Lateral Distribution Functions of Extensive Air Showers

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Abstract—**Ultra High Energy Cosmic Rays (>5 x 10^{19} eV) are an almost unknown and rare component of cosmic rays. Among their characteristics which could be estimated experimentally is the energy. The following paper deals with Ultra High Energy Cosmic Rays of proton, iron and gamma with energy of 100 EeV, arriving at the earth at zenith angles from 0 to 60 degrees. By a Monte Carlo code, the Lateral Distribution Function of the created Extensive Air Showers is derived. This function is used for their energy estimation. Since most of the experimental air shower arrays use Cerenkov detectors measuring the number of muons as a function of the radial distance from the core of the showers, we derive by simulations the number of muons at these distances.**

Due to the fact that almost 90% of the energy of the primary cosmic ray is converted into the electro photonic component of the showers, we also calculate the distribution functions for electrons and positrons as well.

The characteristic features of the distribution functions are discussed for being used for the energy estimation of these highly energetic cosmic particles.

I. Introduction

Ultra High Energy Cosmic Rays (UHECR) have been the argument for studying the early Universe and the experimental estimation of their isotopic composition, direction of arrival and energy was the object of several detectors in the last 20 years.

Due to the fact that these particles have a very low rate (1 per 100 years per km^2), only a handful of such particles have been measured with energies greater than 5 x 10^{19} eV.

The P. Auger Observatory [1] with its effective area of 3000 km^2 will significantly increase this statistics and we hope to shed light and give concrete answers to the clues concerning the status of an UHECR. In addition, due to the interaction of these cosmic ray particles with Cosmic Microwave Background Radiation (CMWBR) filling the whole Universe we do not expect to receive at the earth cosmic ray particles with energies greater than 5x10^{19} eV [2].

Due to their negligible rate UHECRs are not directly detected, but they are studied by the Extensive Air Showers (EAS) which create in the atmosphere when they hit the top of it. As EAS are approaching the surface of the earth, its structure longitudinally and laterally can be studied by measuring the secondary particles produced using fluorescence and Cerenkov detectors, respectively. The study of EAS structure can indirectly give us an estimation of the source, composition and energy of an UHECR.

In this paper, we use the AIRES Monte Carlo code [3] to simulate EAS created by three different UHECRs (protons, irons and gammas) of energy 100 EeV and of zenith angles varying from 0 to 60 degrees. The selected energy fits to the geometry of P. Auger Observatory of which the separation of the Cerenkov detectors is 1.5 km.

II. Lateral Distribution Function

A methodology, among others, to estimate the energy of the UHECRs is to measure the muons density distribution as a function of the radial distance from the foot of the shower core [4]. This number is proportional to the pulse height called Vertical Equivalent Muons (VEM) of the Cerenkov detectors, which detect the showers in a large area of many km^2. For the P. Auger Observatory these detectors consist of the Surface Detector Array [1].

In our lateral simulations of the EAS, we present the Lateral Distribution Functions (LDF) of cosmic ray primaries protons, irons and gammas of the same energy of 100 EeV and different zenith angles [5].

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 [6]. Therefore, one can easily determine the energy of the cosmic particle by multiplying

This project is co-funded by the European Social Fund and National Resources (EPEAEK II)Pythagoras.

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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 that of 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 [7].

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. The conversion factor of 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.

III. AIRES Simulations for Proton, Iron and Gamma Initiated EAS

The LDF is simulated with the MC code of AIRES for two sets of particles, muons and electrons-positrons, respectively [3]. The first secondary component of EAS fits to the surface detector of Auger, measuring muons laterally, while the second secondary component (electrons-positrons) reflects to some possible surface fluorescence detectors deployed laterally. Both sets of simulations consist of a series of simulations for the three UHECR primaries of the same energy of 100 EeV and zenith angles varying from 0^0 to 60^0.
The total number of showers for each run used was 100, the energy thinning was set to 10^{-6} relative and the CPU time exceeded 60 hours for each simulation set. Due to the fact that the electrophotonic component propagates close to the axis of the EAS, its function decreases rapidly with radial distance from the core of the shower and depends on zenith angle. Contrary, due to the spread of muons from the axis of the shower and the little absorption in the atmosphere, its radial variation decreases slowly. All lateral variations range from 200 m to 2000 m in 40 bins (Figures 1-5). Figure 1 shows the variation of muons from the core to radial distances at six zenith angles.

Apparently, at a radial distance of about 1100 m, the number of muons does not strongly depend on the zenith angle of the CR proton, except for the direction of 20^0, while at the same distance for iron (Fig. 2) and gamma (Fig. 3) CR primaries the number of muons depend on the zenith angle. The absolute number of gamma-muons is much less than that of protons and irons, due to the fact that they correspond to the electrophotonic component of the shower.

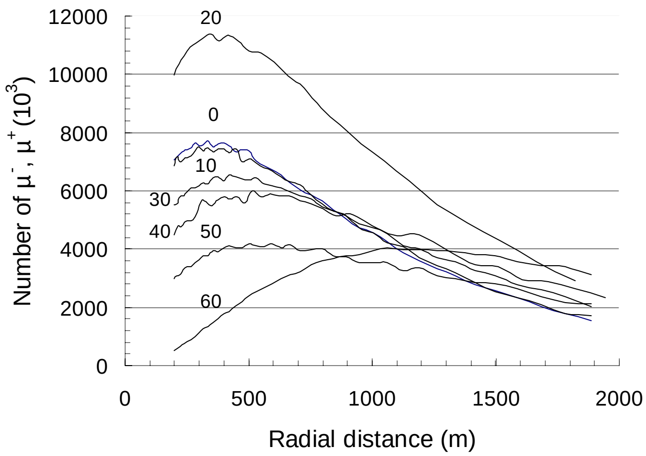

Fig. 1. LDF for muons of EAS of different zenith angles created by UHECR proton of energy 100 EeV.

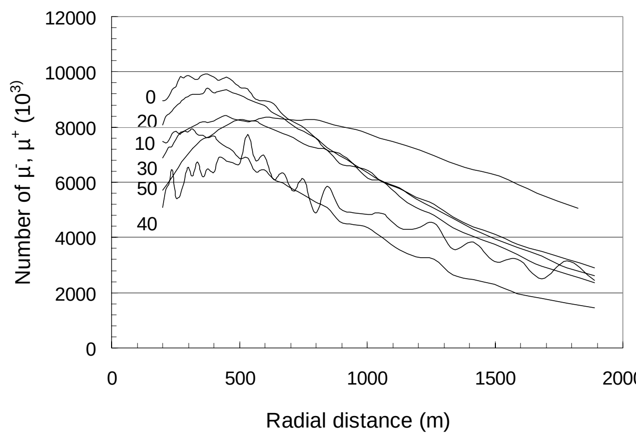

Fig. 2. LDF for muons of EAS of different zenith angles created by UHECR iron of energy 100 EeV.

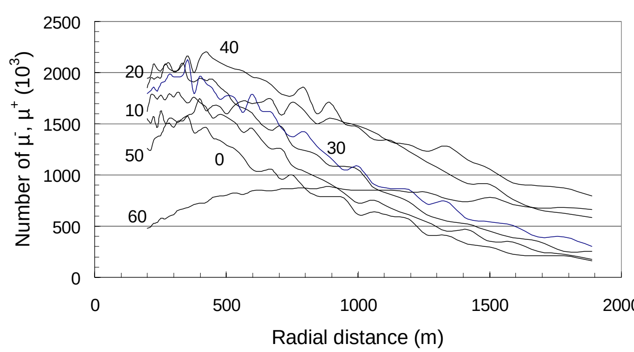

Fig. 3. LDF for muons of EAS of different zenith angles created by UHECR gamma of energy 100 EeV.

IV. Energy Estimation of Primary Proton, Gamma and Iron Nucleus

Several approaches are used to estimate the energies of cosmic rays by using the Lateral Distribution Function of muons.

In this paper we follow the expression used by Yoshida for the AKENO experiment [8].

$$E = 5.25 \times 10^{17} \left(\frac{S(600)}{1m^{-2}} \right) eV \qquad (1)$$

where, E, is the primary C. R. energy and

S(600), the muon density 600 meters from the shower core of vertical air showers.

$$S_\theta(600) = S(600) \exp\left[-\frac{X_0}{500}(\sec\theta - 1) - \frac{X_0}{594}(\sec\theta - 1)^2 \right] \qquad (2)$$

where, $S_\theta(600)$, is the muon density 600 meters from the shower core of inclined air showers.

X_0, is the atmospheric depth of the site (870 g/cm^2) of AUGER Observatory [9] and

θ, the zenith angle.

A number of values $S_\theta(600)$ is obtained by the LDF simulated for vertical and inclined showers created by C.R. protons, gamma and iron nucleus.

Tables I, II and III show the calculated parameters and the resulted energies.

TABLE I
PARAMETERS FOR THE ENERGY ESTIMATION OF CR PROTONS

Items	0 deg	10 deg	20 deg	30 deg	40 deg	50 deg	60 deg
Exp	1	0.968	0.87	0.70	0.45	0.18	0.022
Dens(600)	55.13	54.95	54.07	50.75	40.06	34.27	19.74
$S_\theta(600)$	55.13	56.76	62.20	72.87	88.66	185.15	887.87
E(600)	2.9E+19	3.0E+19	3.3E+19	3.8E+19	4.6E+19	9.7E+19	4.7E+20
Mean E(eV)	1E+20						

TABLE II
PARAMETERS FOR THE ENERGY ESTIMATION OF CR PHOTONS

Items	0 deg	10 deg	20 deg	30 deg	40 deg	50 deg	60 deg
Exp	1	0.968	0.87	0.70	0.45	0.18	0.022
Dens(600)	8.65	11.95	13.20	14.70	16.08	13.94	13.94
$S_\theta(600)$	8.65	12.35	15.18	21.11	35.58	75.32	626.98
E(600)	4.5E+18	6.5E+18	8E+18	1.1E+19	1.9E+19	3.9E+19	3.3E+20
Mean E(eV)	6E+19						

TABLE III
PARAMETERS FOR THE ENERGY ESTIMATION OF CR IRONS

Items	0 deg	10 deg	20 deg	30 deg	40 deg	50 deg	60 deg
Exp	1	0.968	0.87	0.70	0.45	0.18	0.022
Dens(600)	73.64	53.08	72.25	65.97	56.63	56.66	
$S_\theta(600)$	73.64	54.82	83.11	94.73	125.32	306.07	
E(600)	3.9E+19	2.9E+19	4.4E+19	5E+19	6.6E+19	1.6E+20	
Mean E(eV)	6E+19						

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V. DISCUSSION

Some preliminary results could be drawn for the LDF of the showers and the associated primary energies:

1. From Fig. 1, one can observe that all LDF's intersect to each other at a distance of about 1100 m (except for the zenith angle of 20 deg.). Therefore, at this distance the
2. LDF is more or less independent on the zenith angle of the shower.
3. From Fig. 4, which present the same plot in log-log scale as Fig. 1, all LDF's converge at the distance of 2000 km,

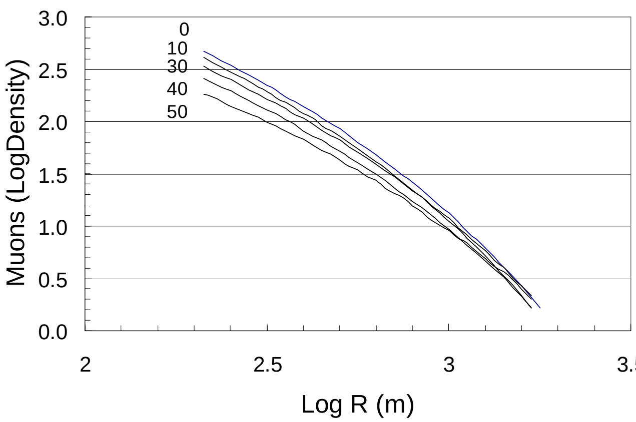

Fig. 4. LDF for muons of EAS of different zenith angles created by UHECR proton of energy 100 EeV presented as density in logarithmic scale

which means that at farther distances than 1100 m the independence of LDF on zenith angle is much stronger. On the contrary, the LDF's for electrons and positrons seem not converging (Fig. 5).

4. Using the well tested expression (2) for AKENO experiment we have got primary energy values approaching the energy set by the AIRES simulations of 10^{20} eV.

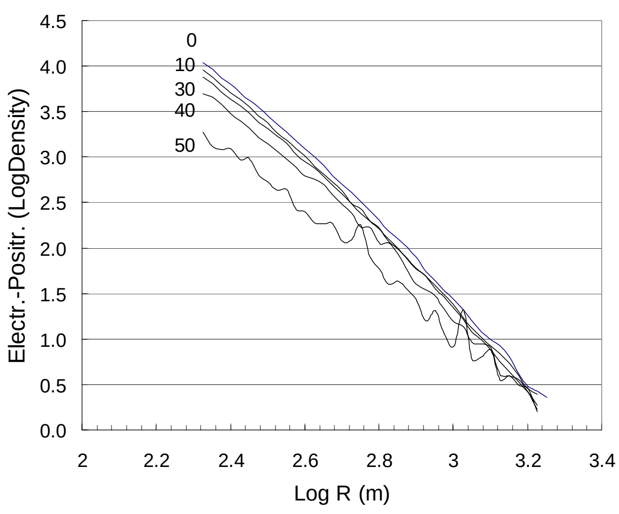

Fig. 5. LDF for electrons and positrons of EAS of different zenith angles created by UHECR proton of energy 100 EeV presented as density in logarithmic scale. The fluctuations for the simulated showers for 50 deg of zenith angle are quite large. Due to the very large fluctuations for showers of 60 deg., the corresponding LDF is omitted. Even larger are the fluctuations for 60 deg.

5. The lower primary energy found for iron nuclei (Table III) is in agreement with the Alan Watson presentation in Santa Barbara, stating that "For S(600), the energy estimates are LOWER if iron is assumed" [10].

One of the main points of the task is the reduction of statistical errors of the simulated LDF. Although observationally, we got a distance of about 1100 m, at which LDF does not strongly varies for several zenith angles, the fact that the distance of 600 m is widely used and tested, hints us to adopt 600 rather than 1100 m as a reference distance.

Acknowledgment

The authors thank Sergio Sciutto for the use of the AIRES Monte Carlo code. The project is co-funded by the European Social Fund and National Resources (EPEAEK II) PYTHAGORAS II.

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