Extensive Air Shower beyond GZK cutoff

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Abstract. Nowadays, ultrahigh energy cosmic rays are subject to intense research of great interest. The existence of such rays with an energy above $10^{20}$ eV is contradicted by the limit GZK due to photopion production, or by nuclei photodisintegration, in the interaction of UHECR with the cosmic microwave background. Many current UHECR experimental investigations, Auger observatory, Telescope Array (TA) and soon Extreme Universe Space Observatory on Japanese Experiment Module (JEM-EUSO) try to answer some relevant questions. What are ultrahigh energy cosmic rays? Where do they come from? How do they acquire such colossal energies? In this work detailed simulations of extensive air showers have been carried out with the help of CONEX program in order to evaluate the shower maximum depth longitudinal profile, Xmax. This parameter and its fluctuations are very sensitive to the primary particle mass.

Keywords: High Energy Cosmic Rays (UHECRs), Extensive Air Showers (EAS), CONEX code, maximum depth longitudinal profile.

1. Introduction
Primary cosmic particles with energy higher than $10^{18}$ eV are called Ultra High Energy Cosmic Rays (UHECRs). At present, these kind of rays have been measured by two biggest experiments: Auger observatory and Telescope Array (TA). By studying closely the UHECRs spectrum, one can notice two important features:

- a flattering at around $5 \times 10^{18}$ eV, the so called ‘ankle’ [1]. Its origin is not perfectly clear. It seems to be either a signature of ultra high energy primary protons interactions with the Cosmic Microwave Background (CMB) [2, 3], or a transition from a galactic to extragalactic sources, or even a transition from an extragalactic proton component to a different extragalactic heavy nuclei one...

- a strongly decrease or cut-off at about $5 \times 10^{19}$ eV. This cut-off predicted by Greisen, Zatsepin and Kusmin (GZK) [4, 5] is primarily due to the protons energy attenuation in the photopion-production interactions with the CMB.

The discovery of their sources will certainly reveal the most energetic astrophysical accelerators in the universe.

When penetrating in the Earth atmosphere, the UHECR collides with the nitrogen or oxygen nuclei and produces a large cascade of secondary particles called Extensive Air Shower (EAS). At the beginning of the evolution of this EAS, the successive interactions increase the number of its particles, hence a decrease of the average energy per particle: it is the development phase. However, along their travel, the secondary particles lose progressively their energy by ionising the air, and the less energetic of them will stop. When the mean energy per particle falls below a critical value, the number of secondaries in motion decreases: it is the extinction phase. When
passing from one phase to the other the number of particles reaches a maximum value, $N_{\text{max}}$ at $X_{\text{max}}$ position. The later parameter is often used to reconstruct the elemental composition of the primary cosmic rays (primary particle identification). The analysis of simulations based on $X_{\text{max}}$ will probably allow us to interpret recent or future UHECRs experimental data (Auger, TA, JEM-EUSO).

2. Simulations methods
The CORSIKA code [6] is one of the best programs describing perfectly the interaction of primary cosmic rays with the atmosphere using the Monte Carlo method. Unfortunately, for UHECRs the execution time of such a program becomes unreasonable despite the use of its THINING option based on a weighted sampling algorithm. In order to circumvent this difficulty, we have used CONEX program version 2r4.37 [7, 8] coupled to different high energy hadronic interaction models EPOS LHC, QGSJETII-04, QGSJET01 and SIBYLL 2.1. and default low energy hadronic interaction model UrQMD 1.3. CONEX program is a one dimensional code combining Monte Carlo simulation of high energy interactions with a fast numerical solution of cascade equation (CE) for secondary particles distribution. CONEX quickly determines the EAS profile including fluctuations. Pierog [9] mentioned a good agreement of CORSIKA and CONEX programs (figure 1) when calculating the fluctuation of the maximum longitudinal profile, $X_{\text{max}}$ (a primary proton and iron nucleus at $10^{18}$ eV. On the other hand, CONEX calculates a fitting of each EAS profile. A Gaisser Hillas formula which gives the approximate number of charged particles as a function of atmospheric depth along the shower axis is determined [10] as following:

\[
N(X) = N_{\text{max}}\left(\frac{X}{X_{\text{max}}}\right)\frac{X_{\text{max}}}{\lambda} \exp \left(\frac{X_{\text{max}} - X}{\lambda}\right)
\]

where; $X$ is the atmospheric depth ($g/cm^2$); $X_{\text{max}}$ is the depth shower maximum ($g/cm^2$), $N_{\text{max}}$ is the number of charged particles and $\lambda$ is a characteristic length parameter (a scale constant with a value $70 g/cm^2$)[11].

Figure 1: Fluctuations of the shower maximum depth $X_{\text{max}}$ around the mean shower maximum depth $\langle X_{\text{max}} \rangle$ for a primary energy of $10^{18}$eV [9].
Figure 2: The $X_{\text{max}}$ and $N_{\text{max}}$ distribution for primary proton, photon and iron at energy $10^{20}\text{eV}$.

Figure 3: The variation of $N_{\text{max}}$ and $X_{\text{max}}$ parameters with energy for primary proton and iron nucleus.

Furthermore, all output data is written to a ROOT file that can be easily manipulated [7]. For our simulations, we used the following CONEX options:

- Primary particle: proton, iron
- Primary particle energy: $10^{18}\text{ eV}$, $10^{20}\text{ eV}$
- Zenith angle: $\theta = 0^\circ$, $\theta = 60^\circ$
- Hadronic interaction Model: EPOS, QGSJET
- Hadrons, muons, electrons and photons energy cut-off, respectively: $1\text{ GeV}$, $1\text{ GeV}$, $1\text{ MeV}$, $1\text{ MeV}$

3. Preliminary results and discussion
First, we studied the maximum charged particle longitudinal profiles distribution, $N_{\text{max}}$, and the shower maximum depth, $X_{\text{max}}$, for primary cosmic-ray protons, iron nuclei and $\gamma$-photons at energy equal to $10^{20}\text{ eV}$ (figure. 2). The average values of $N_{\text{max}}$ and $X_{\text{max}}$ are given in
Table 1: Average $N_{\text{max}}$ and $X_{\text{max}}$ for a primary cosmic-ray proton, iron nucleus and $\gamma$-photon at energy $10^{20}$eV.

|                  | Iron                      | Proton                    | $\gamma$-photon             |
|------------------|---------------------------|---------------------------|-----------------------------|
| $\langle N_{\text{max}} \rangle$ | $(5.875 \pm 0.002) \times 10^{10}$ | $(5.837 \pm 0.009) \times 10^{10}$ | $(6.4 \pm 0.2) \times 10^{10}$ |
| $\langle X_{\text{max}} \rangle$ (g/cm$^2$) | $(770 \pm 1)$             | $(864 \pm 2)$            | $(990 \pm 10)$             |

One can see that for primary proton and iron nucleus the average $N_{\text{max}}$ remains approximately unchanged. This is not the case for the primary photon which has a much smaller $N_{\text{max}}$. One can observe that the lighter the primary particle mass the higher the average shower maximum depth $X_{\text{max}}$.

Figures 3 shows the variation of $N_{\text{max}}$ (left) and $X_{\text{max}}$ (right) parameters with energy for primary proton and iron nucleus. For both primary particles (proton and iron nucleus) the higher the energy the wider the maximum longitudinal profile number $N_{\text{max}}$. There is no significant difference in the two primary particles $N_{\text{max}}$ values. This can be explained by the superposition model used for cosmic ray nuclei. This model treats a nucleus interaction of mass number $A$ and energy $E$ as $A$ proton interactions each with energy $E/A$. Figure 3 (right) shows the variation of the charged maximum longitudinal profile $X_{\text{max}}$ with the primary proton and iron nucleus energy. In all the energy range ($10^{19} - 10^{21}$ eV), we noticed a difference of approximately 100 g/cm$^2$ between the two primary particles $X_{\text{max}}$ values. As we know, this parameter is directly related to the primary particle mass. When comparing the experimental data with such simulations, this should probably lead to the identification of the nature of UHECRs.

4. Conclusion

In this paper, we used the CONEX code which combines a Monte Carlo calculation, of UHECRs interactions with a fast numerical solution of the cascade equation for the resulting distributions of secondary particles. For a given primary photon, proton and iron nucleus we were especially interested about the shower maximum secondary particles number and depth profile. Our simulations confirmed, as it is well known, that the maximum number of secondary charged particles longitudinal profile $N_{\text{max}}$ is proportional to the primary particle energy. An adequate comparison of the values of this parameter obtained experimentally, for example by fluorescence detectors, with the simulations may be gives us a good estimation of the primary energy. We also found that the maximum depth profile, $X_{\text{max}}$, varies linearly with the logarithm of the primary energy. We observed a difference of the order of 100 g/cm$^2$ between the $X_{\text{max}}$ values of the proton and the primary iron nucleus, over the entire energy interval $10^{19}$eV - $10^{21}$eV.

A comparison of the experimental data with the simulations based on $X_{\text{max}}$ values of such energy variations may allow the identification of the primary cosmic particles.

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