ARRIVAL DIRECTION DISTRIBUTION OF COSMIC RAYS OF ENERGY $> 10^{18}$ eV

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ABSTRACT

The Haverah Park air-shower experiment recorded over 8500 events with primary energy $> 10^{18}$ eV between 1963 and 1983. An analysis of these events for anisotropies in celestial and galactic co-ordinates is reported. No very striking anisotropies are observed.

1. Introduction. Seven years ago the Haverah Park group (Edge et al 1978) published a detailed analysis of the arrival direction distribution of cosmic rays above 6×10^{16} eV. Since that publication there have been numerous 'up-dates' reported in conference proceedings and reviews. In this report we concentrate on the cosmic rays above 10^{18} eV where additional running has enabled us to increase our data from 4202 events (Edge et al 1978) to 8565. The additional data have been recorded with the same angular resolution as in the earlier work (rms variation in solid angle $< 10^{-2}$ sr); the energy resolution has been slightly improved by the addition of $3 \times 2.25\ m^2$ detectors at 1 km from the array centre. We describe here the results of an analysis in celestial and galactic co-ordinates; fuller details will be reported elsewhere.

2. Harmonic Analysis in Right Ascension. The results of an harmonic analysis in right ascension over the declination range $90 < \delta < -6^o$ are given as a function of energy in Table 1. Following our previous practice the data are divided in energy $1 - 2 \times 10^{18}$ eV (E5), $2 - 4 \times 10^{18}$ eV (E6), $4 - 32 \times 10^{18}$ eV (E7,8,9) and $> 3.2 \times 10^{19}$ eV (E10). For brevity the notation E5 etc. will be used here. The first and second harmonics are given. Only amplitude uncertainties are quoted; probabilities of those amplitudes arising by chance from a random distribution equal $\exp(-k_o)$ and the phase uncertainty is $57.3/(2k_o)^{\frac{1}{2}}$ degrees, where $k_o = r^2 n/4$ (Linsley 1975).

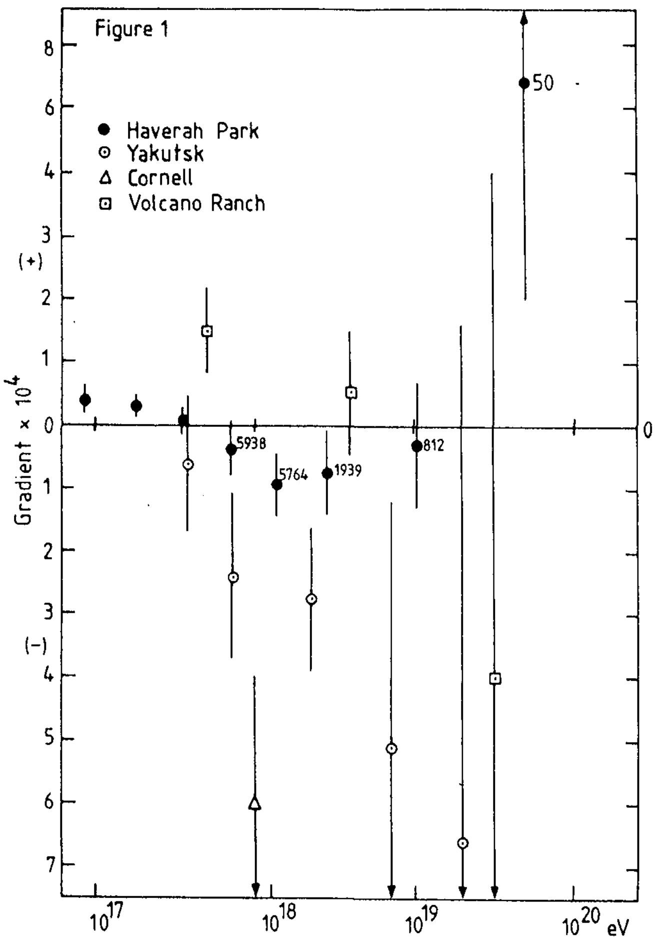
Table 1

	from Edge et al (1978)				Present Work			
	n	r_1%	$\theta_1{}^o$	k_o	n	r_1%	$\theta_1{}^o$	k_o
E5	2832	6.3 ± 2.7	50	2.83	5764	4.4 ± 1.9	67	2.76
E6	978	7.9 ± 4.5	37	1.52	1939	3.7 ± 3.2	17	0.65
E7,8,9	364	7.9 ± 7.4	280	0.55	812	5.7 ± 5.0	272	0.66
E10	28	57 ± 27	163	2.27	50	42 ± 20	179	2.16
		r_2%	$\theta_2{}^o$			r_2%	$\theta_2{}^o$	
E5	2832	3.0 ± 2.7	169	0.64	5764	2.7 ± 1.9	175	1.01
E6	978	11 ± 5	71	2.74	1939	4.3 ± 3.2	80	0.89
E7,8,9	364	18 ± 7	75	2.95	812	13 ± 5.0	83	3.59
E10	28	25 ± 27	59	0.45	50	12 ± 20	166	0.18

It is disappointing to report that the doubling of the Haverah Park data has led to a decrease in all of the amplitudes above 10^{18} eV. Of the 8 amplitudes listed the significance, as measured by k_o, of only 3 have increased. However the most significant amplitude of the new set was also the most significant of the original set: the 2nd harmonic in the energy bin E7,8,9 now has a probability of arising by chance of 2.8%. For 371 events in a similar energy range ($5 \times 10^{18} - 4 \times 10^{19}$ eV) the Yakutsk group find $r_2 = 7.6 \pm 7.3\%$ at $\theta = 114^o$ (Efimov et al 1983). The joint amplitude (n = 1183) is $r_2 = 11 \pm 4\%$, $\theta = 89^o$ with a chance probability of 2.8%.

The probability that the observed sets of 8 k_o's arise by chance from a random distribution has risen from 3% to 10%.

3. Analysis in Galactic Co-ordinates. In 1981 we introduced an analysis in galactic latitude from which a series of gradients of observed number/ expected number as a function of galactic latitude was obtained (Astley et al 1981). The initial analysis was with a data base intermediate in size between that discussed in Edge et al (1978) and that now available; a S-N assymetry was claimed. The gradients given by Lloyd-Evans and Watson (1982) are listed together with the new gradients in Table 2. A correction to the binning algorithm used in calculating the gradients has been made and about 25% more data has been added above 10^{18} eV. The gradients are compared with results from other experiments in Figure 1.



The Haverah Park gradients show deviations from expectation significant at the 4% level ($\chi^2_8 = 1.97$) and in addition (ignoring the most energetic (extragalactic?) events in E10) there is a clear tendency for the gradients to fall and then change sign as the energy increases. However there are strong systematic differences between the various experiments, none of which are consistent with the above gradients, for which no satisfactory explanation has yet been found.

4. Discussion. Wdowczyk and Wolfendale (1984) in an interesting discussion of cosmic ray anisotropy have suggested that the observation of an S-N gradient above 10^{18} eV is an artefact arising from the limited galactic latitude coverage of the Northern Hemisphere experiments.

Table 2

Energy interval	Lloyd-Evans & Watson (1982)		Present Work	
	n	gradient ($\times 10^4$ deg^{-1})	n	gradient ($\times 10^4$ deg^{-1})
E1	18829	- 1 ± 3	18829	3.9 ± 2.4
E2	39982	- 2 ± 2	39982	3.2 ± 1.6
E3	20635	- 4 ± 3	20635	0.7 ± 2.2
E4	5938	-8.5 ± 4.3	5938	-3.6 ± 4.1
E5	4349	-13 ± 5	5764	-9.2 ± 4.1
E6	1499	-16 ± 9	1939	-7.5 ± 7.0
E7,8,9	610	-22 ± 13	812	-3.3 ± 10
E10	38	92 ± 85	50	66 ± 47

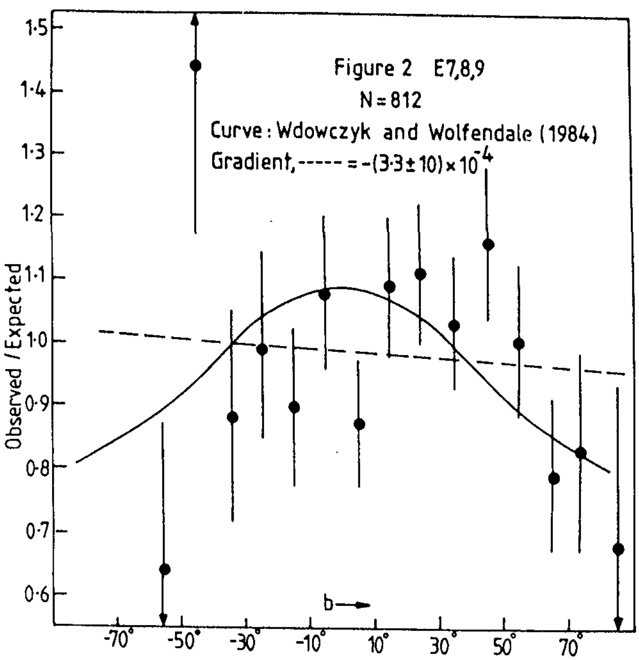
They propose instead that the data should be tested against a model which invokes a galactic plane excess and which predicts that the angular width of the galactic plane as seen in cosmic rays should shrink slowly with increasing energy.

The prediction of this model in which it is suggested that

$$I(b) = I(0)\left[(1 - f_E) + f_E \exp(-b^2)\right]$$

is compared with the data in Figure 2 for f_E, the galactic latitude enhancement factor, = 0.3 (Wdowczyk and Wolfendale 1985, Figure 1(d)). There is some evidence for a galactic plane enhancement.

We have investigated the galactic plane enhancement directly by comparing the number of events within $\alpha \pm 5^o$ of the galactic plane for the declination range $61.6 < \delta < -6^o$. For bins E5, E6, E7,8,9 the observed number of events was 268, 93 and 36 while 250, 83 and 36 were expected. There is clearly no significant evidence of enhancement.



In Figure 3 we compare the first harmonics of Table 1 with the predictions of Hill and Schramm (1985). The best estimate of the amplitude, s, (Linsley 1975) is shown together with 95% and 5% confidence levels. The predictions are derived from a model in which cosmological and bright local extragalactic source fluxes are combined. The injection spectrum slope $\gamma = 2.0$ favoured through their fit of spectrum data predicts rather higher anisotropies above 5×10^{18} eV than are observed.

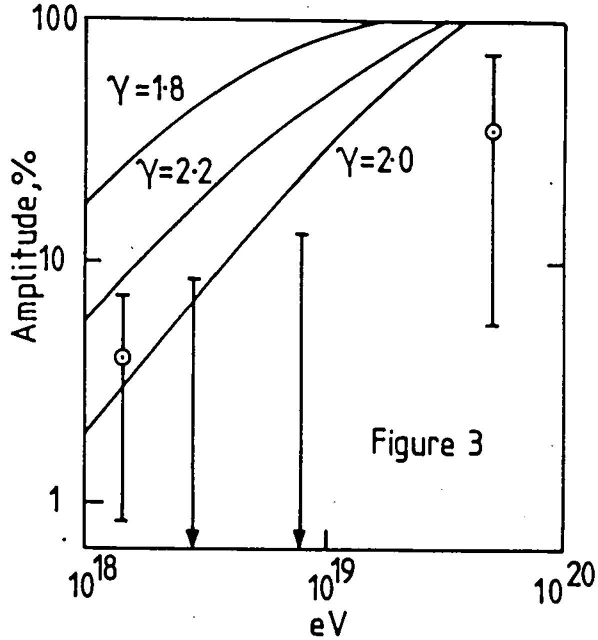


Figure 3

5. Conclusion. High energy cosmic rays ($E > 10^{18}$ eV) are remarkably isotropic. In particular we remind the reader that above 3.2×10^{19} eV (50 events) there is no evidence for a galactic plane anisotropy but there is some evidence for an anisotropy of $(40 \pm 20)\%$ in a direction nearly normal ($\alpha = 180^{o}$) to the galactic plane. Of the 8 events above 10^{20} eV which we have observed, 4 are more than 40^{o} above the galactic plane.

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