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A COARSE-GRAIN SEARCH FOR ANISOTROPY IN THE ARRIVAL DIRECTIONS OF COSMIC RAYS ABOVE 10^{17} eV

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ABSTRACT

The cosmic-ray intensity measured by the Fly's Eye reveals no statistically significant anisotropy when averaged over large solid angles. The sky is divided into six lobes of equal solid angle which are centered on the directions of the galactic coordinate axes. For each of nine logarithmic energy bands, we compare the number of detected cosmic rays in each lobe with the number expected from an isotropic intensity. The excesses and deficits are not large compared to statistical uncertainties in the expected numbers. Harmonic analysis of the right ascension distribution of cosmic rays is also reported for the different energy bands.

Subject headings: cosmic rays: general **-** galaxies: The Galaxy

I. INTRODUCTION

The arrival directions of ultra-high energy cosmic rays can provide information about the locations of their sources and/or properties of the magnetic field in our part of the Galaxy. If cosmic-ray detectors are sampling a charged particle population which fills the universe isotropically, then the measured intensity should also be isotropic. This application of Liouville's theorem requires no specific knowledge of the magnetic fields in the Galaxy (Hillas *1972).* On the other hand, if most ultra-high energy cosmic rays originate within the Galaxy, their arrival directions should manifest the anisotropy of the Galaxy's magnetic field and/or the anisotropy of the cosmic-ray source distribution. The anisotropy should be salient if the thickness of the Galaxy's magnetic field disk is comparable to, or less than, the Larmor diameter of particle orbits. Assuming the magnetic field to have a mean strength of *2.2* ìG and a thickness on the order of 1 kpc, this condition obtains for protons at energies above 10^{18} eV.

Anisotropy studies at energies above 10^{17} eV have not established a clear pattern of preferred arrival directions. Researchers have usually measured anisotropy by evaluating the amplitude of the first harmonic of the cosmic-ray distribution over right ascension (for all detectable declinations). Some authors have suggested that this anisotropy grows with energy from 0.1% at 10^{14} eV to 30% at 3 x 10^{19} eV (Watson *1981;* Hillas *1984;* Fichtel and Linsley *1986).* However, the phase of the measured first harmonic is highly variable above 10^{17} eV, and the amplitudes are not statistically significant in the range 2 x 10^{18}-3 x 10^{19} eV (Edge *et al. 1978;* Watson *1981;* Clay *1987).* Wdowczyk and Wolfendale *(1989)* find support in the published right ascension harmonic analyses for the hypothesis that arrival directions favor Galactic equatorial latitudes, with the concentration near the plane increasing with energy from 10^{18} to 10^{19} eV. However, analyses which have directly evaluated the dependence of the cosmic-ray intensity on Galactic latitude have not confirmed that hypothesis (Eames *et al. 1985;* Baltrusaitis *et al. 1986).*

Models of particle production and propagation in the Galaxy make anisotropy predictions which are generally simple to express in galactic coordinates but awkward when expressed in declination and right ascension. We will emphasize a method of analysis in galactic coordinates which is meant to facilitate the comparison of model predictions with the experimental results.

II. DATA ACQUISITION

The Fly's Eye detects extensive air showers by means of the atmospheric scintillation light produced by a shower's charged particles. The site at Dugway, Utah is at latitude 40°.2. The detector operates on moonless nights without cloud cover, achieving an overall duty cycle of 8.5%. Details of its detection methods have been published elsewhere (Baltrusaitis *et al*.. 1985). Data have been accumulated since 1981 November, and the present report includes data recorded through 1988 December. The detector was not operated from 1985 June through 1985 October, during which time UV-passing filters were installed in front of the phototubes. A total of 28,049 showers have been reconstructed above 0.125 EeV (1 EeV = 10^{18} eV). For this analysis, we use a subset of 15,709 which were recorded during clear weather conditions and whose energies and directions were well determined. The selection of these showers was based on. measurements by an azimuthally symmetrical Fly's Eye. A second detector (Fly's Eye II) has been operating since 1986 November. Since that time, stereoscopic determination of direction has been advantageous for 25% of the selected showers.

In accordance with the Haverah Park nomenclature (Watson 1981), E2, E3, ..., E10 will designate energy bins as shown in Table 1. The number of showers in each bin for this analysis is also recorded in that table.

III. SKY LOBES

a) Methods

An ideal detector would have uniform exposure to the entire 4π sr sky, and it would determine the cosmic-ray intensity with uniform accuracy over the sky. Results might then be conveniently summarized using an expansion in spherical harmonics defined relative to the galactic coordinate basis. One would hope that the coefficients of the low-order harmonic functions

TABLE 1

THE ENERGY

Bin	Energy Range	Number
E2	0.125-0.25 EeV	5028 showers
E3	0.25-0.5	4881
E4	0.5-1.0	3138
E5	1.0-2.0	1579
E6	2.0-4.0	680
E7	4.0-8.0	265
E8	8.0-16.0	97
E9	16.0-32.0	31
E10	>32.0	10

would characterize and quantify the celestial anisotropy. Every real air shower detector, however, is blind to some portion of the sky, and its exposure is non-uniform over those declinations which it sees. Spherical harmonics cannot be computed in that situation. As emphasized by Wdowczyk and Wolfendale (1984), for example, a negative gradient with respect to Galactic latitude could be due to an equatorial excess instead of a southern excess, if the gradient is well measured only at northern latitudes, i.e., the gradient can be attributed to l = 1 harmonics or l = 2. harmonics, depending on what is assumed about the other hemisphere.

Although a rigorous analysis in spherical harmonics is not possible, the type of information which is- carried in the loworder harmonic coefficients can be obtained quite simply by measuring relative excesses and deficits in suitably defined regions of the sky. For the present analysis we divide the entire sky into six (mutually exclusive) lobes of $2\pi/3$ sr each. The centers of the lobes are the six directions defined by the three axes of the galactic coordinate system (cf. Fig. 1). In terms of Galactic latitude and longitude coordinates (b, l) these six directions are the following:

N: (+90, -) north Galactic pole;
S: (-90, -) south Galactic pole;
C: (0, 0) center of the Galaxy;
A: (0, 180) anticenter of the Galaxy;
F: (0, 90) forward along the solar circle (the Sun's orbit about the Galaxy's center);
B: (0, -90) backward along the solar circle.

The lobe which contains an air shower's direction is easily identified using unit vectors to represent directions. The lobe center direction which has the greatest dot product with the air shower direction determines the air shower's lobe of origin. Each lobe is a quadrilateral whose edges are segments of great circles. This division of the celestial sphere can be visualized by imagining a rubber cube which has been inflated to a spherical shape. The edges of the original cube are the boundaries of six lobes.

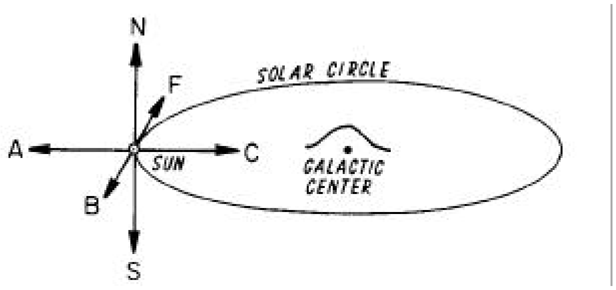

FIG. 1.-Six lobe center directions defined by the galactic coordinate axes.

For any actual data set (e.g., showers in a specified energy band) the number of showers in each lobe is easily counted. That number is meaningful when one knows the number (and fluctuation) expected in each lobe from an isotropic cosmic ray intensity. To evaluate the numbers expected from isotropy, we use "simulation data sets." Each simulation data set is constructed from the actual data set by preserving the zenith angle of each shower, but choosing its azimuth randomly, and randomly selecting a sidereal time from the actual sidereal times of other shower detections. Because the actual data set was produced by an azimuthally symmetrical detector, all azimuthal angles are equally likely if the cosmic-ray intensity is isotropic. Moreover, for isotropic cosmic rays, there should be a time independent flux from each direction in detector coordinates (zenith and azimuth angles), so a shower with particular detector coordinates could have arrived with equal probability at any other time of a shower detection. The different simulation data sets are therefore data sets which could have occurred (given the detector's specific history of operating times and detection rates) if the cosmic-ray intensity was isotropic. An ensemble of simulation data sets yields a distribution of shower counts for each sky lobe. The mean value of a distribution defines the expected number in that sky lobe from an isotropic cosmic-ray intensity, and the width of the distribution is a measure of the expected statistical fluctuations.

Because the simulation data sets have (on average) the same sidereal time distribution as the actual data set, a true anisotropy in right ascension could be partially masked. That is to say, if the actual data set has a nonuniform sidereal time distribution as a result of a cosmic-ray anisotropy (and not simply because of the detector's history of running times and detection rates), then the actual sidereal time distribution is not appropriate for a simulation of isotropy. As a result, the present method is not totally sensitive to anisotropy. (This loss of sensitivity applies also to methods which enforce a uniform sidereal time distribution by selectively discarding some showers or by using shower weights based on sidereal arrival times. If part of the initial nonuniformity in sidereal time were due to a true anisotropy, the magnitude of the anisotropy would be underestimated.) We have evaluated this sensitivity loss in our method by numerical studies in which a known excess in one lobe is built into artificial data sets. Then we see what excess is detected by the method, on average. The result depends on which lobe is given the excess, but the maximum loss of sensitivity amounts to ~10% of the anisotropy. For example, an actual 20% excess in a lobe might be measured as an 18% excess. This sensitivity loss is small compared to the statistical uncertainties in the measurements reported here.

Changes in operating conditions in 1985 November and 1987 August affected the detector's acceptance of showers below 0.5 EeV. The primary effect was to increase the rates of detections at those lower energies. The rate increase, by itself, does not affect the method as long as those showers are studied apart from energy ranges which experienced lesser rate changes. Small changes in the zenith angle distribution also occurred, however, and that could invalidate the method. To be safe, we have done the analysis (below 0.5 EeV) separately for the three epochs of running conditions and then combined the results. In the end, the answers are not different from those obtained by combining the three epochs together.

Results from a sky lobes analysis may depend on a detector's exposure. For example, the Fly's Eye is blind to part of the B sky lobe. Its measurement of the excess (or deficit) in that lobe could therefore differ from a comparable measurement made by a southern hemisphere detector whose exposure includes the entire B lobe.

b) Results

The results of this lobe analysis are shown in Figure 2. Plotted in that figure, for each lobe and each energy band, is the percentage excess (positive or negative) of the actual shower count relative to the expected count. The indicated statistical uncertainty is the percentage rms deviation from the mean value in the simulation data sets. Overall, the fractions of all showers expected in the different lobes are N:0.25, S:0.06, C:0.04, A:0.28, F:0.36, 13:0.01. Together with the numbers of detected showers in each energy band given in Table 1, these fractions give the approximate number of showers for the different points in Figure 2.

TABLE 2

PERCENTAGE EXCESSES

Lobe	0.125-0.5 EeV	0.5-32 EeV
N	-1.4±1.8%	-1.6±2.2%
S	2.2±4.8	9.3 ±4.4
C	-6.7±6.0	2.0±5.7
A	0.6 ±1.6	-2.5 ± 1.8
F	0.6±1.2	0.4±1.8
B	8.7 ± 16.1	13.7 ± 12.1

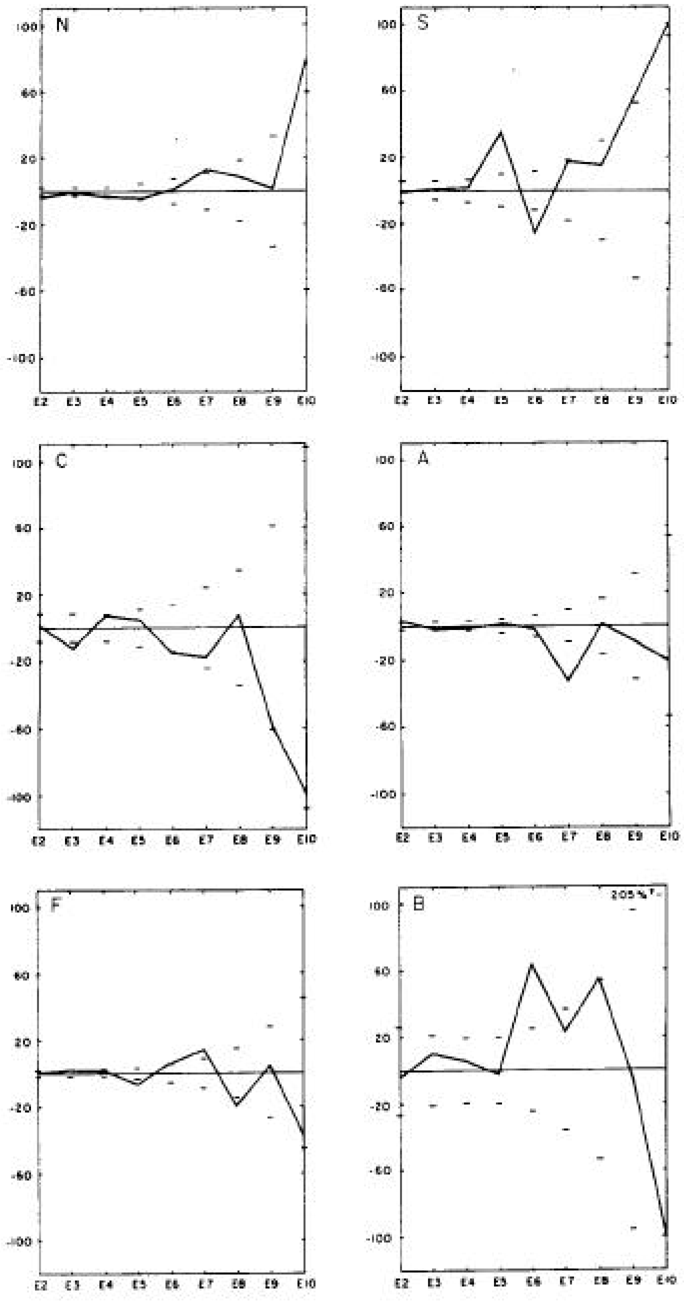

FIG. 2.-For each of the six sky lobes, the percentage excess (positive or negative) is plotted for each energy bin. Also shown, by short horizontal bars, is the rms deviation from 0 excess in the isotropic simulations. Because the Fly's Eye is a northern hemisphere detector, the statistical uncertainties are greater for the S, C, and B directions than for the N, A, and F directions.

Inspection of Figure 2 shows no statistically obvious anisotropy pattern. Although strong percentage excesses and deficits exist, they occur where the statistical uncertainties are also large. No compelling trends with increasing energy are apparent.

Combining energy bands can reduce statistical uncertainties (at the risk of combining disparate anisotropies which may nullify each other). Table 2 gives the results for two broad energy bands. Again, there is no strong evidence of anisotropy.

IV. RIGHT ASCENSION HARMONIC ANALYSIS

The customary method of anisotropy analysis has been to examine the distribution of showers over right ascension, and report an amplitude and phase for the first and second harmonics of that distribution. Table 3 may be useful for comparing Fly's Eye data with reports from other experiments. Linsley (1975) has discussed procedures for such analyses. The amplitude in Table 3 is the length of the Rayleigh vector (which results from plotting each shower on a unit circle according to its right ascension) multiplied by 200 and reported as a percentage. The maximum possible amplitude is 200%, which would occur if all showers were to have the same right ascension.

Because the Fly's Eye has had a nonuniform exposure in sidereal time, the Rayleigh vector has been computed using weighted showers. A shower's weight depends on the hour of its sidereal arrival time, and the 24 different weights are such that every time bin has the same weighted number of showers. The probability in Table 3 is the probability that a Rayleigh vector as great or greater would occur by chance. It is evaluated numerically using trials in which the same set of shower weights are paired with randomly chosen right ascensions.

The second harmonics are evaluated by doubling the right ascension of each shower (so the range of right ascension wraps twice around the unit circle). The phase of the mean Rayleigh vector is then divided by 2 so that it is between 0° and 180°.

In Figure 3, the probabilities from Table 3 are plotted against the corresponding Haverah Park probabilities (Edge et al. 1978). It can be seen that statistically significant amplitudes (low chance probabilities) are not correlated in the two expert' ments. One particular second harmonic has a chance probability less than 0.1 in both experiments, but the measured phases are inconsistent since they differ by 72°. Projecting the Points

TABLE 3

HARMONIC ANALYSIS

		1^{ST} HARMONIC			2^{ND} HARMONIC		Phase
Bin	Energy Range	Amplitude	Probability	Phase	Amplitude	Probability	
E2	0.125-0.25 EeV	1.8%	0.68	37°	2.3%	0.53	78°
E3	0.25-0.5	2.1	0.62	300	2.0	0.63	120
E4	0.5-1	0.7	0.97	238	4.4	0.23	111
E5	1.-2	6.6	0.18	318	10.8	0.012	64
E6	2:4	2.5	0.91	192	9.1	0.25	125
E7	4.-8	16.5	0.17	276	21.4	0.055	179
E8	8.-16	14.4	0.66	235	15.3	0.62	88
E9	16.-32	10.9	0.91	306	39.4	0.29	4
E10	>32	52.7	0.50	180	31.0	0.81	50

of Figure 3 onto the (vertical) Fly's Eye axis, the probability distribution looks uniform. Projecting onto the (horizontal) Haverah Park axis, a modest excess with probabilities less than 0.1 might be viewed as evidence in that experiment for anisotropy. It should be noted that the two experiments do not have equal sensitivity at all energies, based on numbers of showers. For energy bins E2, E3, and E10, Haverah Park has 6.2, 3.3, and 2.8 times as many showers, respectively. For bins E4 through E9, the numbers are within a factor of 2 of each other, with the Fly's Eye having the greater number of showers in bins E7 and E8.

V. DISCUSSION

Some models of cosmic-ray production and propagation predict strong anisotropies at EeV energies which are not confirmed in the present analysis. A prevalent view has been that cosmic rays near 10^{18} eV are predominantly protons of galactic origin (Fichtel and Linsley 1986). In that case, the Larmor diameters of their orbits should be comparable to the thickness of the Galaxy's magnetic disk, and some salient anisotropy is expected. The average large-scale galactic magnetic field is known to point approximately in the direction F, forward along the solar circle (Verschuur 1979). At sufficiently high energies, the only protons confined by the field would be those with large pitch angles, so their arrival directions would be in the F or B lobes. At slightly lower energies, they could be confined even if orbiting perpendicular to the field lines, but only if their orbits were centered on the Galaxy's symmetry plane. Their orbits would then cross the plane (and be detected by us) with directions in the N or S lobes. The C and A arrival directions would correspond to the most poorly confined trajectories, and those lobes should show pronounced deficits. Figure 2 is consistent with a weak anisotropy of that type between 1 and 8 EeV (the highest cosmic-ray energies below the energy spectrum's "ankle"), but, if present, the anisotropy does not stand out clearly above the statistical noise. A different anisotropy pattern might prevail if particle trajectories are governed more by irregular magnetic fields than by the large scale regular field. As suggested by Wdowczyk and Wolfendale (1984), cosmic rays might arrive preferentially from galactic equatorial latitudes, with the N and S lobes having deficits. Figure 2 does not confirm an anisotropy of that type either.

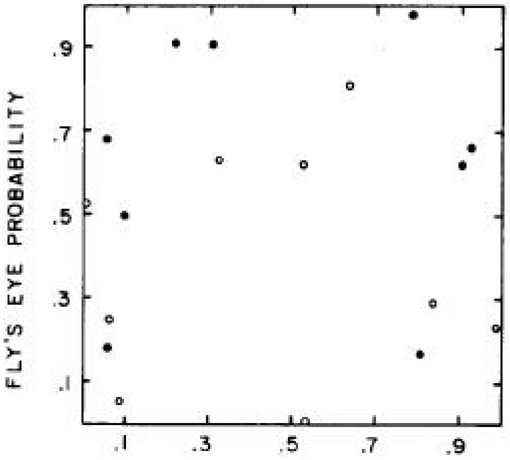

FIG. 3-Chance probabilities (or the measured Fly's Eye right ascension harmonic amplitudes are plotted vs. the corresponding Haverah Park probabilities. Solid circles are first harmonic amplitudes; open circles are second harmonic amplitudes.

The absence of evident anisotropy at these energies suggests that the cosmic rays are not protons which originate in the Galaxy's disk. That does not necessarily mean a universal isotropic population, however. The galactic wind termination shock model of acceleration (Jokipii and Morfill 1985) would presumably be consistent with near-isotropy.

Approximate isotropy might be achieved also by cosmic rays originating in the galactic disk if they are of a mixed chemical composition or a composition dominated by iron nuclei. Fly's Eye composition measurements suggest a mixed composition with less than 50% protons (Cassiday et al. 1990). The arguments for proton anisotropy would pertain to iron at 26 times higher energy. At such high energies, the experimental constraints on anisotropy are weak. Moreover, the salient anisotropy would then be expected at energies above the spectrum's ankle. If the ankle marks a transition from galactic to extragalactic cosmic rays, the anisotropy in the iron nuclei of galactic origin would be masked by the dominant extragalactic population.

For the highest energy bin (E > 32 EeV), the Fly's Eye detects an excess from the Galactic north sky lobe N (cf., Fig. 2). Although the excess is not of great statistical significance, it lends support to previous reports of a strong northern excess at the highest energies (Watson 1981).

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