Normalization of Ionization Yield Function Y for various nuclei

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Abstract: Cosmic rays are an important source of ionization in the Earth atmosphere. The ionization in the stratosphere and troposphere is governed by galactic cosmic rays. They have high energies and produce a complicated hadron-electromagnetic-lepton cascade in the atmosphere resulting to an ionization of the ambient air. The ion pair production is related to various atmospheric processes related to atmospheric physics and chemistry. In this connection, the interest to cosmic rays as ionizing source is rapidly growing. The development of recent models for estimation of cosmic ray induced ionization is in progress. Several recent results important for production of ion pairs in the Earth atmosphere by various primary cosmic ray nuclei are presented. The direct ionization by various primary cosmic ray nuclei is explicitly obtained. The longitudinal profile of atmospheric cascades is sensitive to the energy and mass (charge) of the primary particle. In this study different cosmic ray nuclei are considered as primaries, namely Helium, Carbon, Oxygen and Iron nuclei. The cosmic ray induced ionization is obtained on the basis of numerical model and CORSIKA 6.52 code simulations using FLUKA 2006 and QGSJET II hadron interaction models. The energy of the primary particles is normalized to GeV per nucleon. In addition, the ionization yield function Y is normalized as ion pair production per nucleon. The obtained ionization yield functions Y for various primaries are compared and their shape as a function of the energy and altitude is widely discussed. The presented results and their application are discussed.

Keywords: Atmospheric Ionization, Monte Carlo, Heavy Nuclei, Space Climate.

1 Introduction
Cosmic rays are an important source of ionization in the Earth atmosphere. At present it is well known that they are the main source of ionization in the stratosphere and troposphere. They have high energies and produce a complicated nuclear-electromagnetic-muon cascade resulting to an ionization of the ambient air. The ion pair production is related to atmospheric physics and chemistry as well as to many atmospheric processes. Therefore, the interest to cosmic rays as ionizing source is rapidly growing. In this connection the development and study of recent models for estimation of cosmic ray induced ionization is very important.

1.1 Motivation
The primary cosmic ray (CR) particles impinge the Earth's atmosphere, collide with an atmospheric nucleus and produce new, energetic particles, which also collide with air nuclei etc... Each collision adds a large number of particles to the developing cascade. Generally in such type of cascade process only a small fraction of the initial primary particle energy reach the ground as high energy secondary particles. 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. The stochastic nature of the individual particle production processes leads to a large shower to shower fluctuations. The size of the fluctuations depends on the mass number. The energy loss per distance, respectively ionization, traveled of charged particles (protons, alpha particles, nuclei traversing matter) depends by square of particle charge Z according Bethe-Bloch equation. Therefore the ionization caused by light, middle and heavy cosmic ray nuclei should be considered separately from protons. Moreover in recent studies the contribution of protons is highlighted. The estimation of cosmic ray induced ionization is possible
on the basis of analytical model or on a Monte Carlo simulation of the atmospheric cascade [1].

1.2 Used formalism

Obviously to build an appropriate model for atmospheric ionization due to cosmic rays it is necessary to follow the evolution and properties of the cascade process in the atmosphere, especially the energy and location with corresponding arrival time of the produced secondary particles at given selected observation level. It is necessary to obtain the energy deposit at given observation level with good precision. In present work we apply previously obtained ionization profiles with additional normalization and following the ionization yield function formalism \( Y(1) \) according Oulu model [2].

\[
Y(x, E) = \frac{\Delta E(x, E)}{\Delta x} \cdot \frac{1}{E_{\text{ion}}} \cdot \Omega (1)
\]

where \( \Delta E \) is the deposited energy in layer \( \Delta x \) in the atmosphere and \( \Omega \) is a geometry factor, integration over the solid angle with given zenith angle. Therefore the cosmic ray induced ionization is estimated according (2)

\[
q(h, \lambda_{m}) = \int_{E_0}^{\infty} D(E, \lambda_{m}) Y(h, E) \cdot \rho(h) dE \quad (2)
\]

where \( D(E, \lambda_{m}) \) is the differential primary cosmic ray spectrum at given geomagnetic latitude \( \lambda_{m} \), \( Y \) is the yield function, \( \rho(h) \) is the atmospheric density (g.cm\(^{-3}\)) following the algorithm [3, 4]. In our study we use the CORSIKA 6.52 code [5] with corresponding hadron interaction models FLUKA 2006 [6] and QGSJET II [7] for the simulations of the cascade processes in the Earth atmosphere. For simulation of hadron interactions below 80 GeV/nucleon the FLUKA 2006 is used and QGSJET II for hadron interactions above 80 GeV/nucleon, respectively.

2 Ionization for various Nuclei

We simulate large statistics of events (Helium, Carbon, Oxygen and Iron nuclei) up to 85 degrees of zenith angle, distributed following cosine law. The ion pairs, produced in 1 cm\(^3\) of the ambient air at a given atmospheric depth by one particle of the primary cosmic ray with given kinetic energy per nucleon is determined according to (1) and to expression (2). In our previous works [8, 9] the shape of ionization yield function \( Y \) for various nuclei was widely discussed. The contribution from middle and heavy nuclei dominates in the region up to 20 km above sea level (Fig.1 and Fig.2). As was mentioned above, protons produce cascades that develop, deeper in the atmosphere than cascades from nuclei. As a result the deposited energy from heavy nuclei in the high atmosphere is greater than from protons. In addition the alpha particles produce more ion pairs in the lower energy range, even they are identical to four protons in the high energy range in the sense of cosmic ray induced ionization. Therefore it is important to consider alpha-particles separately from protons and nuclei and normalize [10] ionization yield function \( Y \).

Figure 1. Ionization yield function for various nuclei with energy of 10 GeV/nucleon.

Figure 2. Ionization yield function for various nuclei with energy of 1 TeV/nucleon.

2.1 Normalization of Ionization Yield Function \( Y \) for various Nuclei

In the upper atmosphere the ionization is due mainly to direct ionization. For precise estimation of the contribution to cosmic ray induced ionization of various nuclei at different altitudes, a normalization of ionization yield function \( Y \) is carried out. The ionization yield function \( Y \) (1) is expressed as ion pair production per nucleon (as example the ionization yield function \( Y \) for Helium nuclei is divided by 4, for Carbon nuclei is divided by 12, for Oxygen nuclei by 16 etc...). The results are shown in Fig. 3-7 (1 GeV, 3GeV, 10 GeV, 100 GeV and 1 TeV energy per nucleon of primary nuclei) for Helium, Carbon, Oxygen and Iron nuclei. Generally the ionization rate decreases with atmospheric depth (altitude above sea level) and increases with the energy of primary particles. In addition the ionization yield function \( Y \) is very steep in a
low energy region. In this energy region the ionization is dominated by hadron component. In a high-energy range the ionization yield function \(Y\) is flatter, because muon component takes over [2, 10, 11]. When the energy of primary nuclei is 1 GeV/nucleon and 3 GeV/nucleon (Fig. 3 and Fig.4), as was expected, the contribution from heavy nuclei dominates in the upper atmosphere. In this energy range, the direct ionization in the upper atmosphere dominates. Below 24 km above sea level the ionization is the same for Helium, Carbon and Oxygen nuclei. Below this region the ionization tend to slight increase from Iron nuclei.

![Figure 3](image1.png)

Figure 3. Normalized Ionization yield function for various nuclei with energy of 1 GeV/nucleon.

![Figure 4](image2.png)

Figure 4. Normalized Ionization yield function for various nuclei with energy of 3 GeV/nucleon.

It was recently demonstrated that in a case of 10 GeV/nucleon kinetic energy of the primary nuclei, the contribution of hadron component dominates, with significant impact of the electromagnetic component [8]. In the upper atmosphere till 20 km above sea level dominates the ionization due to heavy and light nuclei. The normalization of ionization yield function \(Y\) (ion pairs per nucleon) leads to similar shape of ionization profiles below 19.5 km above sea level. The obtained ionization yield functions \(Y\) are the same below this level for all primary nuclei (Fig. 5). Therefore in the sense of produced ionization, heavier nuclei can be considered as identical to the corresponding number of alpha-particles, i.e. a Carbon nuclei can be substituted by 3 alpha-particles, an Oxygen nucleus can be substituted by 4 alpha-particles, Iron nucleus can be substituted by 14 alpha-particles, respectively.

![Figure 5](image3.png)

Figure 5. Normalized Ionization yield function for various nuclei with energy of 10 GeV/nucleon.

When the energy of incoming particle is 100 GeV/nucleon (Fig.6) a similar behavior is observed. In the region above 25 km above sea level the capacity for ionization is governed by Iron, Oxygen and Carbon nuclei. Note that the total ionization rate depends on abundance of primary nuclei. Here we compare only the yield functions, which in fact represent the capacity for ionization. The renormalized ionization yield functions \(Y\) for various nuclei are the same below 22 km above sea level. When the energy of incoming particle is 1 TeV/nucleon (Fig.7) we observe the same situation. The renormalized ionization yield functions \(Y\) for various nuclei are the same below 23 km above sea level.
Figure 6. Normalized Ionization yield function for various nuclei with energy of 100 GeV/nucleon.
The observed differences of the shape in all cases are in the upper atmosphere. The reasons are discussed above and are mainly due to the domination of direct ionization in the upper atmosphere by heavier nuclei as well as the cascade development by various nuclei. It was observed that the capacity for ionization of ambient air is in practice the same for Carbon and Oxygen nuclei.

Figure 7. Normalized Ionization yield function for various nuclei with energy of 1 TeV/nucleon.

3 Summary
The full Monte Carlo simulations of cosmic ray induced ionization are important, because they are related to explanation and modeling of different processes in the atmosphere related to atmospheric physics and chemistry. Presently an essential progress in development of physical model for cosmic ray induced ionization processes in the atmosphere is carried out [12]. In these models the contribution of proton nuclei is highlighted. In this connection the contribution of light and heavy nuclei, in addition to protons, to the total ionization is very important. Therefore the full Monte Carlo simulation of atmospheric cascades induced by various nuclei will contribute to precise estimation of cosmic ray induced ionization [13].

In the presented study are shown the ionization profiles due to various primary cosmic ray nuclei, namely Helium, Carbon, Oxygen and Iron nuclei. The normalization of the ionization yield function Y permits to estimate the contribution to total ionization of each nucleon of atmospheric cascade, hence the contribution of various nuclei. The difference between various ionization profiles is observed essentially above the region of Płotzer maximum. In general the obtained ionization profiles are with similar shape and below Płotzer maximum are the same when we deal with renormalized ionization yield function Y. For detailed studies, especially in the upper atmosphere we recommend to apply a specific model or to extend the existing model to the upper atmosphere. In the region of Płotzer maximum and below, in the sense of produced ionization, heavier nuclei can be considered as identical to the corresponding number of alpha-particles, i.e. an Oxygen nucleus can be substituted by 4 alpha-particles, Iron nucleus can be substituted by 14 alpha-particles as has been previously suggested [2]. Therefore for quantitative studies, especially at low altitudes it is possible to apply this convention, which simplifies considerably the simulation. In the upper atmosphere all the nuclei have to be considered separately, since their contribution and shape of ionization yield function are differs significantly.

The obtained results permit to adjust models related to ozone mixing ratio and minor constituents abundance [14-15].

References

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