Ultra high energy cosmic rays simulated with CONEX code

Ghazala Lakel1,* and Mohamed Cherif Talai1,**
1Department of Physics, Badji Mokhtar University of Annaba, P. O. Box 12, Annaba 23000, Algeria

Abstract.
Today, many experiments around the world (Auger Observatory, Telescope Array, and soon Jem-Eusо experiment...) are tracking ultra-high energy cosmic rays. They try to collect some exceptional data that would lift the veil on this type of cosmic rays, mainly to answer why does their energies exceed the GZK cutoff without pointing to astrophysical sources close to our galaxy. Furthermore, we do not really know neither the identity nor the acceleration processes that can provide them with such colossal energy. We have performed, using the CONEX program version 2r6.40 coupled to different hadronic interaction models (QGSJET01, EPOS LHC, SIBYLL 2.1 and QGSJET-II-04) simulations focused on the slant depth $X_{\text{max}}$ of the maximum of the shower longitudinal profile and the charged particle number $N_{\text{max}}$. Theses parameters and their fluctuations are very sensitive to the primary particle mass (identity) and energy. The obtained results are compared for proton and iron primaries at the energy range $10^{18} – 10^{21}$ eV.

1 Introduction

1.1 Primary cosmic rays

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

The identities of these UHECR with energies above the GZK cutoff remain unknown. Discovering 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).

1.2 Extensive Air Shower

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 the slant depth position $X_{\text{max}}$. This later parameter is often used to reconstruct the elemental composition of the primary cosmic rays (primary particle identification). The analysis of simulations based on this parameter $X_{\text{max}}$ will probably allow us to interpret recent and future experimental data (e.g. TA, Auger observatory and soon JEM-EUSO).

2 Simulation method : CONEX code

The physical characteristic quantities of the UHECR, such as their masses, their energies, and their arrival directions, are possible to measure only indirectly. These parameters can be deduced from the properties of the extensive air showers (huge nuclear-electromagnetic cascades) generated when the UHECRs enter into the earth’s atmosphere. Monte Carlo simulations of these EAS, which take into account all the natural physical phenomena occurring during their evolution, could reliably predict these cascades of myriad particles. The CORSIKA code (Cosmic Ray Simulations for KASCADE) [6] is one of the best programs describing perfectly the EAS using the Monte Carlo method.

*e-mail: lakelghazala1@gmail.com
**e-mail: talai.mc@univ-annaba.org

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).
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 $10^{17}$ to $10^{20}$ eV [7].

### Table 1.
Comparison between Monte Carlo simulations and Cascade Equations (CE) by CONEX and CORSIKA codes results [7]

| Monte Carlo (MC) simulations | Cascade Equations (CE) |
|-----------------------------|------------------------|
| Realistic                   | Fast                   |
| Flexible                    | Mean behavior          |
| fluctuations                | No fluctuations        |
| slow                        | Limited to analytic formula |

Unfortunately, for UHECR 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 [8, 9] 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 is a hybrid simulation code that is suited for fast one dimensional of shower profiles, including fluctuations. It combines Monte Carlo (MC) simulation of high energy interactions with a fast numerical solution of cascade equations (CE) for the resulting distributions of secondary particles. For a given primary mass, energy, and zenith angle, the energy deposit profile as well as charged particle and muon longitudinal profiles are calculated. Furthermore an extended Gaisser-Hillas is performed for each shower profile similar to what is implemented in CORSIKA.

The shower simulation parameters, profiles and fit results are written to a Root file [10]. So CONEX quickly determines the EAS profile including fluctuations. A comparison of the two methods both used in CONEX code, Monte Carlo and the numerical resolution of the cascade equation, is shown in Table-1.

Pierog [7] mentioned (fig. 1) a good agreement of CORSIKA and CONEX programs when calculating the fluctuation of the maximum longitudinal profile, $X_{\text{max}} = \langle X_{\text{max}} \rangle$, for primary proton and iron nucleus at $10^{18}$ eV.

### 3 Simulation results

CONEX options involved in our simulations are the following:

- Primary particle : proton, iron;
- Primary particle energy : $10^{18}$ - $10^{21}$ eV;
- Zenith angle : $\theta = 0 - 70^\circ$;
- Energy cutoff: default values;
- Event number: 500 – 1000;
- Hadronic interaction Model: EPOS LHC, QGSJETII-04, QGSJET01 and SiBYLL 2.1.

First, we have studied the maximum charged particle number profiles distribution, $N_{\text{max}}$ (fig.2), and the shower maximum slant depth, $X_{\text{max}}$, distribution (fig.3), for primary cosmic-ray protons, iron nuclei and $\gamma$-photons at energy equal to $10^{20}$ eV. One can see that the fluctuation of the $N_{\text{max}}$ and the $X_{\text{max}}$ parameters is much more pronounced for a primary proton than a primary iron nucleus. We have also plotted the variation of $N_{\text{max}}$ (fig.4) as a function of the primary proton and and iron nucleus energies. For both primary particles (proton and iron nucleus) the higher the energy the wider the maximum longitudinal profile $N_{\text{max}}$. 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 5 shows the variation of the charged maximum slant depth $X_{\text{max}}$ 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_{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.

Moreover, we have studied the variation of N_{max} (fig.6) and X_{max} (fig.7) versus the zenith angle for a primary proton energy of 10^{20} eV. The discrepancy between the different high energy hadronic models regarding the N_{max} parameter is negligible (<5%). However, X_{max} parameter is influenced by the choice of the high energy hadronic model. The discrepancy, in case of primary proton, between the different models is about 60 g/cm^2.

4 Conclusion

For a better understanding of the properties of ultra high energy (UHE), we have used CONEX code to simulate the interaction with atmosphere of primary nuclei (iron, proton) and photon with energy range 10^{19}eV to 10^{21}eV. The most interesting quantities for this purpose are the distributions of the X_{max} parameter and the number of charged particles N_{max}. X_{max} depends strongly on the high energy hadron interaction models which induce large uncertainties in primary particle identification. The next step is to use our recorded data (CONEX) as input ones for the Jem-Euso experiment simulation code (Offline). The study of the fluorescence signal intensity profile will shed more light on the primary mass and energy.

References

[1] R.U. Abbasi et al., Phys. Rev. Lett. 100, 101101 (2008)
[2] C.T. Hill, D.N. Schramm, Phys. Rev. D 31, 564 (1985)
[3] G.A.Z. Berezinsky, V., S.I. Grigorieva, Phys. Rev. D 74, 043005 (2006)
[4] K. Greisen, Phys. Rev. Lett. 16, 748 (1966)
[5] G.T. Zatsepin, V.A. Kuzmin, JETP Lett. 4, 78 (1966)
[6] D. Heck et al., Report FZKA. Forschungszentrum Karlsruhe 6019 (1998)
[7] T. Pierog, Hybrid Simulation and CONEX kernel, KIT (2014)
[8] T. Pierog et al., Nucl. Phys. Proc. Suppl. 151, 159 (2006), astro-ph/0411260
[9] T. Bergmann, R. Engel, D. Heck, N.N. Kalmykov, S. Ostapchenko, T. Pierog, T. Thouw, K. Werner, Astropart. Phys. 26, 420 (2007), astro-ph/0606564
[10] T. Pierog et al., Nucl. Phys. Proc. Suppl. 151, 159 (2006), astro-ph/0411260