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AIRES EAS Simulations for the Energy Estimation of UHECR

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For more precise energy determination of UHECR, the fluctuations of the lateral distribution function play a significant role. We present a series of AIRES EAS simulations for gamma primaries of 100 EeV energy and different primary zenith angles. Due to the fact that electrons and positrons carry the 90% of the UHECR energy, we use these components to derive the lateral distribution functions and determine the distance which does not depend on the zenith angle of the primary gamma ray.

1. Introduction

During the past twenty years one of the clues of Ultra-High Energy Cosmic Rays (UHECR) is the observation by several Extensive Air Shower arrays (EAS) of handful cosmic particles with energies greater than $5x10^{19}$ eV. The extreme low fluxes of such energy particles require large area arrays.

The atmosphere with which cosmic particles interact plays the role of a huge detector within which a large number of elementary particles is created and which develops the structure of an EAS. These particles, which 90% consist of electrons, positrons and photons, form a disc of particles which is propagated with nearly the speed of light forming the base of the EAS front. Upon arrival at the earth surface its radius increases with energy, up to several kilometres. The longitudinal and lateral structure of the showers can give us valuable information of the energy, origin and chemical composition of the cosmic particle.
The dynamics of the behaviour of the lateral distribution of particles in EAS is well understood and is used to determine primarily the energy of the cosmic particle.

2. Lateral Distribution Function

A ground array of detectors (scintillators or Cerenkov counters) samples the charged secondary shower particles as they reach the ground. They determine the energy of the cosmic particle from the particle density variation from the shower core to a radial distance of some km. They measure the so called Lateral Distribution Function (LDF), which is the particle density distribution as a function of the radial distance from the shower core. The separation of the detectors which generally form a large array is proportional to the energy of the cosmic particles under investigation. For example, the separation of the Cerenkov detectors of P. Auger observatory aiming at measuring cosmic particles above 10^{19} eV is 1.5 km covering an overall area of 3,000 km^2 [1].

The primary energy of a cosmic particle is proportional to the sum of particles in the EAS of which a characteristic indicator is the atmospheric depth of shower maximum. In the case that an array is situated at that depth, it will measure more or less this sum of particles which equally share the primal energy of the cosmic particle. It has been shown that this common energy is about 1.4 GeV [2]. Therefore, one can easily determine the energy of the cosmic particle by multiplying this figure with the total number of shower particles at maximum.

However, this energy determination is not always applicable since one must always detect an EAS at its maximum. The atmospheric slant depth varies with the zenith angle at which an UHECR particle enters the atmosphere and the showers reach the observing levels far after their maximum of the cascade development. In addition, the atmospheric depth of shower maximum fluctuates from event to event of equal showers due to the stochastic characteristics of the hadronic showers along their axis. For better energy determination, one should introduce a method less sensitive to the height of shower maximum.
Hillas suggested that the fluctuations of the particle densities farther from the core are smaller and the LDF at such distances (about one kilometre) can be a good energy indicator [3].

Simulations of EAS showed that the density of shower particles becomes stable at radial distances of about one km from the core. This density is proportional to the energy of cosmic particle and does not depend on its chemical composition. In the excellent review paper by Yoshida it is mentioned that the radial distance of 600 m from the core of the EAS has been used to determine the primary energy [4]. The conversion factor from the density of the shower at 600 m to the energy depends on the type of detectors and on the altitude of the site where the array is located. For example, for a Cerenkov detector the conversion factor is almost twice than for a plastic scintillator.

3. AIRES Simulations for Gamma initiated EAS

For cosmic protons and heavy ions the LDF is derived using the AIRES code [5,6,7]. This function decreases rapidly with radial distance from the core of the shower and depends on zenith angle. The shape of the relation of LDF and radial distance in a log-log scale is a parabolic one in the range 200 m to 2.5 km. By applying the same code, we show that this distribution function for a gamma cosmic ray of energy 100 EeV gives similar functions as protons. Figure. 1 shows the variation of the electrons and positrons from the core to radial distances for two zenith angles. Obviously, the decrease is larger for 60 degrees due to the longer slant depth.

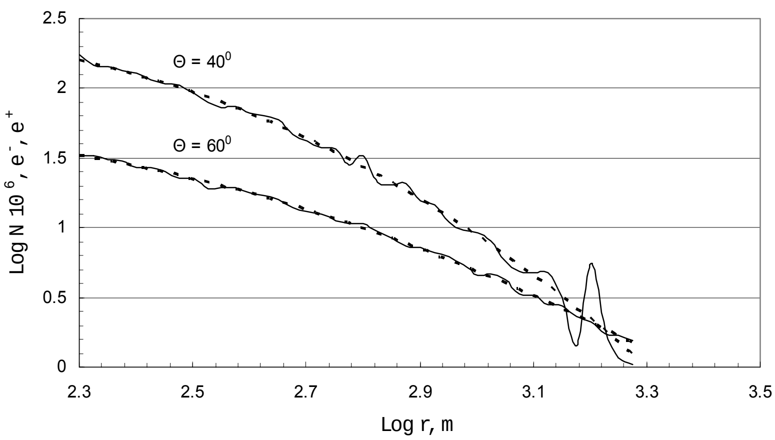

Figure 1. AIRES simulation of a gamma EAS of energy 100 EeV reaching the ground at a zenith angle of 40, 60 degrees, respectively. Dashed lines represent a polynomial fit suggested by Billoir et al [6].

An other set of simulations of lateral distributions of EAS due to gamma primaries, shows that even for theses showers the radial distance in which the distribution of muons is not affected by the slant depth is similar to that of proton showers, 1 km (Figure 2). The lateral distribution of the same simulations but for the electron component is shifted towards closer distances to the shower core (Figure 3).

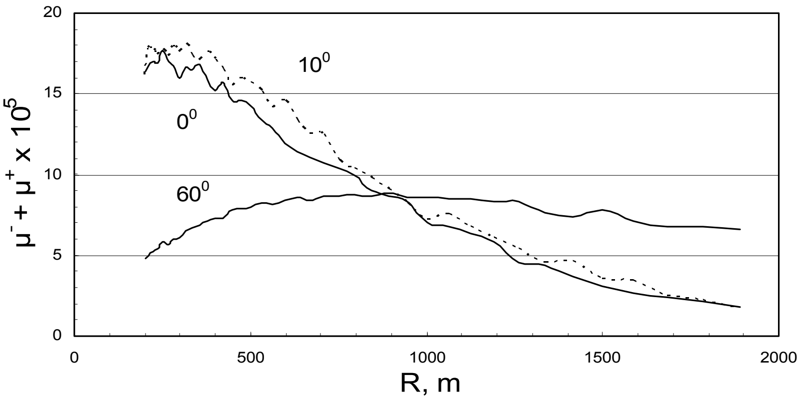

Figure 2. AIRES simulation of an inclined gamma EAS of energy 100 EeV. Lateral variation of the muon component.

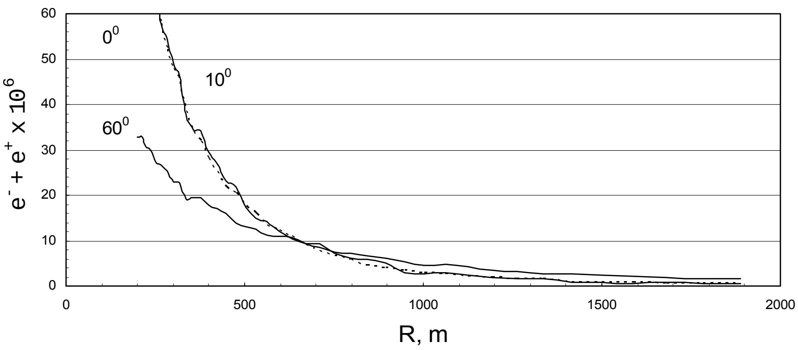

Figure 3. AIRES simulation of an inclined gamma EAS of energy 100 EeV. Lateral variation of the electron component.

4. Conclusions

The lateral distribution function is derived in order to estimate the primary energies. Hillas et al. suggested that due to the fluctuations of hadrons near the core of the shower the appropriate distance is around 600 m [3]. Dai et al. used the same distance by simulations of proton and heavier nuclei showers [8]. For muons, these fluctuations are more pronounced than for electrons (Figure 2). Our simulations concern the LDF of the electron rather than the muon component for gamma primaries of very high energy (100 EeV). These distributions are close to a polynomial fit which is similar to that of muons [6]. In addition, for the same primary gammas both the muon and electron LDFs show already the accepted distances from the shower core, which are not affected by showers of different zenith angles (Figures 1, 2 and 3).

Due to the statistical fluctuations of the simulations, we could not conclude in which distances the shower fluctuations are minimal. We needed CPU times of many days for each set of simulations, while for the presented simulations the CPU time was about three to four days. Nevertheless, these fluctuations decrease after the distance of about 500 m (Figure 2).

5. Acknowledgments

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