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Dependence on Declination of the Intensity of Cosmic Ray Showers with Primary Energies of about 10^{16} eV

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Abstract

The declination isotropy of cosmic ray showers of energies of about 10^{16} eV is studied using data from the Buckland Park extensive air shower (EAS) array and compared with measurements available through an analysis of data in the literature. It appears that an upper limit can be set to the anisotropy in declination at this energy of $\approx 3\cdot 5\%$, limited by timing uncertainties in array directional measurements.

1. Introduction

The deviation from isotropy of cosmic radiation is of great interest since this parameter might be expected to provide information intimately related to the source of the particles. Cosmic rays are known to be highly isotropic and typical values of measured anisotropies are of the order of 1% or less, at least up to particle energies of $\sim 10^{17}$ eV. Measurements of anisotropies at low and medium energies are usually made with detecting systems whose counting rates are recorded as a function of the right ascension of the local zenith, which varies with the rotation of the Earth (local sidereal time). This technique is strongly reliant on atmospheric collimation. At energies above $\sim 10^{15}$ eV, a more sophisticated experiment is possible employing cosmic ray shower detectors which can record the individual shower arrival directions and a parameter which is closely related to the energy of the primary particle (i.e. the shower size). It is then possible, within the limited acceptance angle of the system, to study the dependence of the cosmic ray intensity on declination, north or south of the zenith declination. We wish to discuss here data which are available from our own experimental work and the published literature concerning the dependence of cosmic ray intensity on declination for shower primary energies of about 10^{16} eV. We will investigate the upper limits which can be set on the magnitude of this dependence.

This work should be viewed as an extension of observations of anisotropy in right ascension which have recently been reviewed by Linsley and Watson (1977). The information which is available on the anisotropy at $\sim 10^{15}$–10^{16} eV is rather old now, being derived from counting rate experiments rather than analyses of individual showers. Some representative results would be those of Escobar *et al.* (1960) with a sidereal anisotropy of $0\cdot 8 \pm 0\cdot 2\%$ at 2×10^{15} eV, and those of Farley and Storey (1957) giving $2\cdot 3 \pm 1\cdot 0\%$ at 3×10^{15} eV.

In order to investigate the declination dependence, one is required either to view to the north and south independently from a given site or to compare absolute vertical intensities from two sites of different latitudes. Both procedures present significant problems. The former presents problems of measuring large angles from the zenith and also of counting statistics, since observations are made at angles which have reductions in flux due to geometrical reductions in array collecting area. The latter procedure is difficult since absolute calibration between arrays is necessary. This procedure has proved most difficult since arrays are rarely at similar atmospheric depth, detectors are rarely of identical design, and calibration procedures are not standardized. Nonetheless, Clay and Gerhardy (1982) have recently compared absolute intensities at Adelaide and Akeno and put an upper limit of $\sim 10\%$ on the difference in intensity between the sites.

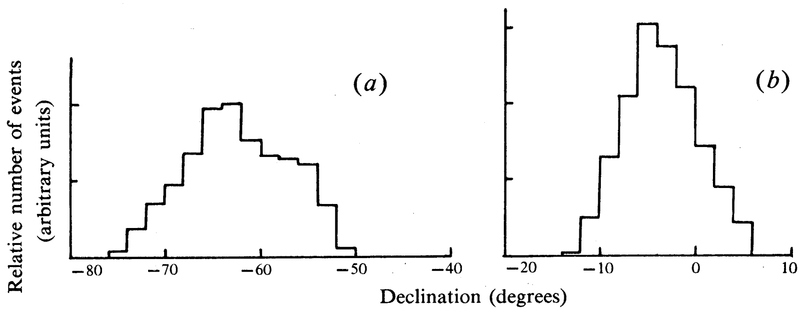

Fig. 1. Declination distribution of shower arrival directions for two lobes of selected showers (see text) at Buckland Park for (*a*) the southerly beam and (*b*) the northerly beam. In the period of observation, 4079 events were detected in the southerly beam and 3830 in the northerly beam.

2. Observations at Adelaide

The EAS array of the University of Adelaide is located at Buckland Park, a sea level site. The array operation has been described recently (Crouch *et al.* 1981), but briefly the array is sensitive to showers with sea level sizes of $\gtrsim 10^5$ particles, has a total effective collecting area of $\sim 30\,000$ m^2, and measures arrival directions with an angular accuracy of $\sim 3 \sec\theta$ by employing a fast timing square of detectors.

We have examined data recorded by the Buckland Park array over a period of about four years to determine whether or not there was a preference for shower arrivals to be from the north or south. To this end we took an azimuthal quadrant of $\pm 45°$ about a northerly direction and one also of $\pm 45°$ about a southerly direction, and determined the number of showers observed in each quadrant with zenith angles $\geqslant 29°$ and $< 40°$. This selection procedure had the aim of obtaining two nominally identical regions of the local sky but with quite separate declination distributions. The array as a whole records about 7×10^4 events per year but the zenith angle distribution of the showers is quite steep due to atmospheric attenuation. Further, in order to avoid some regions of the array size response that might be suspect due to collecting areas which are unduly sensitive to size, and also to avoid employing too large a range of sizes, we chose to limit accepted shower sizes to the range $2 \cdot 3 \times 10^5$–$1 \cdot 8 \times 10^6$ particles. Showers which were poorly analysed, either in terms of poor directional or size analysis (in terms of internal consistency of the data) were rejected. A mean shower primary energy of $\sim 10^{16}$ eV is the result. The declination distribution of the showers from the two azimuthal quadrants is shown in Fig. 1, where it is clear that showers are selected quite effectively over two limited declination ranges with good separation.

We found that a total of 7909 showers were accepted in the two ranges of interest and these were distributed with 4079 showers from the southerly quadrant and 3830 showers from the northerly one. This distribution appears close to that expected for complete isotropy. However, when tested statistically it becomes clear that there is a probability of greater than 99% that the distribution differs from random.

Air shower arrays determine shower arrival directions from fast timing of the shower front between spaced detectors. In our case these detectors make up a square with sides of 30 m. Directional accuracy then depends on timing resolution and the effective array baseline in the plane of the shower front. The latter is appreciably reduced at large zenith angles. Together with a rather steep shower zenith angle distribution, these directional uncertainties can be a limitation on intensity measurements at large zenith angles.

We note that a 3% variation between the intensities of the north and south beams would result from a systematic imbalance in our fast timing of ~ 1 ns. This is close to the practical limit of our timing procedures and the observed difference in intensity should therefore be regarded as a $\sim 3\%$ upper limit for showers with a median size of about 6×10^5 particles (which correspond to a $\sim 10^{16}$ eV primary energy for an atmospheric depth of $\sim 1200\ \mathrm{g\,cm^{-2}}$).

3. Experimental Work of Others

The problem of a declination dependence of the anisotropy at 10^{16} eV has not been discussed extensively before. There are, however, some relevant data. For instance, Clay and Gerhardy (1982) have compared the mean vertical intensities at a fixed shower size (of about 10^6 sea level particles) and shown that measurements made in Japan and Australia agree to within 10%. There are also some other data available in the literature which may throw light on the problem with some extra analysis. These are discussed below.

Directional measurements have been made by Clark (1957) from the northern sky (latitude 42·5° N.) and by Chitnis *et al.* (1960) from the equatorial sky (latitude 10·22° N.). These measurements surveyed the sky in order to determine whether or not specific areas of the sky were preferred source directions for cosmic ray showers (of typical sizes $\sim 10^5$ particles). The results were presented in a form suitable for the analysis of isotropies, or clumping, in terms of right ascension. These authors gave the numbers (or weighted numbers in terms of on-time) of events in intervals of 10° by 10° for right ascension and declination. This distribution is uniform in right ascension but has projection effects built into the declination distribution. We decided to determine whether these declination distributions were uniform in terms of the number of showers coming from northerly or southerly directions at each site. The problem is non-trivial since the right ascension–declination distribution has the array response built into it as well as pure projection effects. We therefore wish to ask whether the distributions found for the northern and equatorial skies are consistent with a uniform azimuthal distribution of showers at each site; and in particular whether or not there is a significant north–south excess or deficit.

Both Clark (1957) and Chitnis *et al.* (1960) gave detailed information on the intensity of showers with zenith angle. These data correspond to a rate absorption length of

$\sim$100–120 g cm^{-2}. In principle, it is possible therefore to use the published data for each site and to simulate the array response to determine the expected declination distribution. This procedure is somewhat complicated since, in reality, the absorption length is slightly dependent on both shower size and atmospheric depth. We therefore chose an equivalent but more simple procedure and simulated the response of these two arrays using shower distributions found at Buckland Park.

Table 1. Declination distributions of showers at four different sites, giving number of events observed (O) and predicted (P)

The declinations are in degrees

Northern (42·5° N.)			Equatorial (10·22° N.)			Equatorial (0°)		Southern (34·6° S.)		
Dec.	O	P[A]	Dec.	O[B]	P[C]	Dec.	P	Dec.	O	P
−10–0	13	6	−50–−40	0	3	−60–−50	1	−90–−80	7	4
0–10	82	66	−40–−30	19	35	−50–−40	49	−80–−70	89	77
10–20	231	217	−30–−20	245	285	−40–−30	306	−70–−60	498	487
20–30	492	459	−20–−10	906	1001	−30–−20	1041	−60–−50	1322	1333
30–40	597	619	−10–0	1929	2134	−20–−10	2066	−50–−40	2483	2505
40–50	621	612	0–10	2676	2921	−10–0	2915	−40–−30	3039	2994
50–60	396	423	10–20	2745	2913	0–10	2944	−30–−20	2732	2780
60–70	166	199	20–30	2269	2092	10–20	2152	−20–−10	1725	1696
70–80	58	53	30–40	1371	1060	20–30	1004	−10–0	764	755
80–90	5	6	40–50	529	310	30–40	285	0–10	135	158
			50–60	94	47	40–50	36	10–20	8	13
			>60	9	1	50–60	3			

[A] Normalized from 12 802.
[B] Weighted average number of events observed, individual entries normalized to 12 802 total.
[C] 12 802 events simulated.

The Buckland Park array is basically similar to the northern and equatorial arrays. The detected shower size distributions are rather similar and, more importantly, the zenith angle distributions of detected showers agree well (compare Clay and Gerhardy (1981, 1982) with Clark (1957) and Chitnis *et al.* (1960)). We therefore expect the distribution of showers with zenith angle to be similar for each array. We have chosen to use the distribution of detected shower arrival directions (in terrestrial coordinates) to determine the declination distributions expected at the northern and equatorial sites, by assuming that the Buckland Park zenith and azimuthal shower arrival directions correspond to those found for arrays at those latitudes. Our procedure was therefore to take Buckland Park records shower by shower and calculate the declination of each shower's origin on the assumption that the array was sited first at 42·5° N. and then at 10·22° N. Additionally, the azimuthal arrival direction of every second shower was reversed (by 180°) in order to ensure that any small anisotropy at Adelaide would not be transmitted to the simulation. This procedure was carried out for well analysed showers falling within predetermined (small) distances of the array centre and recorded in 1980. A total of 12 802 showers was available. As a check to the procedure, the same calculation was carried out for an equatorial site of latitude 0·0°; thus, we also simulate our own results in the same way as a check, since we expect that the low 3% upper limit of the anisotropy would cause the simulated and observed distributions to be essentially identical.

The resulting distributions are shown in Table 1 where a comparison is made between simulated (predicted) and observed declination dependences. These data are presented in terms of the experiment with poorer counting statistics in each case. The northern sky data contain 2661 events and the equatorial data $\sim 10^5$ events. The simulated data contain 12 802 events.

It is clear from Table 1 that the equatorial (0°) simulation proves to be symmetrical in declination, as expected. Also, there is no statistically significant evidence for an anisotropy in the Buckland Park southern data. It also appears that the data from the northern site are close to the isotropic distribution. However, there are serious discrepancies between the observed data from the equatorial site at 10·22° N. and its simulation, there being an appreciable excess of observed events from the north.

4. Discussion of Results

There appears from the equatorial (10·22° N.) experimental work to be a case for suggesting that an appreciable anisotropy exists for cosmic rays of energy $\sim 10^{16}$ eV. However, these data are not consistent with other data presented here. The data from the northern site show no evidence for an appreciable excess from the higher northern declinations and the combination of Akeno and Adelaide data puts an upper limit to the intensity anisotropy well below that implied by the equatorial experiment (of well over 10%). It would appear likely therefore that this particular experiment contains an appreciable systematic bias in its arrival direction derivation, possibly amounting to several degrees. Such a bias could be produced by one detector channel being systematically different to others in its time response, or there could possibly have been a non-horizontal array ground plane.

Table 2. Upper limits to the difference in intensity at different declinations

The primary energy of the cosmic ray showers is $\sim 10^{16}$ eV

Difference	Upper limit	Experiment
I(10°–30° N.)/I(50°–70° N.) − 1	$\lesssim$10–20%	Northern[A]
I(20°–40° N.)/I(20° S.–0°) − 1	$\lesssim$30%	Equatorial[B]
I(60° S.)/I(5° S.) − 1	$\lesssim$7%	Present work
I(35° S.)/I(35° N.) − 1	$\lesssim$10%	Buckland Park–Akeno[C]

[A] Clark (1957). [B] Chitnis *et al.* (1960). [C] Clay and Gerhardy (1982).

The data from the northern experiment are suggestive of a small excess from the south. There is an excess of observed events over that simulated of $\sim$5–10% and a corresponding deficit for northerly events. Since the counts from the south are consistently high and those from the north low, it is possible that this effect is also a systematic effect. The data are, of course, normalized but this would still only reduce the number of degrees of freedom of the analysis marginally. One can therefore probably use the observed anisotropies in declination only as upper limits on the true astrophysical anisotropy. Table 2 contains these upper limits to the difference in intensity measured at different declinations. These data are presented in terms of measured intensity ratios and, on the assumption that a conventional anisotropy may be derived from them, can be converted simply to a value of $(I_{max} - I_{min})/(I_{max} + I_{min})$. For instance, the 7% upper limit for the Buckland Park data would correspond to a conventional anisotropy upper limit of $\approx 3\cdot5\%$.

5. Conclusions

We have examined experimental data concerning the dependence on declination of the intensity of cosmic radiation with energies of $\sim 10^{16}$ eV. Upper limits of any dependence are not stringent when compared with the data on the dependence on right ascension. However, the best now available suggests a useful upper limit on the declination anisotropy $(I_{max}-I_{min})/(I_{max}+I_{min})$ of $\approx 3 \cdot 5\%$, which is comparable with some current limits on the anisotropy in right ascension at these energies.

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