Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 539–542

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

Lateral Distribution Functions of Extensive Air Showers

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Abstract: This The energy is among the characteristics of Ultra High Energy Cosmic Rays (E>5 x 10^{19} eV) which could be estimated experimentally. The following paper attempts to estimate the energy of an UHECR proton by applying a Monte Carlo simulation code. A number of vertical extensive air showers is simulated to derive the Lateral Distribution Functions of the shower muons. The scenario of simulations is adopted to a Cerenkov surface detector situated at the North pole at sea level. Due to the fact that the Lateral Distribution Functions show minimal fluctuations of the muon density at a distance larger than 900 m from the core of the showers, and because at this distance from the core of a shower the distribution functions for inclined showers coincide, we select the distance of 900 m to derive the energy of the primary protons. We compare results for this site with the site of P. AUGER Observatory.

Introduction

Despite the fact that Ultra High Energy Cosmic Rays (UHECR) have been detected for more than four decades their origin still remains elusive. Among others, the experimental estimation of their particle composition, direction of arrival and energy have been researched.

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 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 [1]. In addition, due to the interaction of these cosmic ray particles with Cosmic Microwave Background Radiation (CMBR) filling the whole Universe, we do not expect to receive at the earth conventional cosmic ray particles with energies greater than 5x10^{19} eV [2]. Due to their negligible rate, UHECR are studied by Extensive Air Showers (EAS), which are created in the atmosphere when they interact with it. As EAS are approaching the surface of the earth, their 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 vertical EAS created by a proton of energy of 100 EeV. The selected energy is suited to detector arrays like the P. Auger Observatory of which the separation of the Cerenkov detectors is 1.5 km.

Lateral Distribution Function

A methodology, among others, to estimate the energy of the UHECR is to measure the muon density distribution as a function of the radial distance from the foot of the shower core [4]. 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) proton cosmic rays with energy of 100 EeV [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 shower 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 the maximum of the cascade development. In addition, the atmospheric depth shower maximum fluctuates from event to event of equal showers due to the stochastic characteristics of the hadronic component propagating 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 [4].

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.

AIRES Simulations for proton initiated EAS

The LDF is simulated with the MC code of AIRES for muons [3]. This component of EAS fits to the surface detector of Auger, measuring muons laterally.

Due to the spread of muons from the axis of the shower and the little absorption in the atmosphere, their radial density decreases slowly. All lateral variations range from 50 m to 2000 m in 40 consecutive bins.

Hillas et al. [4] proposed an estimation of the primary energies of a cosmic ray particle creating an EAS observed at the Haverah Park array by using the parameter ρ(600) which is the muon density at 600 m from the core.

In this paper we use the AIRES Monte Carlo code [5] to estimate the energies of UHECR with a similar technique. Our simulations are applied to a Cerenkov experiment situated at the N. Pole at sea level using a primary proton of the energy of 100 EeV. The total number of showers used for each run was 100 and the energy thinning level was set to 10^{-6} relative to the energy of the primary proton. To search for a common distance from the core where inclined showers coincided, we plotted the number of muons as a function of distance (Fig. 1). Fig. 1 shows the variation of muons from the core to radial distances at four zenith angles. Apparently, the radial distance at which we have more or less the same number of muons for all four zenith angles is 900 m.

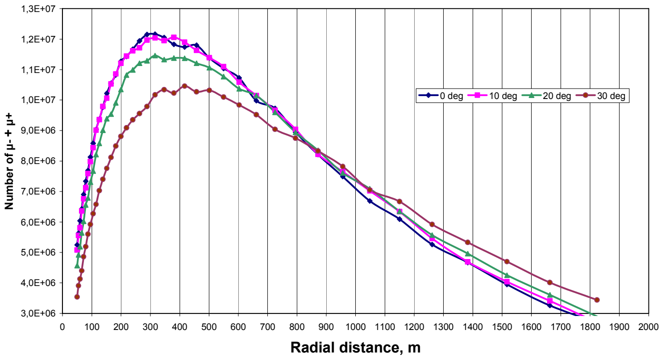

Figure 1: Variation of muons from the core to radial distances at four zenith angles

A second desired condition for the energy estimation is the distance at which we have minimal fluctuations of the number of muons. We use the statistical fluctuations of the number of muons per meter to estimate it, assuming linear interpolation between consecutive points. Fig. 2 shows the fluctuation of muons per unit length as a function of radial distance. It seems that from a distance of about 900 m fluctuations are minimal.

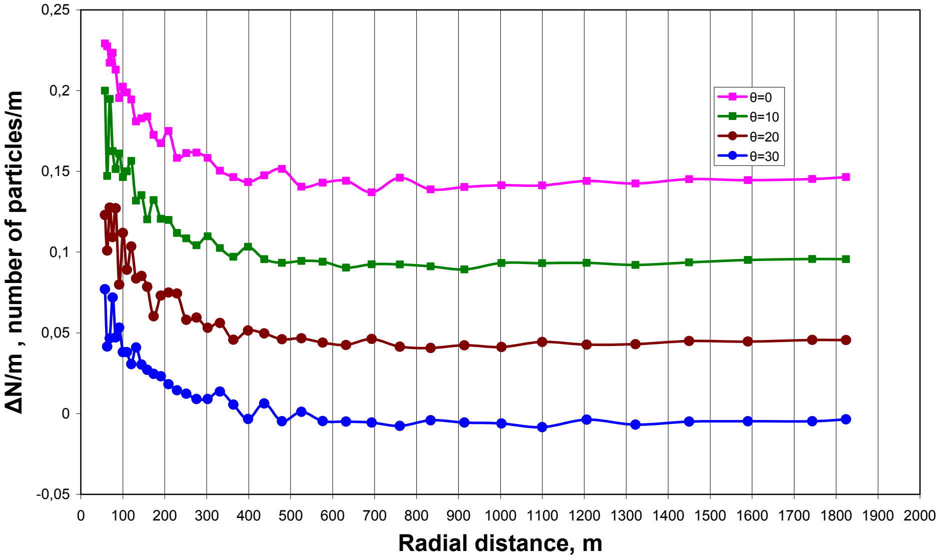

Figure 2: Fluctuation of the number of muons per unit length as a function of radial distance. For a better view, we introduced a vertical displacement of the curves

Due to the fact that at the distance of about 900 m the fluctuations of the muon number is minimal and this number is the same for inclined showers too, we adopted S(900), as the muon density at 900 m from the core of the shower.

Energy estimation for vertical protons

Yoshida [6] reported that for the estimation of the energy of an UHECR by a Cerenkov detector array located at sea level, the following empirical formula can be used,

$$E = 5.25 \times 10^{17} \times \left[S(900) \big/ m^{-2} \right] eV \qquad (1)$$

As we have already mentioned, for an experiment situated at N. Pole at sea level, the most adaptive parameter as an energy estimator is S(900). Therefore, we used the above empirical formula retaining the factor 5.25 which is related to the type of the detector (water Cerenkov).

For this reason, we simulated a large number of EAS created by vertical protons of energies ranging from 10^{19} to 10^{20} eV. This energy range characterizes the P. Auger Observatory.

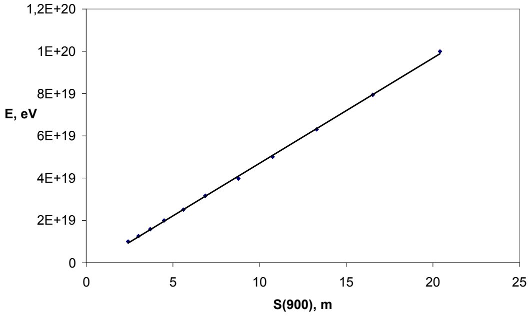

Figure 3: Variation of E with S(900)

Fig. 3 shows the variation of E with S(900). It is obvious that there is a linear relation between E and S(900). The analytical form of the equation is,

$$E = 5.25 \times 10^{17.97} \times S(900) - 2.69 \times 10^{18} \qquad (2)$$

Applying the above formula we could calculate the energy estimations and compare them with the simulated (4th and 1rst column of Table I).

The Pierre. Auger site

Our simulations have been applied for a general site at the North Pole at sea level. Since the site of P. AUGER Observatory is different (35.20° S, 69.20° W, 1400 m a.s.l.), we simulate similar vertical EAS for the two different locations.
Fig. 4 shows the number and density of muons as a function of radial distance.

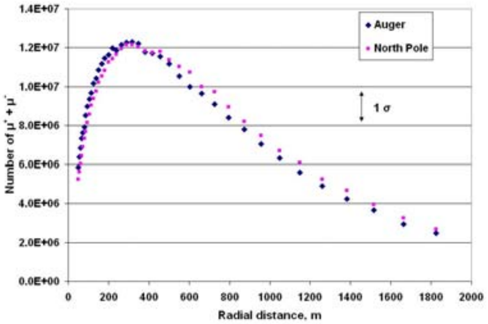

Figure 4: The number of muons as a function of radial distance at the Auger site (diamond) and at N. Pole (rectangular). One σ is the mean standard deviation.
We observe a slight deviation of the LDF for N. Pole and AUGER sites, but inside the statistical error.

Discussion

To apply the LDF of muons of a shower for the estimation of the energy of an UHECR proton, we searched for a distance at which both fluctuations of muon densities are minimal and of the same value as for vertical and inclined showers (0^0 to 30^0). Using in principle eq. 1, we were able to simulate a similar expression which linearly connects the energy of the UHECR proton and the muon density at 900 m. The comparison between the simulated energies and the theoretical (10^{19}-10^{20} eV) show negligible deviations (Table I).
If for vertical showers and 100 EeV cosmic protons simulations are applied at the site of Auger Observatory (El Nihuil, Argentina), the deviations are within one sigma and therefore there is no any significant difference between this site and the N. Pole (Fig. 4).

Table 1

$E_{simulation.}$ (eV)	S(900) (m^{-2})	Energy estimation (eV)	δE (eV)	% δE
1.00E+19	2.41	9.32E+18	6.80E+17	7
1.26E+19	3.01	1.23E+19	2.89E+17	2
1.58E+19	3.69	1.57E+19	1.49E+17	1
2.00E+19	4.49	1.97E+19	2.53E+17	1
2.51E+19	5.61	2.52E+19	-8.11E+16	0
3.16E+19	6.86	3.15E+19	1.23E+17	0
3.98E+19	8.77	4.10E+19	-1.19E+18	3
5.01E+19	10.8	5.08E+19	-6.81E+17	1
6.31E+19	13.3	6.35E+19	-4.04E+17	1
7.94E+19	16.5	7.96E+19	-1.67E+17	0
1.00E+20	20.4	9.89E+19	1.10E+18	1

Acknowledgments

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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