

A COARSE-GRAIN ANISOTROPY STUDY OF COSMIC RAYS ABOVE 10^{17} EV

G.L. Cassiday, R. Cooper, B.R. Dawson, J.W. Elbert, K.D. Green, D.B. Kieda, E.C. Loh, M.H. Salamon, J. Smith, P. Sokolsky, P. Sommers, S.B. Thomas, and B.M. Wheeler

Department of Physics, University of Utah, Salt Lake City, UT 84112 USA

Abstract

When averaged over large solid angles, the cosmic ray intensity measured by the Fly's Eye reveals no statistically significant anisotropy. The sky is divided into 6 quadrilateral regions of equal solid angle which are centered on the directions of the galactic coordinate system's axes. For each of nine energy bands, we compare the number of detected cosmic rays in each region with the number expected from an isotropic intensity. Plots show the percentage deviations together with the statistical uncertainties.

Introduction. Patterns in the arrival directions of ultra-high energy cosmic rays could provide information about the locations of the cosmic ray sources and/or properties of the magnetic field in our part of the Galaxy. An isotropic extragalactic particle population would produce an isotropic intensity within the Galaxy. This is a consequence of Liouville's theorem and 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 in the Galaxy's disk, a magnetic field of finite extent should not mask the anisotropy of the cosmic ray source distribution. The anisotropy should be salient if the Larmor diameter of particle orbits is comparable to, or greater than, the disk thickness of the Galaxy's magnetic field. Taking the magnetic field to have a mean strength of 2.2 μ G and a thickness on the order of a kpc, this condition is satisfied for protons with energies above 10^{18} eV.

The analysis method used in this report is based on the galactic coordinate system and goes beyond looking for a galactic latitude dependence in the cosmic ray intensity. The method is meant to facilitate comparison of the experimental results with anisotropy expectations derived from any model. We divide the entire sky into 6 (mutually exclusive) lobes of $2\pi/3$ steradians each. The centers of the lobes are the 6 directions defined by the 3 axes of the galactic coordinate system (cf. Figure 1). In terms of galactic latitude and longitude coordinates (l, b), these six directions are the following:

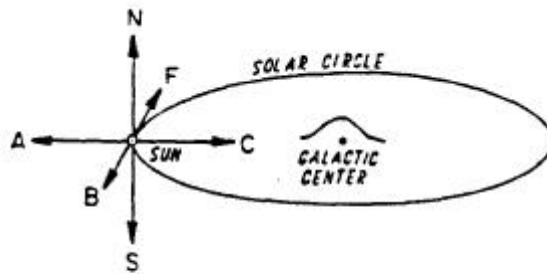


Fig. 1

| | |
|----------------|---|
| N : (+90, -) | North galactic pole. |
| S : (-90, -) | South galactic pole. |
| C : (0, 0) | Center of the Galaxy. |
| A : (0, 180) | Anti-center 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. |

Each cosmic ray shower is assigned to a lobe by finding which of the six direction unit vectors has the greatest dot product with the shower's direction vector.

For each lobe, the number of observed cosmic rays is compared with the number which the detector should have detected if the cosmic ray intensity were isotropic. The percentage deviation from the expected number is reported along with the percentage uncertainty due to statistical fluctuations. Results are presented for nine independent energy bands.

The data. A description of the Fly's Eye detectors and operation has been published (Baltrusaitis et al. 1985). Data have been accumulated since 1981 November, and the present report includes data recorded through 11-Jul-1989. A total of 30,694 showers have been reconstructed above 0.125 EeV (1 EeV - 10^{18} eV). For this analysis, we use a subset of 16,819 showers 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. The showers can be segregated into the energy bins defined by Haverah Park (Watson 1981) as in the following table.

| Energy bin name: | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 |
|--------------------|-------|------|------|------|-----|-----|------|------|----------|
| Lower bound (EeV): | 0.125 | 0.25 | 0.5 | 1.0 | 2.0 | 4.0 | 8.0 | 16.0 | 32.0 |
| Upper bound (EeV): | 0.25 | 0.5 | 1.0 | 2.0 | 4.0 | 8.0 | 16.0 | 32.0 | ∞ |
| Number of showers: | 5425 | 5215 | 3350 | 1691 | 712 | 280 | 101 | 35 | 10 |

Calculating the expected number in each lobe. 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 were 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 number in that sky lobe which would be expected from an isotropic cosmic ray intensity, and the width of the distribution is a measure of the expected statistical fluctuations.

Results and discussion. 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 deviation of the actual shower count from 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, B:0.01. These fractions, together with the

numbers of detected showers in each energy band given in Table 1, indicate the approximate number of showers for the different points in Figure 2.)

Inspection of Figure 2 shows no statistically obvious anisotropy pattern. Although large percentage excesses and deficits exist, they occur where the statistical uncertainties are also large. (A possible exception is the southern (S) excess for energies between 1 and 2 EeV, the excess being 33.6% with a statistical uncertainty of only 8.1%.) No compelling trends with increasing energy are apparent.

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 is 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 (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, protons 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.

A more detailed report on this analysis (but based only on data through 1988) has been submitted for publication (Cassiday et al 1989). That report includes a harmonic analysis in right ascension and a comparison with published Haverah Park results (Edge et al 1978).

Acknowledgement. Work was supported, in part, by NSF grant No. PHY-8720450.

References

- Baltrusaitis R.M. et al. 1985 Nucl. Instrum. Methods A240, 410.
 Cassiday G.L. et al 1989 "A Coarse-grain Search for Anisotropy in the Arrival Directions of Cosmic Rays Above 1011 eV," to appear in Ap. J.
 Edge D.M. et al. 1978 J. Phys. G 4, 133.
 Fichtel C.E. and Linsley J. 1986 Ap. J. M, 474.
 Hillas A.M. 1972 Cosmic Rays (Pergamon) p. 20.
 Verschuur, G.L. 1979, Fund. Cosmic Phys. 5 113.
 Watson, A.A. 1981, Cosmology and Particles, ed: Audouze J. et al, 16th Moriond Meeting, Singapore Nat. Printers, p. 49.
 Wdowczyk J. and Wolfendale A.W. 1984, J. Phys. G IQ, 1599.

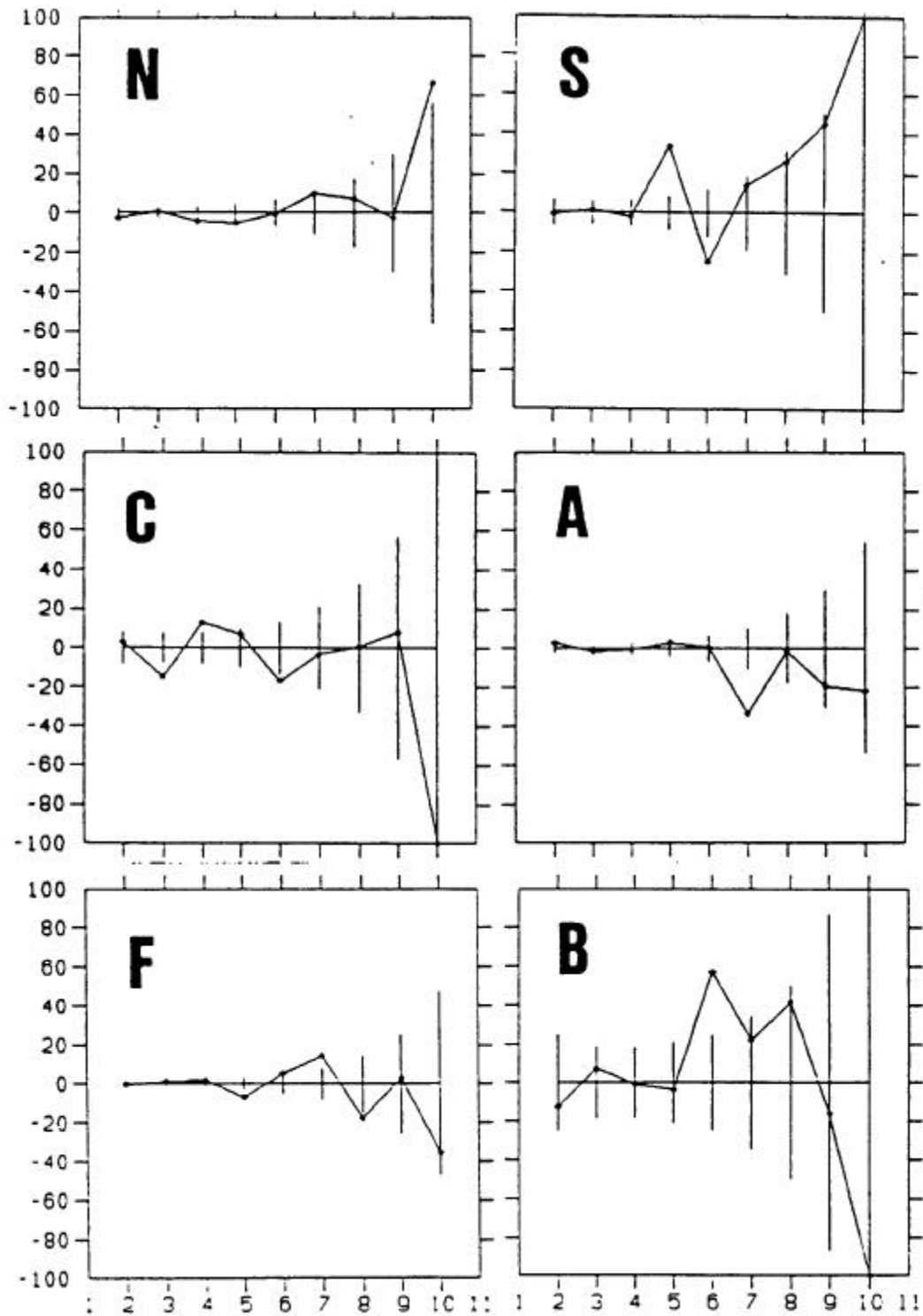


Fig. 2

The percentage deviation from the expected number of showers in lobes N, S, C, A, F, and B. Vertical bars denote the RMS percentage deviation from the mean values in simulation data sets. For each lobe, results are plotted for the 9 energy bins E2, E3, ..., E10.