ULTRA HIGH ENERGY COSMIC RAY SPECTRUM

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ABSTRACT

Ultra-high energy cosmic rays have been observed by means of atmospheric fluorescence with the Fly's Eye since 1981. The differential energy spectrum above 0.1 EeV is well fitted by a power law with slope 2.94 ± 0.02. Some evidence of flattening of the spectrum is observed for energies greater than 10 EeV, however only one event is observed with energy greater than 50 EeV and a spectral cutoff is indicated above 70 EeV.

1. Introduction. The Fly's Eye experiment has been described in detail elsewhere[1]. Since November 1981, it has been in operation with 67 mirrors and 880 photomultiplier tubes. Results of the analysis of the data collected up to September 1984 are presented here. During this period, 2408 well measured events with energies greater than 0.1 EeV were detected in 1278 hours of live time.

2. Energy and Spectral Calculation. The energy of an event is estimated by fitting the measured longitudinal development profile of the shower to both Gaussian and unconstrained (3 free parameters) Gaisser-Hillas[2] curves. These curves are integrated to obtain the total track length of the shower particles, and then converted to total 'electromagnetic' energy by the relation

$$E_{em} = \varepsilon_0/X_0 \int N_e(x)dx$$

where ε_0/X_0 is the ratio of critical energy of an electron to its radiation length in air, giving the total rate of energy loss by ionization and excitation. The loss rate used here is 2.18 MeV g cm^{-2}. Total energy of the primary particle is then calculated by correcting the 'electromagnetic' energy for undetected energy using estimates of this lost energy derived by Linsley[3]. These range from 13% at 0.1 EeV to 5% at 100 EeV. This method of energy estimation relies only on low energy interactions and is essentially model independent. Shown in Fig. 1 is the raw energy distribution of observed events.

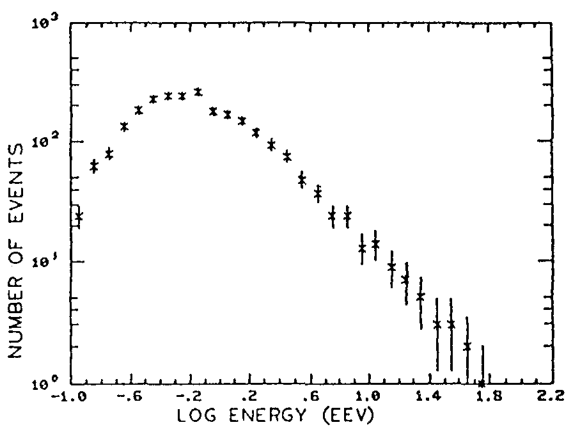
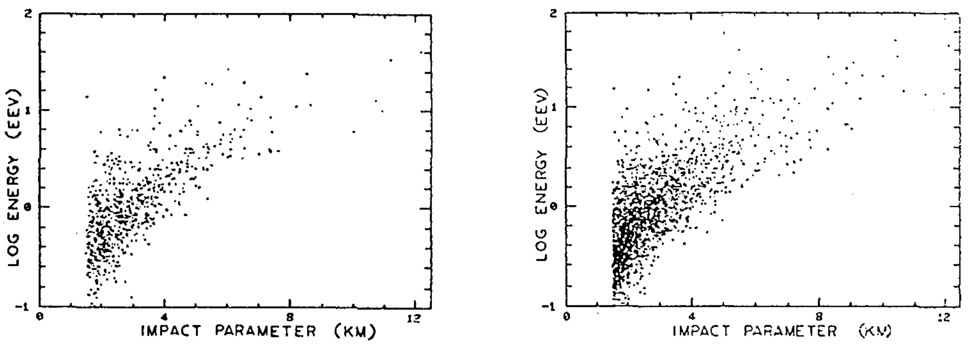


Figure 1. Raw Energy Distribution of Fly's Eye Data.

To obtain the energy spectrum from these data, the energy dependent Fly's Eye aperture must be calculated. This has been done using a Monte Carlo simulation of the system. In this simulation quasi-random trajectories and first interaction depths for the events are chosen from an isotropic distribution, and the showers are developed using the constrained Gaisser-Hillas[2] parameterization and shapes obtained from the real data sample, thereby ensuring consistency between the simulation and the data base. Triggering Monte Carlo events are stored and analyzed using the analysis programs which are used on the real data. The sensitive aperture of the Fly's Eye is then calculated from the ratio of accepted to tried Monte Carlo events. Scatterplots of the distribution of events in impact parameter and energy for both (a) Monte Carlo and (b) real events are shown in Fig. 2. There is excellent agreement between these distributions, indicating that the simulation is a good representation of the Fly's Eye. Figure 3 shows the effective Fly's Eye aperture calculated from the simulation.



(a) (b)

Figure 2. Energy vs Impact Parameter Scatterplots for (a) Monte Carlo and (b) Fly's Eye Data.

The self-consistency of the analysis programs is also checked by the processing of the Monte Carlo events with the analysis routines and comparing the results with the original Monte Carlo event parameters. Response functions for (a) zenith angle, (b) impact parameter and (c) energy are shown in Figure 4.

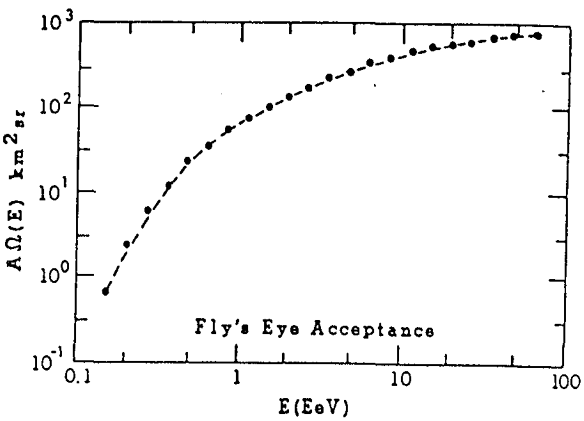


Figure 3. Fly's Eye Sensitive Aperture.

3. Results. Using the above techniques, the differential energy spectrum of the observed data has been calculated. It is shown in Figure 5 plotted as $E^3 j(E)$. The spectrum is essentially flat between 0.1 and 10 EeV with a slope of 2.94 ± 0.02. Between 10 and 50 EeV, there is the appearance of a bump,

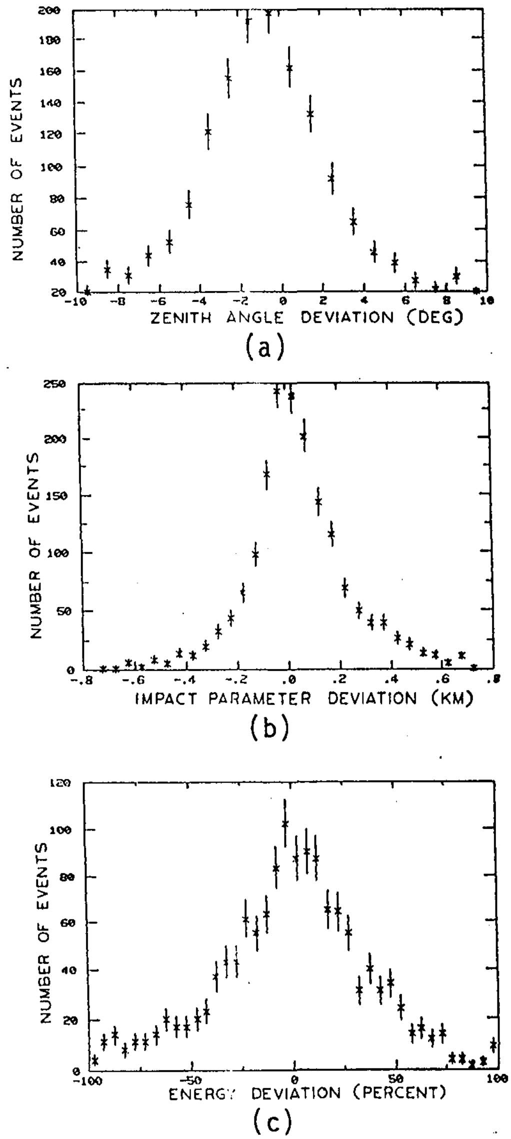


Figure 4. Analysis Response Functions for (a) Zenith Angle, (b) Impact Parameter, and (c) Energy.

with 62 events in this interval compared with 46 that would be expected if the spectrum continued with the same slope as at lower energies. Since the uncertainty in this predicted value is small, the significance of the bump is roughly $16/\sqrt{46} = 2.4\sigma$. If the spectrum between 10 and 50 EeV is fitted by a power law, the slope is found to be 2.42 ± 0.27, about 2σ flatter than the value at the lower energies. Only one event is observed with energy greater than 50 EeV. This should be compared with 11 ± 5 events which would be observed if the spectrum continued above 50 EeV with the same slope as between 10 and 50 EeV.

4. Discussion and Conclusions.

It should be noted that between 1 and 50 EeV, the Fly's Eye energy spectrum is in good agreement with that of the Haverah Park[4] experiment, although differences exist above and below these energies. This agreement provides a useful check on the operation of the system, since in this energy regime, the Fly's Eye aperture is well simulated and data collection statistics are good. Below 1 EeV, the acceptance is rapidly changing and threshold simulations and errors in the estimates of analysis efficiency could acocunt for any differences. This possiblity is being investigated. However, above 50 EeV, the discrepancy appears to be real. Here the Fly's Eye aperture is increasing (albeit slowly) and most of the extra events expected would have fallen within the 50 EeV acceptance where the agreement is good. The efficiency for detection and analysis of these events should be higher due to the increased brightness of the resultant air shower.

The spectral shape derived is consistent with that predicted by Hill and Schramm[5] for source distances between 70 and 150 Mpc, with a Greisen[6] cutoff above a recoil pileup of the primaries.

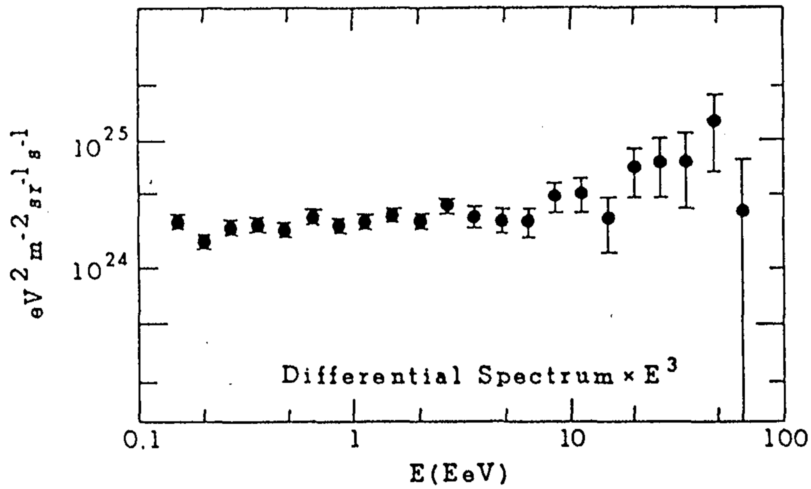


Figure 5. Fly's Eye Differential Energy Spectrum.

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References.

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