THE PRIMARY COSMIC RAY SPECTRUM ABOVE 10^{19} eV

G. Brooke, G. Cunningham†, P.J.V. Eames, M.A. Lawrence,
J.C. Perrett, R.J.O. Reid and A.A. Watson.

Department of Physics, University of Leeds, LEEDS 2.

† now at Institute of Transport Studies, University of Leeds.

ABSTRACT

We describe progress on a re-evaluation of the spectrum of cosmic rays determined with the Haverah Park shower array. Particular attention is paid to the reality of some giant showers.

1. Introduction. We are engaged in a re-appraisal of the energy spectrum of cosmic rays above 10^{18} eV as determined with the Haverah Park shower array. Here we offer a progress report on work which is motivated by the continuing controversy over the shape of the spectrum above 10^{19} eV - in particular the Yakutsk group have questioned the reality of events of 10^{20} eV - and by the recent re-investigation of the predicted shape of the spectrum above 10^{19} eV if the sources of these particles are at cosmological distances (Hill and Schramm 1985).

2. Cosmic Ray Energy Spectrum. The differential energy spectrum derived from our work above 10^{18} eV is shown in Figure 1. Above 3.5×10^{18} eV the spectrum has been updated by the addition of events recorded to December 1983. A detailed analysis of possible sources of systematic error has been made taking into account the effects of uncertainties in zenith angle, lateral distribution fluctuations, core location and attenuation length, (Cunningham 1982). For energies between 8×10^{17} and 3.5×10^{18} eV systematic selection effects and analysis errors dominate over statistical uncertainties and detailed simulations have allowed a deconvoluted spectrum to be derived. Above 3.5×10^{18} eV the error analysis has been conducted on a shower-by-shower basis and the statistical errors have been shown to be at least twice as great as the instrumental errors. We do not yet regard the spectrum of Figure 1 as our 'final' spectrum as further refinements will be possible as our detailed knowledge of showers increases but we wish to emphasise that we have considerable confidence in the durability of the intensities and energies assigned above 10^{19} eV. The major differences between this spectrum and those published at Kyoto are (a) the exclusion of events with $\theta > 45^{\circ}$ (as we now regard our knowledge of the structure function to be incomplete above this angle) and (b) use of an energy dependent structure function measured in showers of $10^{17} - 5 \times 10^{18}$ eV (Coy et al 1981) and in a small number of large showers which fell during the period of that experiment. The main features of the spectrum are the flattening above 10^{19} eV and its continuity to just beyond 10^{20} eV. At the Paris conference we pointed out that the flattening may also be interpreted as a dip in the spectrum (Bower et al 1981) and suggested that if particles above a few times 10^{18} eV were ~~o~~f extragalactic origin then the dip might well be due to electron-pair production. This interpretation has been confirmed by the detailed analysis of Hill and Schramm (1985).

The Haverah Park and Yakutsk spectra (Vaselev et al 1983) are compared in the lower part of Figure 1. The spectra are found to agree reasonably well until about 3×10^{19} eV when the absence of large showers in the Yakutsk spectrum becomes apparent.

In recent years a number of $1\,m^2$ blocks of scintillator have been incorporated in the Haverah Park array making possible a comparison between the model calculation conversion used by the Haverah Park group and the calorimetric approach of the Yakutsk group. We have shown elsewhere that the calibration is good (to within better than 20%) up to at least 5×10^{19} eV and similarly that the Volcano Ranch energy estimates are in accord (Bower et al 1983a, b). Also the Sydney experiment offers evidence of a flattened spectrum above $\sim 4 \times 10^{19}$ eV (Horton et al 1983); that spectrum may extend to 4×10^{20} eV (Linsley 1983). We do not plot the Sydney spectrum here because of uncertainties about the energy calibration.†

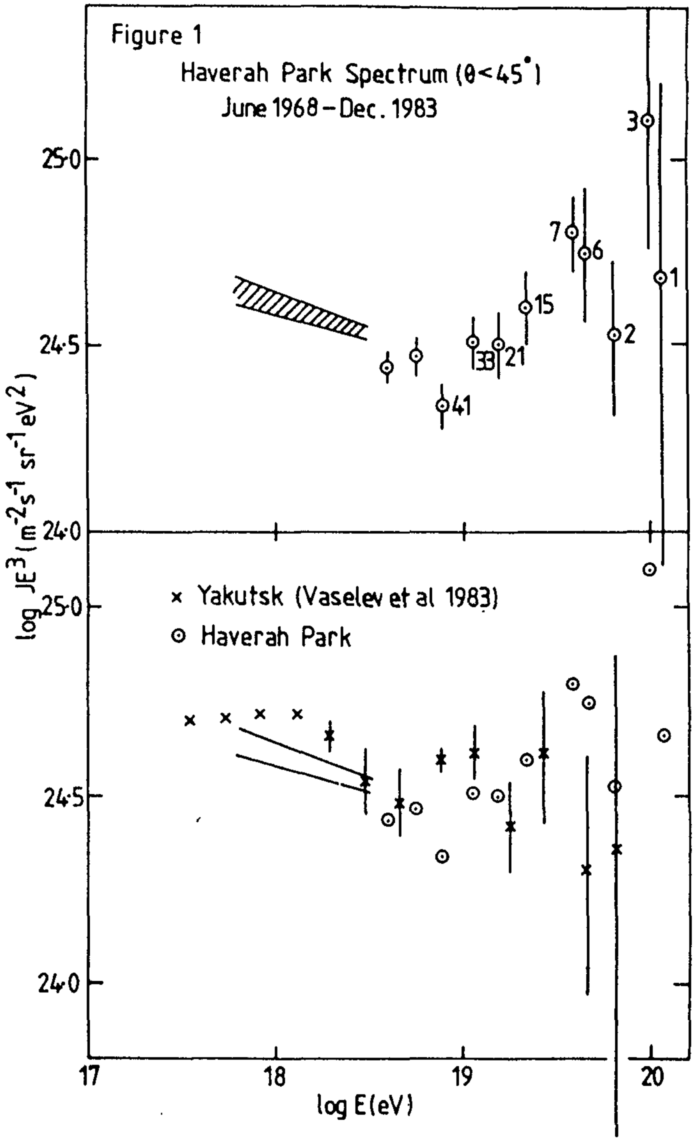
Figure 1

3. Events of 10^{20} eV. The 4 most energetic events included in the spectrum have been assigned energies $> 10^{20}$ eV. Brief details of these are given in Table 1; maps of the density pattern observed in each event were published in the World Data Catalogue although the sizes have been slightly altered as a result of the revised lateral distribution function now adopted. Three of the events have risetime information available at one or more of the $34\,m^2$ detectors and are discussed in that context in HE 4.7-6 (Lawrence et al).

Of the events in Table 1 by far the most outstanding in terms of number of densities and precision of core position is 17684312. Unfortunately this event was recorded in the epoch before scintillator densities were being recorded. One of the most energetic events with scintillator density information is 21220296, a map for which has been published elsewhere (Bower et al 1983c) and these two events are contrasted in Table 2.

Table 1

Reference number	angle θ	α	δ	b	r_1(m)	Energy (eV)	World Data Catalogue	Rise-times
8185175	35	353°	19°	-40°	443	1.02×10^{20}	p78	None
17684312	35	201°	71°	46°	376	1.05×10^{20}	p86,87	1
9160073	30	199°	44°	73°	1384	1.05×10^{20}	p79	2
12701723	29	179°	27°	78°	1093	1.21×10^{20}	p83	4

Table 2 : Comparison of two giant air showers

	21220296 (J Phys G 9, 1569 1983)	17683412 (World Data Catalogue pp86-7)
Zenith angle	13°	35°
Number of water-Cerenkov detectors and distance range	24 $150 < r < 2170$ m	50 $90 < r < 2500$ m
Number of 1 m^2 scintillators and distance range	8 $420 < r < 680$ m	-
S(600) m^{-2}	157	
ρ(600) m^{-2}	64	105
ρ_V(600) m^{-2}	66	136
Primary energy:		
Yakutsk calibration	5.3×10^{19} eV	-
Hillas relation	5.0×10^{19} eV	1.1×10^{20} eV

The estimated error in the assigned size ($\rho(600)$) for each of these events is $\sim$10%; this error includes core location uncertainty, stationary error and allowance for lateral distribution uncertainty and is so small because of the exceptional symmetry in the detector density patterns. The risetime measurements in each event are also in agreement with these analyses. Event 17683412 is unquestionably twice as large as 21220296 which in turn, through the scintillator and water-Cerenkov densities, has two independent energy estimates of $\sim 5 \times 10^{19}$ eV.

In addition to the 4 events discussed above we have recorded a further 4 events which we believe are $\gtrsim 10^{20}$ eV. These are not included in our energy spectrum because they arrived from zenith angles > 45° and/or the cores fell outside of the array boundary. The flux derived from all 8 events in this total exposure of $657\,\mathrm{km}^2\,\mathrm{sr}\,\mathrm{y}$ is $\left(4\,{}^{+2}_{-1}\right) \times 10^{-16}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ and is consistent with that deduced for the 4 events of Table 1, namely $I(>10^{20}\,\mathrm{eV}) = \left(3\,{}^{+2}_{-1}\right) \times 10^{-16}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$.

4. Discussion and Conclusions.

The proven existence of cosmic ray events with $E > 10^{20}$ eV demands explanation. Presumably the source of these events must be relatively close to the earth but it can hardly be galactic as $|b| > 40^\circ$ for all 4 events of Table 1. The inferences drawn about the ability of the Cygnus X-3 system to accelerate large fluxes of cosmic ray nuclei to 10^{17} eV/nucleon (Hillas 1984) leads naturally to speculation that a suitably scaled up system, perhaps in the nucleus of an active galaxy, can accelerate particles to 10^{20} eV and beyond.

Our current best estimates of the integral intensities above 10^{18}, 10^{19} and 10^{20} eV are

$$I(>10^{18}\,\mathrm{eV}) = (1.9 \pm 0.2) \times 10^{-12}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$
$$I(>10^{19}\,\mathrm{eV}) = (2.1 \pm 0.2) \times 10^{-14}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$
$$I(>10^{20}\,\mathrm{eV}) = (3 \pm 2) \times 10^{-16}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

Further details of our analysis will be published elsewhere.

Acknowledgements. The continuing assistance of Paul Ogden, Mansukh Patel, Sue Hopper and Julie Ingle in obtaining and reducing these data is gratefully acknowledged as is the financial support from the Science and Engineering Research Council (UK). AAW would like to thank the Yakutsk group for their hospitality during April 1984.

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† After preparation of this paper was completed (22 May 1985) the issue of Physical Review Letters (22 April 1985), which contains the new spectrum deduced from Fly's Eye, reached us. We do not agree with the Fly's Eye group's conclusion that an end to the cosmic ray spectrum has been observed. A comment on their letter is being prepared for submission to Physical Review Letters.