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New results from Gauhati University miniarray detector

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We report here the results of reanalysis of original data of the GU miniarray detector using CORSIKA code with QGSJET model of high energy hadronic interactions. The GU miniarray detector was used to detect giant EAS by the method of time spread measurement of secondary particles produced in atmosphere. It consists of eight plastic scintillators of carpet area $2m^2$, each viewed by fast PMTs. The energies of the air showers have been reestimated in this analysis leading to a modified relation between primary energy and shower size. A revised energy spectrum is reported for 10^{17}eV to 10^{19}eV primary energies.

1. Introduction

The GU miniarray [1] was an unconventional detector used to detect giant extensive air showers (EAS) initiated by ultra high energy cosmic ray (UHECR) particles with air nuclei. It was based on the Linsley effect [2] which is the increase in the spread of arrival times in a particle sample from a given shower with the increasing distance from the shower centre. Thus the measured time spread of particles striking a localized detector system gives an estimate of the distance (r) to the shower axis. The number of particles give the measure of the local particle density (ρ). From these measurements, the shower size (N_s) was estimated from the lateral distribution function $\rho(N_s,r)$. Finally, the primary energy (E_0) corresponding to an event with the estimated shower size N_s was derived using the best fit relation in agreement with QGS model and Yakutsk data [3]. This detector was operational during the period from October 1996 to April 1998. We present here a reanalysis of these data by using CORSIKA [4] with the high energy hadronic interaction model QGSJET [5]. Here we reestimate the primary energy from the best fit relation between the N_s and E_0 obtained from the new analysis [6].

2. Data analysis

To study the cascade development in the atmosphere, it is best to use a Monte-Carlo code to simulate the same taking into account all knowledge of high energy hadronic and electromagnetic interactions involved. In this work the extensive air showers are generated by CORSIKA [4] version 6019 with QGSJET01 model [5] for high energy hadronic interactions. CORSIKA is an open program package for performing a complete 4-dimensional simulation of air shower with primary energies from 10^{12}eV to 10^{20}eV. It was originally developed to perform simulations for the KASCADE experiment at Karlsruhe [7] and it has been refined over the past years. Here we invoked the QGSJET01, to simulate high energy hadronic interactions because this model is very successful in explaining experimental results in the high energy range.
For our Monte-Carlo data library we have simulated 500 vertical showers in the energy range from 10^{17}eV to 10^{20}eV with an energy slope of -2.65, proton and iron as primary particles. Statistical thinning [8] of shower particles was applied at the level of $10^{-4}E_0$ with a maximum particle weight limit of 10^{30}. The threshold energies are 0.1GeV for hadrons, muons and electromagnetic component. Figure 1(a) shows the comparison of shower disk thickness at different distances from shower axis as calculated from CORSIKA [9] with results from Linsley's original equation [1, 2] for the same. This figure shows a reasonable agreement between these

two ways of calculation with slight discrepancy in the higher core distances. We have parameterized the particle density distribution for large shower and medium core distances (100 m $<$ r $<$ 1000 m) by using our simulated miniarray data for proton and iron initiated showers separately [6]. Figure 1(b) shows the lateral density distribution for proton and iron initiated showers simulated for the miniarray using CORSIKA as compared with earlier relation [1, 10] used for miniarray analysis. There is a noticeable disagreement between CORSIKA and the earlier relation. The effective area of the miniarray detector is an annular ring [6] with outer radius determined by density threshold $\rho_1 = 1.5$ m^{-2} and its inner radius determined by the minimum time spread σ_1 as selected [1, 6]. Simulation of detector response for all the charged particles in the vertical direction

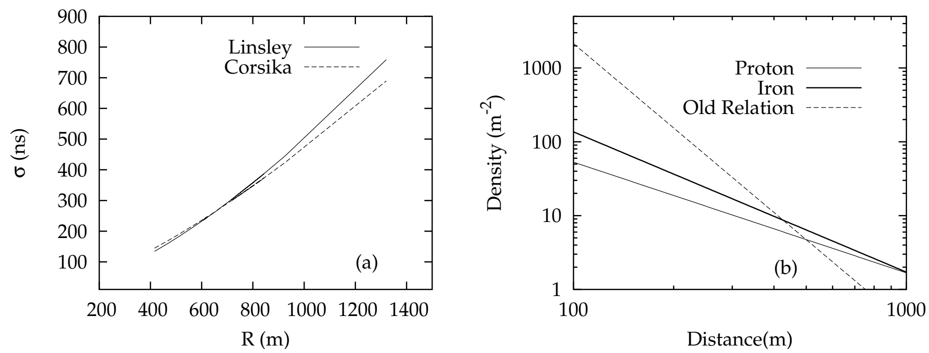

Figure 1. (a) Shower disk thickness versus distance from the shower axis. Linsley's relation is shown in comparison with the simulation. (b) Lateral particle density distribution obtained from the simulation and from the old relation.

of miniarray has been performed. Particles are collected for 500 simulated showers within the annular area ranging from R_{min} to R_{max} [6] and for primary energies from 10^{17}eV to 10^{20}eV with minimum detectable energy of the particles as 100 MeV. From this, mean particle density at different core distances have been calculated. For the minimum detectable shower size [6] and the threshold density, events are counted for all those simulated showers for different primary energy bins. Figure 2(a) shows the variation of effective area of miniarray with primary energy. The effective area increases with the increasing energy. The simulated data is not in close agreement with the data from old relation [1]. The primary energy for each shower is reconstructed using the estimated value of N_s. The calibration curve for proton and iron primaries are plotted in figure 2(b) and are compared with the simulation and the best fitted relation with Yakutsk data [1, 3], that was used for previous miniarray data analysis. There is a noticeable difference between the old and the new calibration, which leads to the reconstruction of energies [6].

3. Results and Discussion

Numerical calculations show that for our miniarray of 2 m^2 area, minimum acceptable shower sizes are 1.57×10^7 for proton primary and 9.67×10^6 for iron primary with a minimum time spread $\sigma_1 = 100$ ns and for a given threshold density $\rho_1 = 1.5$ m^{-2} [6]. Figure 3(a) shows the event distribution as a function of shower disk thickness(σ). Figure 3(b) shows differential energy spectrum derived from the reanalysis of the miniarray data assuming proton and iron primaries as compared with old analysis and results of Yakutsk, AGASA and HiRes [11]. A compilation of spectrum derived from Akeno and Haverah Park data by Nagano and Watson [12] is also shown in figure 3(b) for comparison. It is observed that,

(1) New analysis gives estimates of primary energy significantly higher than the previous analysis. Energy

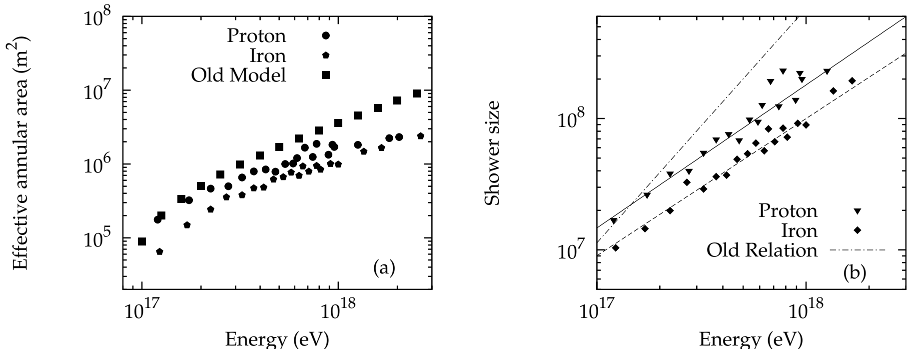

Figure 2. (a) Effective area of miniarray versus primary energy of proton and iron simulated showers are compared with the results from old relation. (b) Shower size (N_s) versus primary energy of proton and iron simulated showers. Solid line represents energy calibration curve for proton and the dotted line for iron.

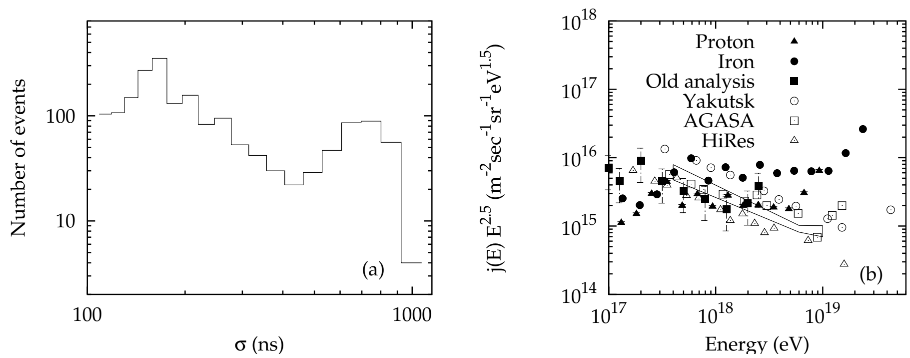

Figure 3. (a) Event number distribution as a function of shower disk thickness (σ). (b) Miniarray differential energy spectrum. Data for proton and iron are obtained from reanalysis of experimental data using CORSIKA assuming proton and iron as primary cosmic ray particles. Region between solid lines give the flux as compiled from Akeno and Haverah Park data by Nagano and Watson (2000) [12].

spectrum after reanalysis is found to span from 10^{17}eV to 10^{19}eV for proton primary and from 10^{17}eV to $10^{19.4}$eV for iron primary and further confirms the irregular behavior of energy spectrum at ultra high energy region with a prominent dip.

(2) The differential energy spectrum shows structure similar to that observed by other world groups. Spectral breaks are found to occur at higher energies compared with old method of analysis. The spectrum becomes steeper around $10^{17.5}$eV and $10^{17.7}eV$ and flattens around $10^{18.7}eV$ and $10^{19.1}eV$ for proton and iron primaries respectively forming a dip. Earlier analysis showed a dip around $10^{18.2}$eV. A comparison of our results with other world data are shown in the table 1.

(3) There is a significant difference between spectra predicted by pure proton and pure iron assumptions. However, proton assumption results agree more with Nagano and Watson compilation within spectral range from $10^{17.5}$eV to $10^{18.5}$eV. Beyond 10^{19}eV results of different giant arrays are contradictory. AGASA provides strong evidence for the existence of cosmic rays with energies beyond Greisen-Zatzepin-Kuzmin (GZK) cut-off. By contrast, data from the HiRes detector in the US are compatible with the existence of the GZK

Table 1. A comparison of overall slope of the differential energy spectrum.

Experiment	Slope	Energy range (eV)
Yakutsk	-3.031±0.047	$10^{17.5}$ - $10^{19.8}$
AGASA	-2.884±0.059	$10^{17.6}$ - $10^{19.2}$
HiRes-I	-3.151±0.036	$10^{17.2}$ - $10^{19.2}$
Miniarray(old analysis)	-2.938±0.108	$10^{17.0}$ - $10^{18.8}$
Miniarray(new analysis,p)	-2.360±0.075	$10^{17.0}$ - $10^{19.0}$
Miniarray(new analysis,Fe)	-2.207±0.067	$10^{17.0}$ - $10^{19.4}$

cut-off. More statistics is therefore necessary to resolve this important feature related to Astrophysics.
(4) The differential energy spectrum corresponding to best least square fit in the energy region $10^{17.0}$eV - $10^{19.0}$eV is derived as,

$$j(E_0) = j_0 E_0^{-p} \tag{1}$$

For proton primary $j_0 = 7.107\times10^{12}$, p = 2.360±0.075 and for iron primary $j_0 = 2.772\times10^{10}$, p = 2.207±0.067.

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