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Estimating the Lateral Distribution of High Energy Cosmic Ray Particles by Depending on Nishimura-Kamata-Greisen Function

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Abstract. The calculation of charged particles density in Extensive Air Showers (EAS) that reach the earth's surface is described through estimating the lateral distribution function (LDF) at very high energies of different primary particles. The simulation of LDF is performed through the simulator of air shower which is called AIR-shower Extended Simulations (AIRES) system (2.8.4a version). The LDF simulation is performed for different charged particles like the muons, electron-positron pair production and all charged particles as well as gamma rays at very high energies (10^{16}, 10^{18} and 10^{19}) eV. The influence of the primary energies, primary particles (such as the proton and the iron nuclei) and the zenith angle (θ) on the charged particles LDF that generated in the EAS has been taken into the account. The calculation of charged particles LDF is fulfilled using “Nishimura-Kamata-Greisen” (NKG) function. The LDF using NKG function is compared with that simulated using AIRES system and gave a good agreement at high energies for (electron and positron) secondary particles, which were initiated by the primary proton.

Keywords: Cosmic rays, lateral distribution function, extensive air showers, AIRES, NKG function.

1. Introduction

The Cosmic rays (CRs) are particles hitting the earth atmosphere at a rate of about (10^3 particles/m^2 Sec). They are distinguished by their high energies. Most CRs are relativistic, having energies comparable to or somewhat greater than their masses [1, 2]. A high-energy CRs study are one of the most challenging in astroparticle physics fields. High energy CRs in the EAS detection are produced in the atmospheric Earth [3, 4]. The EAS are electromagnetic radiation cascade and ionized particles which generated in atmosphere via interaction of a primary CRs together with a nucleus of an atom in the air. Then, it produce a massive amount of the secondary particles like the electrons-positrons pair production, muons, neutrons, as well as gamma-rays, etc [3, 5]. This point of cascade development may be defined as maximum shower [6]. LDF of the charged particle in EAS is the amount required to observe the cosmic radiation of the Earth, which is often derived from EAS observations [3]. The parameter used to describe the lateral density shape can be called the parameter of the lateral profile of

NKG function “Nishimura - Kamata - Greisen function” [7, 8]. It is so important in order to perform an extensive numerical simulation of an EAS to infer the properties of the elementary cosmic ray that results in it. The number of charged particles ultra high energy CRs may be so massive and it may exceed the (10^{10} particles), so these processes require highly complex computing resources to understand and simulate them [9, 10]. Because shower growth is a complex random process, LDF depends on many independent parameters. Simulations are often used to describe the entire event from the first interaction until the electronic signal is registered to the detectors. The Monte Carlo technique is used to simulate LDF from EAS [11]. The current calculations results illustrate that the density of charged particles that reach the surface of the Earth, like the electron-positron pair production, muons, and all the charged particles, as well as gamma-rays by simulating the LDF. It is performed via utilizing the system of Monte Carlo AIRES at the ultrahigh energies (10^{16}, 10^{18} and 10^{19}) eV. The LDF was calculated for different formulas of NKG and was compared with that simulated using AIRES system.

2. Theory

2.1. Lateral Distribution Function (LDF)

LDF of the charged particles in the EAS is a required quantity of the Earth's observations of CRs. Also, it is an important quantity for CRs from the surveillance of a ground, that are mostly derived from the EAS observables [12]. Experimentally, studying of EAS can be achieved on the ground surface detectors, also underground and at numerous mountain rising via determining several quantities of the LDF, such as a density of the charged particles that produced in EAS as the function of the distance from the shower core. The LDF can be described as the shower structure of cascade at different atmospheric depths [13, 14]. An expression which is widely utilized to describe the form of LDF is a lateral shape parameter in the NKG-function [7, 8]. In 1950, Kamata and Nishimura approached an approximated analytical equation for the angular and lateral distribution of the shower particles in an approximation of cascade B theory that made by Nishimura-Kamata function. Practically, the commonly used approximation of the results of calculation proposed by Greisen, that was called (NKG-function), which summarized the research of the average characteristics of multidimensional cascades (mainly electron-photon) at ultrahigh energy CRs [15].

In 1958 Kamata and Nishimura have solved the equations of Landau for LDF of photons and electrons in the (approximation B) of the cascade theory. A solution evaluated in Moliere units appears to be the shower age function (s), characterizing the cascade development solved the Landau's equations have been reached to [7, 8]:

$$\mathbf{f(R/R_M) \propto \left(\frac{R}{R_M}\right)^{s-2}\left(1+\frac{R}{R_M}\right)^{s-4.5}} \;\ldots\ldots\ldots\ldots (1)$$

Where R is a distance from a shower core; R_M is Moliere radius and s is the shower age. In EAS there are hadrons, muons, photons and electrons, so that NKG-function can't directly be applied: a lateral distribution form, at least, is the function of zenith angle and energy. Therefore, there may be the distance of the core shower interval for the given essential energy (E_o), where one can neglect the contribution of muons and hadrons to the measured charged particles density and where approximately the LDF form is just the shower age function.

The lateral distribution of an electromagnetic cascade can be parameterized by the NKG-function [7, 8]:

$$\boldsymbol{\rho_e(R) = \frac{N_e}{2*3.14*R_M^2} * C(s) * \left(\frac{R}{R_M}\right)^{(s-2)} * \left(\frac{R}{R_M}+1\right)^{(s-4.5)}} \ldots\ldots (2)$$

where $\mathbf{C(s)}$ is the normalizing factor which is given by [16]:

$$\mathbf{C(s) = 0.366\, s^2 * (2.07 - s)^{1.25}} \quad \text{.........} \quad (3)$$

$\boldsymbol{\rho}_{\mathbf{e}}(\mathbf{R})$ is the electrons density as a function of the distance from the shower core; $\mathbf{R_M}$ at sea level equal to 78 m; the shower age parameter (s), where the NKG-function is valid for the range 0.8 <**s**< 1.6; $\mathbf{N_e}$ is a total number of electrons in EAS that is given as [9]:

$$\mathbf{N_e = 10^6 \left[\frac{E_0}{10^{15}\, eV}\right]^{1.03}} \quad \text{..................} \; (4)$$

The electromagnetic cascade produces approximately most of the charged particles in the EAS and through the ionization of the electron that most of the shower energy is dissipated [17]. The results of analytical parameterizations of Monte Carlo calculations and the cascade equations solution for LDF of the electron in the air showers are depended on the function of NKG [18]. NKG function was applied with distinct sets of parameters for many years for LDF description for different components of EAS. The LDF of electrons can be expressed in a form [18]:

$$\boldsymbol{\rho}_{\mathbf{e}}(\mathbf{R}) = \mathbf{N_e \frac{0.028}{R_{m.s}^2} \left(\frac{R}{R_{m.s}}\right)^{-1.2} \left(1 + \frac{R}{R_{m.s}}\right)^{-3.33} \left(1 + \left(\frac{R}{10\, R_{m.s}}\right)^2\right)^{-0.6}} \quad \text{......} \; (5)$$

3. The Results and Discussion

3.1. LDF Simulation using AIRES System

AIRES, a set of different programs and subroutines which are utilized for EAS simulations of particles interaction development, that initiated after high energy primary CRs interacting with the nuclei of air in atmosphere and manage all associated output data [19]. The AIRES system can provides a complete propagation of particles in the true medium in the atmosphere, through observing the Earth’s curvature and the geomagnetic field features [19]. Many particles can be taken into the consideration via the simulations utilizing the AIRES system like: electron-positron pair production, muons and gamma rays. In EAS, the incident primary particles, may be proton, iron nuclei or other particles with extremely high energies up to (10^{21}) eV [19].

Figs. 1 and 2 display the simulated lateral density of many secondary’s as a function of (the distance from the shower core) to the surface of Earth by using AIRES system with thinning energy (the ratio between the energy of secondary particles to the energy of primary particles) (ϵ_{th}=10^{-7} Relative) of primary particles (proton and iron nuclei), respectively. The effect of the primary energies (10^{16}, 10^{18} and 10^{19}) eV and zenith angles (θ = 0°, 10°, 30° and 45°) was taken into account density of secondary charged particles which are produced in the EAS. Through these figures, it can be noticed that the lateral density of different particles increases with increasing the primary particle energies and the density of many particles and decreases with the increasing of distance from the shower core. Figs. 1 and 2 display the possibility for distinguishing the direction and spreading the inclined primary particles on detectors in EAS arrays through the variation of zenith angles and types of primary particles.

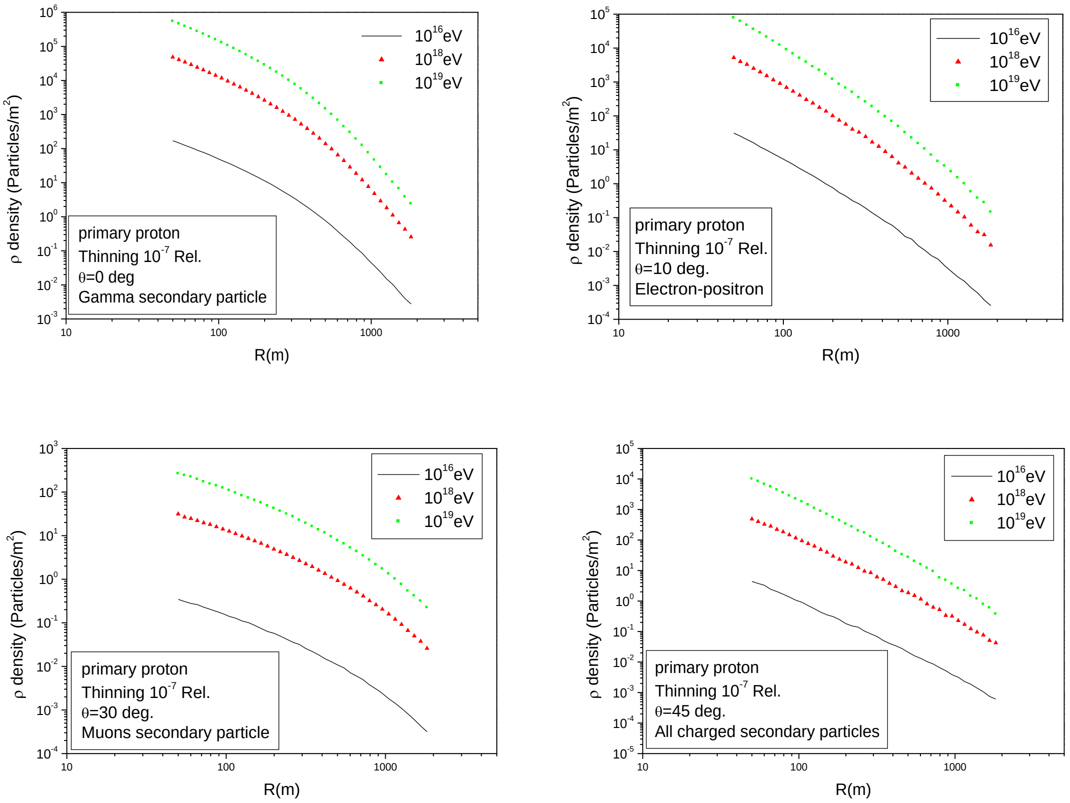

Fig.1. Effects of primary energies of primary (p) on densities of secondary particles at various zenith angles (θ = 0°, 10°, 30° and 45°).

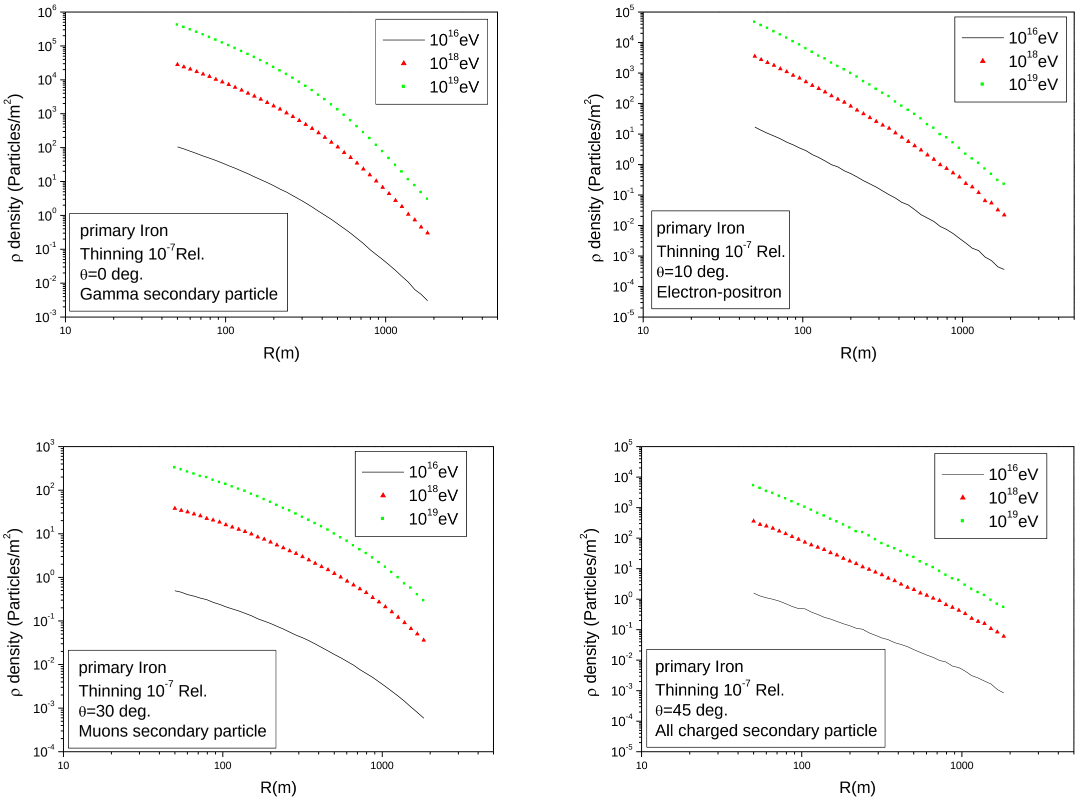

Fig.2. Effects of primary energies of primary (Fe) on densities of secondary particles at various zenith angles ($\theta = 0^\circ$, 10°, 30° and 45°).

3.2. *Comparison between the simulated LDF of primary proton and iron nuclei*

Fig. 3 demonstrates the comparison between the simulated LDF of the primary proton with that simulated for iron nuclei using AIRES system with the thinning energy ($\epsilon_{th}=10^{-7}$ Relative). This figure present a very interesting point of particles such as gamma, (electron-positron pair production), muons and all charged particles which are initiated via the primary proton and iron nuclei at the energies (10^{16}, 10^{18} and 10^{19}) eV and zenith angle ($\theta = 0^\circ$, 10°, 30° and 45°), which are very close to each other. Through the comparison one can demonstrates the possibility for reconstruction the type and energy of the EAS primary particles.

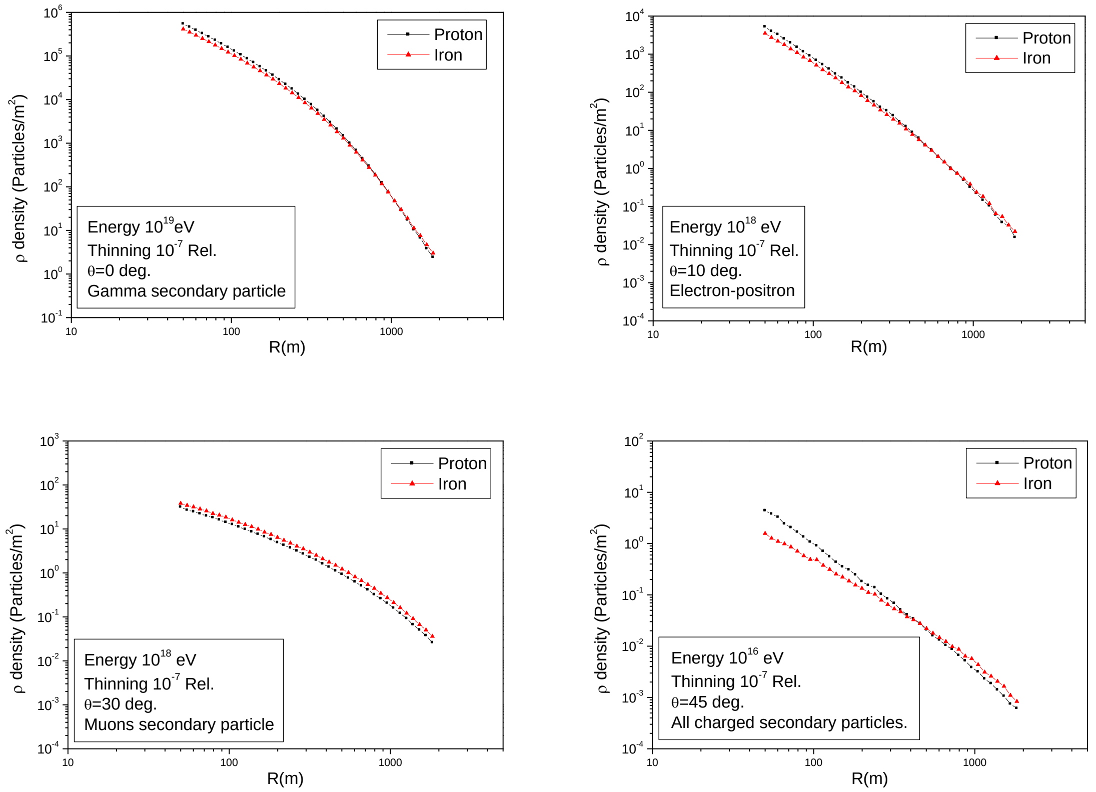

Fig.3. The comparison lateral density of the secondary particles that were initiated by primary (p and Fe) at energies (10^{16}, 10^{18} and 10^{19}eV) and zenith angle ($\theta = 0^\circ, 10^\circ, 30^\circ$ and 45°).

3.3. The comparison between NKG function and simulated LDF

Fig. 4 shows the comparison between the estimated LDF that performed using AIRES system with the results of NKG function that obtained from the equation (5). This figure demonstrates that the results gave a good agreement simulated data by AIRES system for electron and positron particles, which are initiated by primary proton at the energies (10^{16}, 10^{18} and 10^{19}) eV with thinning energy ($\epsilon_{th}= 10^{-7}$ Relative) for vertical showers.

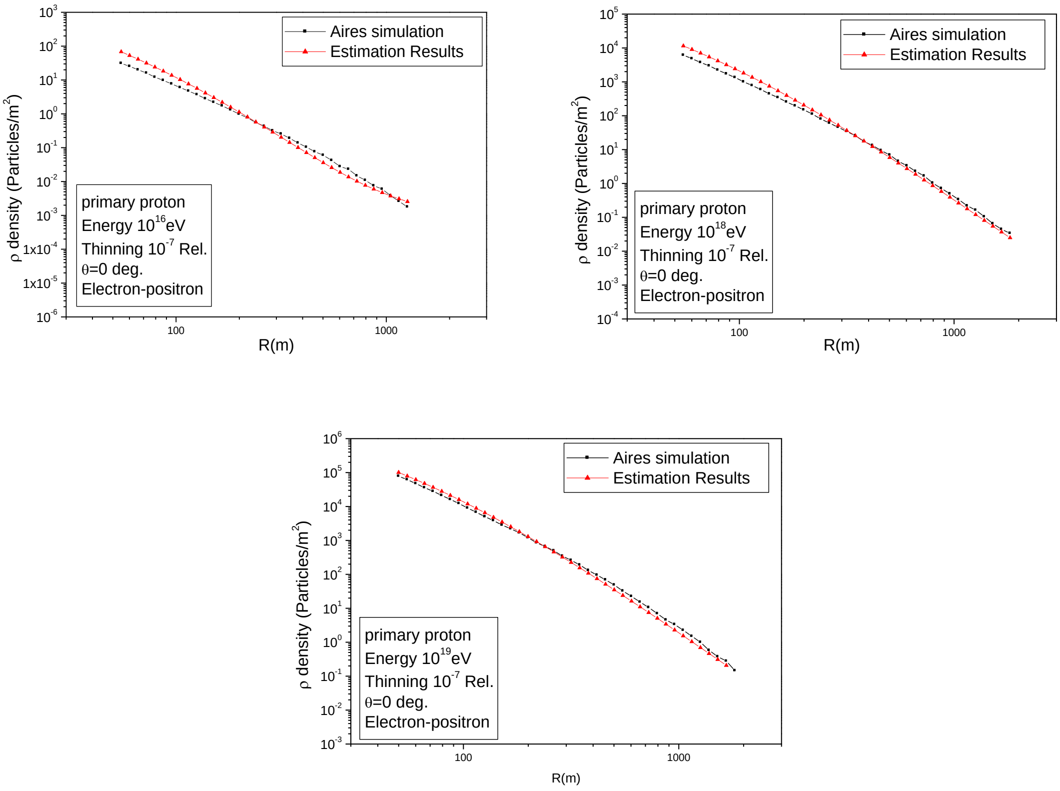

Fig. 4. Comparison between the simulated LDF with the results obtained using the NKG function.

4. Conclusions

In the present work, the effects of EAS are described by estimating the LDF at very high energies of different cosmic ray particles. The charged particles LDF like electron-positron pair production, muons, gamma rays and all charged particles that reach the Earth's surface was simulated utilizing the AIRES system for the two primaries (p and Fe) at very high energies. The influence of the primary particles, the energies, thinning energy and the zenith angle (θ) on the lateral densities of produced charged particles in EAS is taken into consideration. The simulation of lateral structure of the charged particles that reaches the Earth's surface demonstrates the capability for determining the primary cosmic ray particle and its primary energy. A significant feature of a current work is the creation of the library of samples of lateral structure which can be used to analyze real events of EAS that have been detected and also registered in the arrays of EAS.

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