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Energy, altitude, and mass dependence of steepness of the lateral distribution function of electrons and muons in extensive air showers

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ABSTRACT

In the present work, the energy and mass dependence of the steepness of the lateral distribution function of electrons and muons (η) are investigated. Based on a CORSIKA simulation, different characteristics of η for proton, helium, oxygen, and iron primaries in the energy range 10^{14}–10^{17} eV are presented. It is found that η is a mass sensitive parameter, and its potential as a mass discrimination parameter between light and heavy primaries is studied. Moreover, the altitude dependence of η for KASCADE and Auger experiments (110 and 1400 m) is discussed. It is shown that the Auger experiment is potentially more effective for applying this parameter as a mass discriminator between light and heavy cosmic ray components, especially at high energies.

1. Introduction

The reconstruction of direction, energy, and mass composition of cosmic rays from extensive air shower (EAS) data is the main challenge facing cosmic ray researchers. Although the estimation of the energy and direction of cosmic rays from EAS data is relatively easy and some measurable parameters at ground level can be used to calculate this without large systematic uncertainties, estimating the primary mass is a very difficult task. Showers produced by different primaries present differences that are due to variations in the primary energy, the uncertainties in the hadronic interaction models, and the fluctuations of the showers. It is true that data about the elemental composition of the primary cosmic ray, especially its energy dependence, can provide important clues about its origins, but at present they are associated with large uncertainties. Various methods used in different experiments have not only exhibited inconsistent results in the estimation of the primary mass, in the case of individual showers, but also in the mean mass composition at certain energies [1]. In order to determine primary mass, one must measure the properties of secondary particles generated by the primary nuclei in the atmosphere. The interaction of high energy cosmic ray particles with atmospheric nuclei creates an EAS which is distributed over a large area, perpendicular to the direction of propagation of the original particle. The disc of secondary particles may extend over several hundred meters from the shower axis, with maximum density at the centre of the disc, which is called the shower core. The measurement of secondary parameters such as lateral density distribution conveys important information about the shower development and type of primary nuclei involved. The exact form of the lateral distribution function (LDF) is still uncertain. The majority of analytical parameterizations of the LDFs of different EAS components are traditionally based on the NKG function [2]. The steepness of this function, given by η, is sensitive to the depth of the shower maximum (X_{max}), and therefore to the primary composition [3]. In this work, we study the energy, mass, and altitude dependence of the lateral distribution function steepness, η, by analysing the simulated lateral distribution of the electron and muon components of light (proton and helium) and heavy (oxygen and iron) primaries in the energy range from 10^{14} to 10^{17} eV for vertical incidents, using the CORSIKA-7400 code [4], with the hadronic interaction models qgsjet-II-04 and gheisha _200d for high and low energy primaries, respectively. The numbers of generated events for each primary in the 10^{14}–10^{17} eV and 10^{16}–10^{17} eV ranges were 300 and 100, respectively.

2. Lateral distribution function

Instead of using the NKG function, for each simulated shower at a given energy a lateral distribution function is parameterized with the use of expression (1) [5].

$$\rho(r) = kr^{-(\eta + (r/r0))} \quad (1)$$

The lateral distribution of the electrons was found to be well fit, especially near the core, by this modified power law LDF with $r_0 = 4000$ m. In Fig. 1, the lateral distributions of the electrons and

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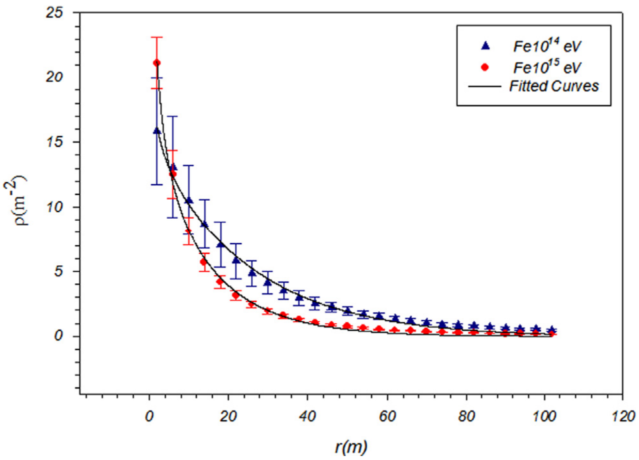

Fig. 1. Lateral distribution of electrons for vertical 10^{14} and 10^{15} eV iron primaries at 110 m observation level (KASCADE). The lateral distribution and error bars of the 10^{14} eV iron primary are multiplied by a factor of 70.

the corresponding fitted curves for 10^{14} and 10^{15} eV iron-initiated showers at the 110 m observation level are shown. As can be seen, expression (1) generates a line of good fit. Also, it can be clearly seen that the electron density distribution corresponding to 10^{15} eV is steeper than the 10^{14} eV distribution (Note that in order to show these two graphs on one plot, the lateral distribution and its error bars for the 10^{14} eV reading are multiplied by a factor of 70.). In order to investigate the energy and mass dependence of the lateral distribution function steepness, η, simulated lateral distributions have been fitted using the expression (1) and the best value of η for each distribution has been obtained. The R squared parameter [6] was more than 0.995 for all fitted curves.

2.1. Energy and mass dependence of η

The slope of the lateral distribution function is correlated with the depth of the air shower maximum (X_{max}). The more penetrative the air shower, which has less spatial distance to the observer, the steeper the radial distribution and vice versa. On the other hand, the main effect of a variable mass on showers with the same initial energy is a characteristic shift in the position of the shower maximum. Cosmic ray nuclei share their energy amongst A nucleons and, therefore, their showers can, to a first approximation, be described as a superposition of A nucleon-induced sub-showers with an energy of E/A each. Thus, showers of heavy primaries are less penetrative, and hence they tend to develop higher up in the atmosphere than nucleon showers of the same energy. Therefore, X_{max} is an observable with a strong connection to the primary mass. Additionally, the maximum depth also depends on energy. The higher the energy, the longer is the shower and the deeper is X_{max}. Based on the above argument, the steepness of the lateral distribution function, η, is sensitive to the depth of the shower maximum (X_{max}), and therefore to the primary mass and energy.

2.1.1. Lateral distribution of electrons

The fitted values of the electron lateral distribution steepness parameter (η) for simulated light (proton and helium) and heavy (oxygen and iron) primaries in the energy range from 10^{14} to 10^{17} eV for vertical incidents at the 110 m observation level are shown in Fig. 2. There are many interesting features in this figure. As can be seen, for all primary masses η is increased by increasing energy, but for each primary mass, by increasing the primary energy the lateral distribution function steepness ($d\eta/dE$) increase rate is decreased. This means, by increasing the energy, the lateral

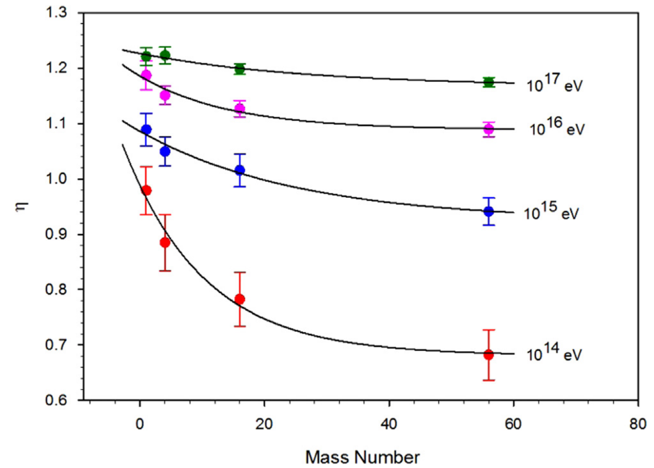

Fig. 2. η for Electron LDF as a function of primary mass for different primary energies at 110 m observation level (KASCADE), from simulation (points) and related fitted curves (lines).

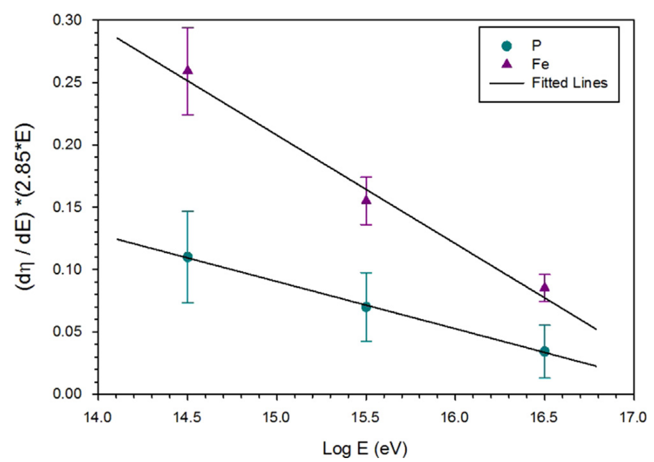

Fig. 3. $d\eta/dE$ for Electron LDF as a function of primary energy for proton and iron primaries at 110 m observation level (KASCADE), from simulation (points) and related fitted lines.

distribution function of the electrons develops to far distances from the shower core, so this broadening overcomes the steepness induced by increasing X_{max}. Also, it can be seen in Fig. 2 that for all primary energies, η decreases with increasing primary mass (decreasing X_{max}), and consequently iron primaries in the 10^{14}–10^{15} eV energy interval have a maximum value of $d\eta/dE$. In Fig. 3, $d\eta/dE$ as a function of primary energy for proton and iron primaries is shown.

2.1.2. Lateral distribution of muons

Muons penetrate the atmosphere deeply and are very important components of EAS. They are produced early on in air showers and probe the initial shower development. They interact poorly in the atmosphere, are sensitive to the elemental composition of primary cosmic rays and to the characteristics of nuclear interactions during the development of a shower [7], and can be effectively registered with widely spaced ground arrays [8]. In order to parameterize a simple lateral distribution function for muons, we have tried the modified power law LDF of expression (1). We have found that $r_0 = 500$ m results in the best possible fit for simulated data with this function. This differs considerably from the r_0 for the LDFs of electrons (4000 m) and muons (500 m), which is due to the reduced interaction of muons with the