The Cosmic Ray Spectrum Above 10^{17} eV

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ABSTRACT

We present the final analysis of the data obtained by the Sydney University Giant Airshower Recorder (SUGAR). The data has been reanalysed to take into account the effects of afterpulsing in the photomultiplier tubes. Event data was used to produce a spectrum of "equivalent vertical muon number" and from this, a model dependent primary energy spectrum was obtained. These spectra show good evidence for the "Ankle": a flattening at 10^{19} eV. There is no sign of the cut-off which would be expected from the effects of the universal black body radiation.

1. Introduction

The work was performed using an array which was operated at an atmospheric depth of 980 g cm^{-2} on a site a few hundred km north of Sydney (latitude 30° 32' south, longitude 149° 36' east). The array and its results are described in some detail in (1) and (2).

The geometry of the array was 54 points on a square grid where we operated autonomous "stations". At peak development, 47 of these points were occupied by operating stations. These were established on a set of nested square grids with spacings of 1600, 800 and 400 m. Each station had two liquid scintillator tanks buried 50 m apart in a north-south direction. The effective area of each scintillator was 6.0 m^2 viewed by a single EMI 9623B photomultiplier tube. The threshold energy for detected muons was 0.75 secθ GeV, where θ is the zenith angle of the incident particles. The shape of each tank was designed so that a particle traversing any part of the scintillator at a given angle would produce the same light flux on the photomultiplier tube.

The output (charge) pulse from the PM tube anode was deposited on a capacitor which then discharged with a decay time of 3.0μs. The potential difference across the capacitor was amplified and fed to a discriminator set to trigger for a signal greater than or equal to that due to three coincident vertical muons passing through the scintillator. The width of the signal above the threshold was timed using a 10 MHz clock. Ideally, the width is proportional to the logarithm of the charge deposited by the PM tube. This arrangement, known as a logarithm height to time converter, is due to Suga and his coworkers. Its advantages are that it covers a wide dynamic range of signals and the number of clock pulses provides a convenient record of pulse size. The principal deficiency of this converter is that it makes the detector system prone to errors if the photomultiplier afterpulses. This problem is further discussed below.

The log height to time converter gave signals greater than the threshold at a rate of 30 per second; this was constantly monitored, as was the rate of pulses corresponding to more than 8 simultaneous vertical muons passing through the tank.

Identical signal processing was used on both detector channels. If both discriminators at a station fired within 350 ns, a master trigger was generated and the following information was then recorded by a local tape recorder:

(a) the time of the event as determined from the transmitted timing signal,

(b) the widths of the pulses at the output of the discriminators (recorded with 100 ns resolution).

Such "local" events occured at a rate of about 12 per hour. At regular intervals simulated "local" events were generated by injecting simultaneous electrical pulses into the PM tube anode circuits of both detectors at the station. Four different sizes of injected pulses were used in sequence, covering the dynamic range of the system.

2. Event Analysis

The taped records of the local events were collected from all the stations, transferred to a computer and compared to find coincidences, within 80 μs, between three or more stations. Such coincidences are referred to as "array" events. Events were rejected from further analysis if the participating stations were collinear or if the signal times were not consistent with the passage of an air shower (the latter being classified "unphysical"). During the eleven years of operation 15327 events were recorded; of these 1238 were collinear, 270 unphysical and 2 events were rejected on other grounds. Most of the events were registered in the minimum number of stations, namely three.

The direction of the shower axis was obtained by the method of fast timing. If three stations participated in a shower, then a straight geometrical fit of a plane front was made to the timing data. If four or more stations participated in an array event, then a weighted least squares method was used to fit a plane shower front to the data. The number of muons in the shower and the location of the shower axis was found by a maximum likelihood method taking into account the records of all stations of the array (triggered or not). The likelihood expression consisted of: a term Q giving the probability of the observed responses of the triggered stations, a term P giving the probability of zero responses from non triggered stations and a term giving the a priori probability of the occurrence of a given shower size as proportional to N_μ raised to the power -3.0.

The term Q was originally taken to be a Poissonian distribution with the mean set equal to the expected number of particles (above 100 particles this was replaced by a normal distribution with a fractional standard deviation of 10%). In the present analysis and that reported at the Bangalore Conference (3 and 4) we used a new formula for Q which was obtained after consideration of the possible effects of afterpulsing in the PM tubes of the array. Further details are given in the appendix. We feel quite confident that the new value of Q properly accounts for the effects of afterpulsing (5).

The expected densities of muons were calculated using a structure of the Greisen type (6) modified to allow for the dependence of the outer slope parameter on zenith angle.

3. The Size Spectra

The array was operated to produce a list of showers containing the following information:

Time and date of event
Zenith angle of shower axis θ
Muon number N_μ
Position of axis X,Y

In order to obtain shower spectra it is necessary to evaluate the array exposure; i.e. the effective area times the running time. We computed this using techniques substantially the same as described in Bell et al (1). A Monte Carlo method was used to simulate shower detection by our array; the probability of a station being operational was made to correspond to its average fractional on-time during an epoch. The total time of observation was divided into seven epochs during each of which the array configuration and station performance were substantially constant. The shower list and exposure information were combined to produce seven different spectra of N_μ taken at different zenith angles, these are shown in figure 1. These spectra differ from one another because the threshold energy of the muons increases with the secant of the zenith angle and because showers of different zenith angle are at different stages of development, even though their primary energy may be the same.

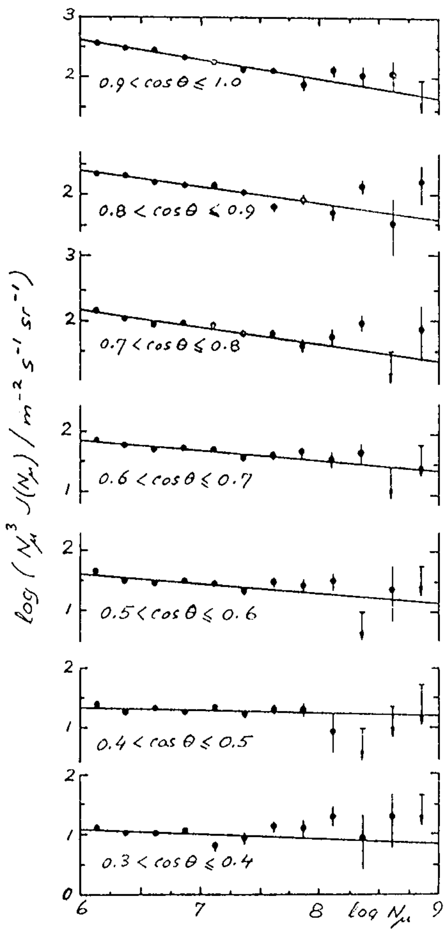

Figure 1. The differential shower size (N_μ) spectra for various zenith angle bins (θ). The ordinate is the flux multiplied by N_μ^3. The lines are fitted by maximum likelihood to the lowest seven data points in each range of θ.

For the seven lowest N_μ bins in each of the zenith angle bands, we used the maximum likelihood method to fit a differential power law spectrum of the form

$$J[N_\mu(\theta)]\, dN_\mu = J_\theta (N_\mu / N_r)^{-\gamma_\theta}\, dN_\mu$$

where $N_r = 3.16 \times 10^6$

The five upper size bins were excluded from the fit since it appears that there may be a flattening of the primary energy spectrum for $N_\mu > 10^8$. In any case, because of the small number of events in these bins, the effect of including them in the fit is marginal. J_θ and γ_θ were found to depend on $\cos\theta$ in a linear manner allowing an analytic method (3) to be used to combine all the spectra into a single spectrum of the quantity N_v: the equivalent vertical muon number, which is the size (N_μ) the shower would have had if it had entered the atmosphere vertically. The operation above is equivalent to using the well known "equal intensity cut method" (7) to obtain a shower size at any desired atmospheric depth. The spectrum of N_v shown in figure 2 is for all showers with $\theta < 60°$.

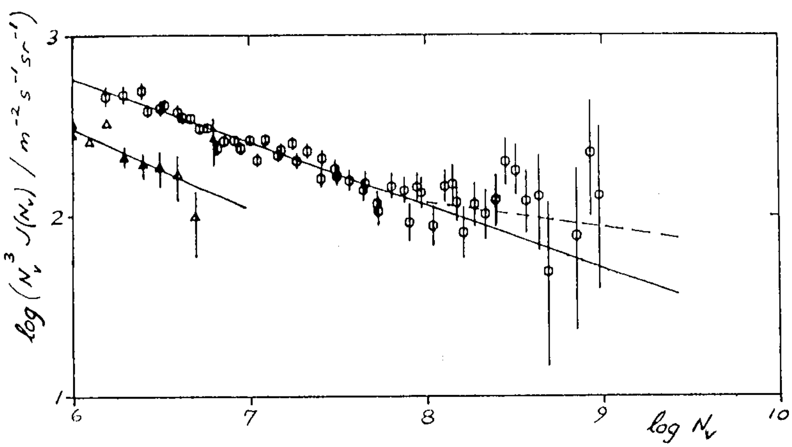

Figure 2. Differential equivalent vertical muon number (N_v) spectrum obtained by combining the various muon number spectra at different zenith angles. Line (a) is the maximum likelihood fit to showers with log $N_\mu < 7.75$ and line (b) is a similar fit for log $N_\mu > 7.75$ Each point represents the intensity in a (N_μ;θ) bin. Also shown is the result from the Akeno group ($1 < \sec\theta < 1.1$) and (c) is their fitted line.

The line (a), with a differential slope of 3.35 ± 0.01 is fitted to all events with log $N_\mu < 7.75$. (If showers with θ up to 73° are included the slope steepens to 3.36.)

It will be noticed that the equation of line (a) is effectively the same as presented by us in the 18th International Cosmic Ray Conference at Bangalore (3). Since then we have used an improved method of dealing with saturated detectors and this is the only difference between the two analyses. The effect of afterpulsing was handled identically in the two cases.

We also show on figure 2 the N_μ spectrum from Akeno (8). We are able to explain the disagreement between our spectrum and the Akeno one by taking into account:

(a) differing altitudes of the two arrays,
(b) different threshold energies for entry of muons into the detectors,
(c) different array geometries leading to muon densities being measured at different distances from the shower core, and
(d) the use of different structure functions.

In a similar way we are able to explain the disagreement between the our spectrum and those of the Nottingham and Yakutsk groups (9) and (10).

Note the flattening of the spectrum above log $N_v = 8$. A line fitted to events with log $N_\mu > 7.75$ has a slope of 3.15 ± 0.14. One can compare the expected number of events which have log $N_\mu > 8$ according to line (a) (namely 58) with the observed number (78). χ_1^2 gives a probability of 1% that this should arise by chance. A stronger test, with the straight line fitted to all the data gives a χ^2 probability of 3%.

4. Energy Spectra

The equivalent vertical muon size spectrum can be transformed into a primary energy spectrum using a conversion formula which is conventionally represented as a power law

$$E = E_r(N_v/N_r)^\alpha$$

N_r is usually chosen to be in the middle of the range of shower sizes; in our calculations we used $N_r = 10^7$.

Two different models were used to obtain this conversion: the so-called Sydney model (11) and Hillas model E (12). In what follows we use the latter because of its general acceptance by workers in the field.

The relevant relation is

$$E = 1.64 \times 10^{18} \, (N_v/10^7)^{1.075}$$

Figure 3 shows the spectrum produced.

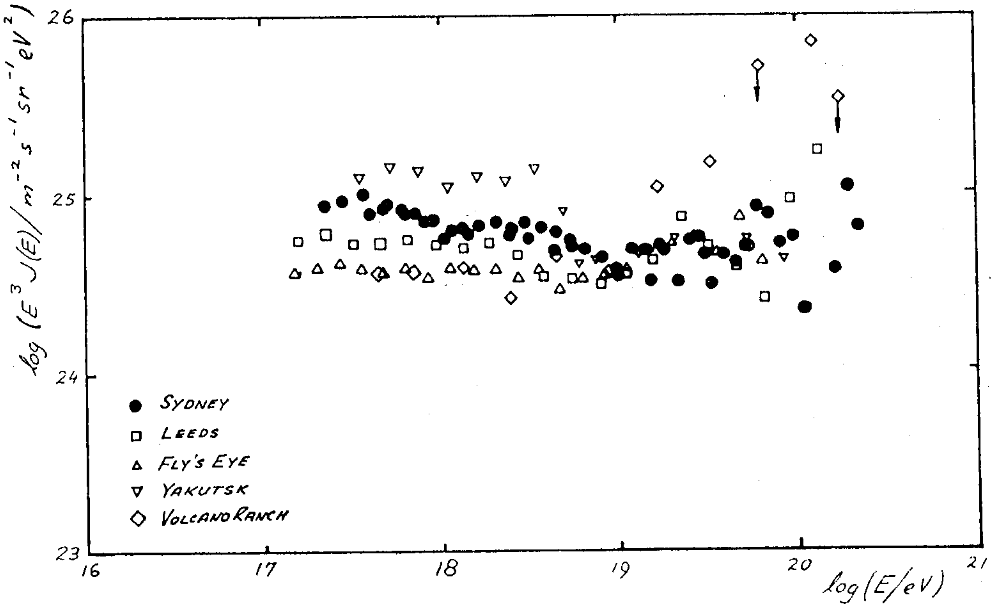

Figure 3   Comparison of energy spectra from various groups and our spectrum converted by the Hillas E model (solid circles). Each spectrum is differential with the ordinate equal to the flux multiplied by E^3.

The squares are from the Leeds group at Haverah Park (13)
The triangles are from the Utah group (14)
The diamonds are from Volcano Ranch as quoted by (15)
The inverted triangles are from the Yakutsk group (16)

As with the N_v spectrum we have fitted two lines (which for clarity are not shown on figure 3), one below and one above $\log N_\mu = 7.75$ with differential slopes of 3.19 ± 0.01 and 2.99 ± 0.13 respectively.

On figure 3 we also show the spectra from the Leeds group (13), Utah group (14), Volcano ranch as quoted by (15) and the Yakutsk group (16). The Leeds and the Volcano ranch spectra show the ankle feature and we confirm this. Another item of interest is the possibility of a spectrum cut-off at $\sim 5 \times 10^{19}$ eV due to black body photons acting on particles from sources $\geq$ 10 Mpc distant. There is no sign in our own spectrum of such a cut off. As described in section 3, the spectral slope flattens above 10^{19} eV and according to the Hillas E model we have eight showers above 10^{20} eV.

5. Conclusions

We have determined the spectrum of cosmic rays for energies

$> 10^{17}$ eV using data from a site at 31° south latitude. We used Hillas model E to find the energies of our events. The differential energy spectrum has a slope of 3.19 ± 0.01 below about 10^{19} eV and the slope flattens to 2.99 ± 0.13 above this energy. The spectrum extends beyond 10^{20} eV with no sign of a cut off due to the Universal Black Body Radiation.

Appendix - Afterpulsing

An unfortunate feature of the logarithmic height to time converter is that pulses arriving late in a particular signal can keep it above threshold and hence cause the original signal height to be substantially overestimated. Ordinary random noise pulses from the PM tube are too infrequent to affect the results whereas pulses generated within a PM tube and occurring after a genuine air shower signal pulse can have serious effects. This phenomenon is known as afterpulsing.

We looked at the possibility of excluding afterpulses by using electronic gating techniques but found that the inevitable gate pedestal created more problems than it solved.

The seriousness of the effects of afterpulsing was not realised until the latter part of the experiment; even then, technology could not provide a practical solution. However we have developed a statistical method to account for the effects of afterpulsing. The technique incorporates the effects of afterpulsing and other signal enhancements into the probability distribution used in the shower fitting program. We describe below how this was done.

During the last stages of the experiment we recorded for each station a sample of pulses, each of which had its height as well as it width measured. Samples were collected from all stations as part of the local event records and for a few stations, the comparison between pulse height and width was carried out for single tanks as well (17).

From inspection of these data we chose a typical detector and removed its photomultiplier for further investigation of afterpulsing effects at larger pulse sizes. To this end we reactivated one of the original pilot arrray stations in Sydney and installed in it a PM tube with average afterpulsing. Data from this station was recorded for 8 days in a similar manner to the recordings made in the SUGAR array. To examine afterpulsing for pulses exceeding the height amplifier saturation level, the pulse height measuring system was connected to the output of the first stage of the preamplifiers rather than at the output of the final stage. We then ran the station for a further nine months in this "low gain" mode. The longer period was needed to accumulate an adequate data set at the lower rate.

We used the results from the average tube as a model for all the others in the SUGAR array. An alternative approach would have been to establish a correlation between parameters derived from the data taken in the height/width runs and calibration data collected during the normal running of each station. If this had been successful; it would have allowed us to apply retrospective corrections to each station for any time in the array's operation. However we found no significant correlation allowing this to be done. Instead, the behaviour of the average tube was applied to all detectors of the array for the duration of the experiment. This was done by changing the probability distribution used in the shower analysis program.

The data from the average tube was analysed statistically and a new formula was produced for the quantity Q used in the maximum likelihood expression (see main text). Q was previously Poissonian (with a mean set equal to the expected number of particles) for < 100 particles and was normally distributed with a fractional standard deviation of 10% for > 100 particles. The new distribution for Q is of the gamma type. Its mean and standard deviation were fitted to the data from the average PM tube. The fit gave a constant fractional standard deviation of 30% and a mean which depended on the expected particle number n as

$$(2.3 + 0.9n + 0.004n^2)(1.25 \cos\theta)^{(0.40 - 0.45 \log n)}$$

where θ is zenith angle of the particles (taken as equal to the zenith angle of the shower).

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