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Cosmic ray energy spectrum above 10^{17} eV observed from Gauhati university mini array data

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Abstract

The Gauhati University Mini Array consisting of eight plastic scintillator of carpet area $2m^2$, each viewed by fast PMT's (Thorn EMI 9807B) has been operated since September 1996. The Array detects Giant Extensive Air Showers by the method of time spread measurement of secondary particles produced by the UHE Cosmic Rays in the atmosphere. All the eight detectors are connected to a data acquisition system capable of recording arrival time spread of secondary particles upto 2.5μS. We have reanalyzed the data recorded by the array through April 1999.The paper presents the derived energy spectrum above primary energy $E=10^{17}$eV. The best fitted differential energy spectrum observed by the Array is :

$$j(E)=10^{25.38}\times E^{-3.04\pm.06}\ m^{-2}\ sr^{-1}\ s^{-1}\ eV^{-1}.$$

1 Introduction

Every well determined feature of cosmic ray energy spectrum will have considerable impact on theories of the origin, acceleration, and propagation of cosmic rays. Particle accelerators at present can only provide particles upto a maximum energy of~10^{14}eV. But in cosmic rays particles beyond 10^{20} eV are available. UHE cosmic rays have gained importance as a result of highest energy events above 10^{20} eV being recorded by a number of research groups. According to the theory of GZK cutoff, no primary cosmic ray particle should exceed energy of 10^{20} eV. Therefore study of such events with enough statistics is important for astrophysical purpose of origin. A giant extensive air shower can be conventionally detected using a large number of ground based detectors covering a wide area (several km^2). As suggested by Prof. J. Linsley, this can be done by a low cost method requiring a few closely packed detectors capable of measuring arrival time spread of individual shower particles (Linsley, 1986). The idea has been pursued by us and a Mini array detector has been installed in the Physics Department , Gauhati University. This detector array is specially designed to measure, both the charge particle density and their arrival time at the detector level. This paper presents the characteristics of the energy spectrum derived from the collected data by the present experimental setup.

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2 The experiment

The anode pulses from the eight detectors are amplified and then carried to the control room via co-axial cables (Type:RG58U). In the control room, all the eight pulse signals are discriminated to provide corresponding logic signals. The discriminated output is then individually shaped into narrow pulses of 20nS width and OR'ed together to give a serial pulse train. The serial pulse train is then branched into the time digitizer, the oscilloscope (Tektronix , TDS520, 500MHz , 500MSamples per sec) and the trigger unit. The trigger circuit senses the incoming pulse train and generates the necessary trigger pulse. Once triggered, the number of detector pulses and their relative time positions are stored in the time digitizer and the scope. The microprocessor (μP, 8086) stores the data from the time digitizer in RAM and transmits the data to the computer via serial port. The pulse waveform is recorded by the scope and is transferred to the PC (486DX2) via GPIB interface. The microprocessor also monitors the status of the detectors at a predetermined interval and also handles the recording and transfer of data of each event to the PC via RS232 interface. Details about the data acquisition system is presented elsewhere (Bezboruah et al, 1998; BezboruahT et al, 2001).

3 Data selection criteria

Numerical calculations (Bezboruah et al, 1999) show that for a given threshold density ($\rho_1 = 1.5$ /m^2), the minimum detectable shower size increases and the shower rate decreases with increasing time spread . A mini array should be able to pick out very few large air shower events from a swarm of irrelevant events including the counter noises, the background soft radiations and small air showers. In order to eliminate the large number of small air showers a minimum time spread has to be assigned. For a miniarray of 2m^2 area, a minimum acceptable shower size of 7.5×10^6 requires a minimum time spread $\sigma_1 = 100$ nS . In view of the small particle density encountered, each scintillator is not expected to receive more than one particle at a time from a shower.

4 The simulation results

The data are artificially simulated by using Monte Carlo simulation method. The result of the simulation gives an estimate of the errors in the measurement of shower of fixed size10^7 , 10^8 and 10^9 as 43.4% , 34% & 36% respectively.

For the present experiment, primary energy is derived as a secondary parameter from the measurement of shower size N , using the relation

$$E(\text{ in eV }) = 1.122\times 10^{13}\times N^{0.56}$$

Average percentage error in energy estimation is found to be ~ 22%.

5 Experimental results

Data have been collected during 1996 to 1999 for more than 1000 hours. Most of the data collected do not belong to true large shower events. The data are reduced by the selection process and by visual inspection. True large air shower events with a time spread of shower front $\sigma \geq 100$nS and with local particle densities $\rho \geq 1.5$/m^2 are selected and analysed. They belong to shower of size $N \geq 7.5\times10^6$.

6 Energy spectrum

The energy spectrum derived from the Mini Array data exhibits remarkable structure. The differential energy spectrum considering the event above threshold($\rho_1 \geq 1.5$/m^2) is shown in the fig.1. The spectrum becomes steeper around $10^{17.6}$ eV and flattens around $10^{18.2}$eV and forms a dip. We divide the energy spectrum into three energy ranges and fit them to a power law in each region(Table 1). Table 1 also lists the overall fit regardless of the details of the spectrum, though the overall spectrum doesn't resemble a single power law. All the fits were done with the chi - squares fitting. A comparison has been done between the chi-squares fitting and maximum likelihood method. In general the two methods show minor differences.

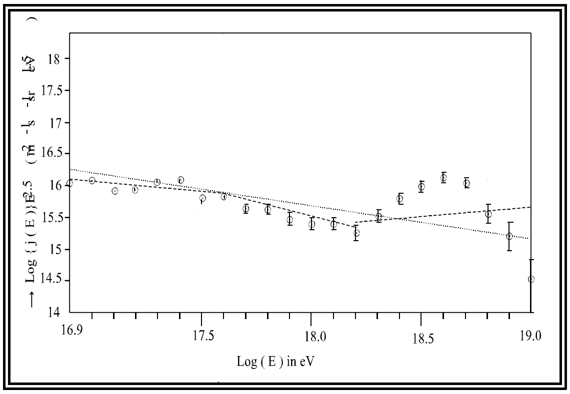

Fig.1: Mini Array Differential Energy Spectrum . Points Data. Dashed Line : Best Fit in Each Region. Dotted Line : Best Fit Upto $10^{18.2}$ eV.

For overall Mini Array energy spectrum fitted with chi-squares fitting gives spectral slope of $-2.79 \pm .05$ while the maximum likelihood method gives a value of -2.77. The spectral slope within the energy range $10^{17.6}$ - $10^{18.2}$ eV is $-3.29 \pm .09$ from chi-squares fitting while maximum likelihood method gives -3.27. The two numbers agree within the errors. To show the significance of the dip the number of events expected from the overall fit (renormalized to the observed number of events at $10^{17.6}$ eV) are listed in table2 with the observed number of events. The expected number of events between $10^{17.6}$ eV and $10^{18.2}$ eV is 794 while the observed number is 590. The significance of the deficit is 7.52σ. To show the significance of flattening above $10^{18.2}$eV, we use the normalization and slope from the total fit upto $10^{18.3}$ eV. The total number of events observed above this energy is 538 while the expected number of events is 222. The significance of this excess is 21.18σ.

The existence of the dip can be also seen from analysing the raw data, by plotting event distribution weighted by $E^{1.5}$ as in fig.2. From fig.2 it is also seen that there is a dip formed around $10^{18.2}$ eV for the Mini Array energy spectrum.

7 Discussion and conclusion

The artificial shower simulation for the fixed shower of sizes 10^7, 10^8 and 10^9 predicts proportional errors of 43.8%, 34.0% and 36.0% respectively in the estimation of the shower size by using a Mini Array of area $2m^2$. The simulation gives an average error of 22% in the measurement of energy by the Mini Array.

However if we consider all the densities and shower front thicknesses above threshold then energy spectrum as shown in fig.1, shows spectral changes similar to those observed by other large groups with overall slope of -2.79. However this slope is much lower than that calculated by others (Bird et al, 1994) and is due to the abnormally large number of events

Table1
NORMALIZATION AND SPECTRAL SLOPE OF j(E)

Energy Range (eV)	PowerIndex	χ^2	Log normalization	Normalized at (eV)
$10^{16.9}$ - $10^{19.0}$	-2.79 ± .04	37.08	-29.34	10^{18}
$10^{16.9}$ - $10^{17.6}$	-2.89 ± .12	27.50	-29.26	10^{18}
$10^{17.6}$ - $10^{18.2}$	-3.29 ± .09	12.54	-29.45	10^{18}
$10^{18.2}$ - $10^{19.0}$	-2.54 ± .06	35.55	-30.62	$10^{18.5}$
$10^{16.9}$ - $10^{18.3}$	-3.04 ± .06	28.40	-30.86	$10^{18.5}$

recorded by the Mini Array in the higher energy range (a significance of 21.18σ excess). This over estimation in the higher energy side may be due to inclusion of some delayed particles, which are not real part of the true shower front and

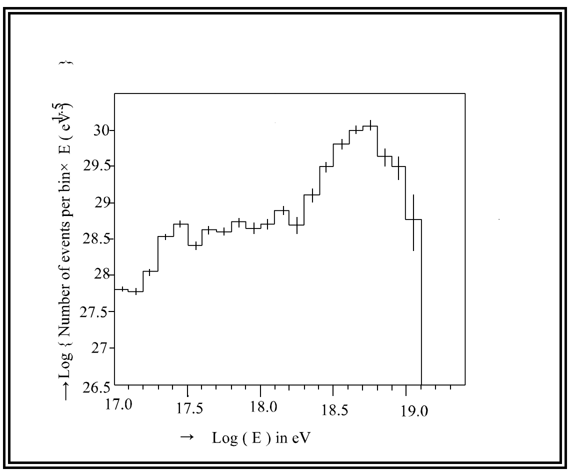

Fig .2: Mini Array Event Distribution Weighted by $E^{1.5}$ as Function of Energy.

thereby falsely increasing the thickness of the shower front. This gives an overestimation of the core distance, leading to higher energy estimation for a given particle density. Hence we consider the overall spectrum for Mini Array upto $10^{18.3}$eV with a slope of -3.04 ± .06 which is in reasonable agreement with those calculated by the other groups. The differential energy spectrum corresponding to best fit (Chi-squares fitting) in the energy region $10^{16.9}$ eV to $10^{18.3}$ eV is derived as :

$$j(E) = 10^{25.38} \times E^{-3.04 \pm .06}\ m^{-2}\ sr^{-1}\ s^{-1}\ eV^{-1}$$

A dip is clearly seen from the Mini array energy spectrum as also observed by other groups.There is qualitative agreement in the spectral changes. Each group has observed a significant deficit between 10^{18} eV and 10^{19} eV when compared to expectations of a continuation of the lower energy spectrum. However, the extension of the dip in case of Mini Array is much smaller than the others. The reanalysis shows a marked improvement in the slope of the energy spectrum in the lower energy region. The spectral break observed at $10^{17.6}$eV, is in agreement with other world groups.

The spectral break at $10^{17.6}$ eV is due to a possible change in cosmic ray composition from predominantly light to predominantly heavy. The break at the position of dip ($10^{18.2}$ eV) indicates a possible change from galactic to extragalactic origin or possibility of a new cosmic ray source.

The overestimation of event rate at higher energy range may be due to inclusion of some delayed particles, small detector area and associated triggering criterion. By increasing the area of the Mini array so that atleast 10 to 20 particles are detected per event, the unwanted events may be distinguished by careful investigations. It is therefore proposed to extend the area of the mini array and to include one optical channel in order to collect genuine highest energy events.

Table2
SPECTRUM SLOPES

Experiment	Slope	Energy Range (eV)
Havera Park	$3.14^{+0.05}_{-0.06}$	$10^{17.6}$ - $10^{20.0}$
Akeno	3.04 ± 0.04	$10^{15.7}$ - $10^{19.8}$
Akeno (Array 1)	3.24 ± 0.18	$10^{17.8}$ - $10^{18.8}$
Akeno(Array 2)	3.16 ± 0.08	$10^{18.3}$ - $10^{19.0}$
Yakutsk	3.23 ± 0.08	$10^{18.3}$- $10^{19.0}$
Fly's Eye (Mono)	3.07 ± 0.01	$10^{17.3}$ - $10^{19.6}$
Fly's Eye (Stereo)	3.18 ± 0.02	$10^{17.3}$ - $10^{19.6}$
Mini Array	3.04 ± 0.06	$10^{16.9}$ - $10^{18.3}$

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