x E_{ion} \quad (1)$$

where $\triangle E$ is the deposited energy in a atmospheric layer $\triangle x$, Ω is the geometry factor integration over solid angle and E_{ion}=35 eV is the ionization potential

[5].The atmospheric ionization is obtained on the basis of equation (2)

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

where D(E) is the differential CR spectrum, Y defined according (1) and ρ is the atmospheric density.

The evolution of atmospheric cascade processes can be followed on the basis of Monte Carlo simulations. For this purpose a recent version of CORSIKA 6.52 code [6] with corresponding hadronic interaction models FLUKA 2006 [7] and QGSJET II [8] is used for the simulations. The FLUKA 2006 is used for simulation of hadronic interactions below 80 GeV/nucleon and QGSJET II for hadronic interactions above 80 GeV/nucleon, respectively.

Cosmic Ray Simulations for KASKADE (CORSIKA) code [6]is one of the most widely used in the last years atmospheric cascade simulation tool in cosmic ray and astroparticle physics. The code simulates the interactions and decays of nuclei, hadrons, muons, electrons and photons in the atmosphere up to extreme energies. The result of the simulations is detailed information about the type, energy, direction, location and arrival time of the produced secondary particles at given selected observation level. In addition the energy deposit by different shower components and particles at given observation levels is easy to estimate.

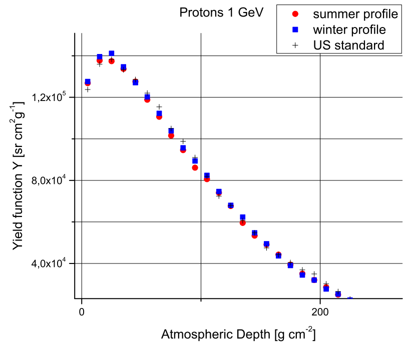

Fig. 1: Ionization yield function Y for primary proton induced showers with 1 GeV energy

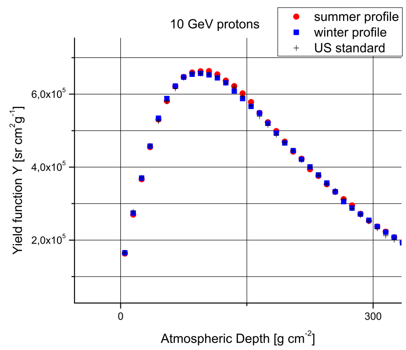

Fig. 2: Ionization yield function Y for primary proton induced showers with 10 GeV energy

III. Ionization yield function Y for winter and summer atmosphere

The US Standard Atmosphere model (with the 1966 Supplement) provides the temperature and pressure profiles at the northern hemisphere, for mid-latitude winter and summer, as well as average atmosphere. In this connection, it is important to study the impact of the different parameterized atmospheric profiles on energy deposit of different shower particles, respectively ionization yield function (1).

We simulate 5000 events (proton nuclei) per energy point up to 70 degrees of zenith angle. We compare the ionization yield function Y for proton incoming showers in wide energy range, precisely 1 GeV, 10 GeV, 100 GeV and 1 TeV kinetic energy of the primary particle. The atmospheric depth parameterization according to Linsley US Standard Atmosphere model [9] is implemented as the default profile in majority of Monte Carlo codes, including CORSIKA. In this work we compare winter, summer profiles and US standard atmosphere profiles. The main reason for this study, are the observed seasonal variations of the atmospheric profiles and the observed differences in altitudes of shower maximum [10], [11].

The results are presented in Fig.1-4 for 1 GeV, 10 GeV, 100 GeV and 1 TeV kinetic energy of the primary protons respectively. For 1 GeV incoming protons (Fig. 1) the ionization yield function Y in practice are the same below 200 g/cm^2 for winter, summer and US standard atmospheric profiles. In the region of Pfotzer maximum the ionization rate tend to slight increase for winter profile.

The ionization rate for US standard atmospheric profile is between the rates for winter and summer profiles. In the case of 10 GeV proton induced cascades (Fig. 2), we observe slight increase of ionization rates for summer atmosphere in the region of Pfotzer maximum comparing to winter profile. The behavior of ionization yield function Y below 200 g/cm^2 is the same as in the previous case.

When the energy of the primary proton is 100 GeV (Fig. 3), the situation is quite similar. The ionization rates for summer atmosphere are grater then those for winter profiles. The ionization rates for US standard atmospheric profiles in are not distinguishable with the rates for summer atmospheric profile. The behavior of ionization yield function Y below 200 g/cm^2 is the same as in the previous case.

Finally in (Fig. 4) we observe more complicated behavior of the ionization yield function Y for the different profiles. Generally the ionization rates for US standard atmosphere are below the rates for summer and winter profiles. In the upper atmosphere till to Pfotzer maximum, the cosmic rays produce more ion pairs in the winter atmosphere.

The rates are in practice equal in the Pfotzer maximum

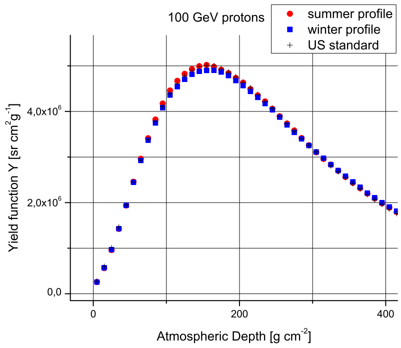

Fig. 3: Ionization yield function Y for primary proton induced showers with 100 GeV

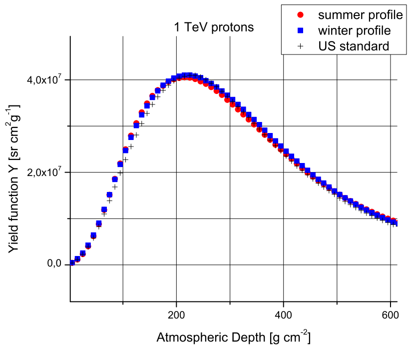

Fig. 4: Ionization yield function Y for primary proton with 1 TeV energy

and after that we observe increase of ionization rates for winter profile comparing to summer atmospheric profile. Below 200 g/cm^2 the ionization rates for summer and winter profiles in practice coincide. The discussed above effects are due to the fact that the atmosphere influences the longitudinal atmospheric cascade process development. This leads to different energy deposit , respectively ionization yield function (1). Investigation of various atmospheric profiles and comparisons with the US standard show significant effects, especially in Pfotzer maximum.

IV. Discussion

In the general case the largest uncertainties in numerical simulation of cascade processes in the atmosphere are related to the assumed models for hadronic interactions. In addition the standard version of CORSIKA code is designed for simulations with practically vertical incidence. In the energy range around the knee and for incoming particles with very inclined zenith angle the majority of the shower particles are absorbed in the atmosphere. The longitudinal shower development is be followed by CORSIKA in vertical bins by counting all particles crossing horizontal layers and summing the deposited energy between two consecutive horizontal layers. In the SLANT option the horizontal layers are replaced by skew planes perpendicular to the shower axis and arranged in a spacing, which corresponds to a regular increment in the penetrated atmospheric mass thickness along the shower axis. Each time a shower particle crosses such a skew plane it is counted for the longitudinal particle distribution, and the energy deposited between two adjacent skew planes is added up to obtain the longitudinal energy deposit distribution. As a result the calculation of the energy deposit is more precise comparing to the standard option. This permits to investigate second order effects for atmospheric cascade processes simulations such as the impact of different atmospheric profiles. The observed differences are very significant and are present essentially in the region of Pfotzer maximum. In all cases in the low atmosphere the observed differences are negligible. The importance of atmospheric variations depends on the shower angle and primary particle. The more inclined an air shower is the more important is the detailed knowledge of the atmos- pheric profile. For vertical showers, the influence of atmospheric profile variations can be nearly neglected, but for incidence angles larger than 40 degrees, the use of the US standard atmosphere biases the interpretation of extensive air showers. Obviously an additional study of the impact of the different atmospheric profiles on the energy release of different shower components is important [12] and necessary, as well as for other incoming particles [13].

V. Conclusion

In the presented study was demonstrated the impact of different atmospheric profiles in CORSIKA code on ionization yield function Y. The difference is observed essentially in the region of Pfotzer maximum. The presented results are important for studies related with influence of cosmic rays on atmospheric processes and the space weather. In addition they give the possibility to study several season variations of the different processes.

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