Aniosotropy Analyses of EeV Air Showers Measured by the Fly's Eye

D.J. Bird, S.C. Corbato, H.Y. Dai, B.R. Dawson, J.W. Elbert, M.A. Huang, D.B. Kieda, S. Ko, C.G. Larsen, E.C. Loh, M.H. Salamon, J.D. Smith, P. Sokolsky, P. Sommers, J.K.K. Tang, and S.B. Thomas

High Energy Astrophysics Institute
Department of Physics, University of Utah, Salt Lake City, UT 84112

ABSTRACT

Several different analysis methods are used in a search for large-scale anisotropy of cosmic rays with energies above $10^{17.5}$ eV. No statistically significant deviation from isotropy is found.

The Fly's Eye detector has operated on moonless nights since 1981 November. Through 1992 July, Fly's Eye I has recorded, under good weather conditions, 16,832 air showers with reliable reconstructions and energies above $10^{17.5}$ eV. Stereo reconstruction is used in this data set only for those showers which were also measured by Fly's Eye II, which became operational in 1986 November. We report here a variety of different searches for anisotropy.

1. Sky lobes analysis. This is a simple method to search for large-scale patterns of arrival directions. The method has previously been described in detail (Cassiday *et al.* 1990a, Cassiday *et al.* 1990b). The sky is divided into 6 equal lobes centered on the directions defined by the 3 axes of the galactic coordinate system. They are labeled North, South, Center, Anticenter, Forward, and Back. Here Forward and Back refer to the sun's motion along its orbit in the galactic plane. For each lobe, there is an observed number of showers. There is also an expected number obtained by assuming an isotropic intensity. In Table 1, we report the number observed in each lobe, the percentage excess (negative means a deficit), and also the statistical significance. The significance is taken to be

v = (observed number - expected number) / (uncertainly in expected number).

The expected number for each lobe and its uncertainty are derived from simulation data sets. An ensemble of simulation data sets gives a distribution of results for each sky lobe. The mean of a lobe's distribution is the expected number for that lobe, and the RMS width of the distribution is used as the uncertainty in the expected number. Each simulation data set is created from the actual data set by changing each shower's sidereal time of detection to another sidereal time randomly chosen from the set of sidereal detection times. Table 1 gives results for 4 disjoint logarithmic energy ranges. There is no statistically significant excess or deficit for any sky lobe in any energy range.

2. Angular dependences. Cosmic ray intensity might be expected to vary with galactic latitude (angle with respect to the South-North axis). Perhaps even more variation is expected with pitch angle relative to the galactic magnetic field (Berezinsky and Mikhailov 1987), which is approximately the angle with respect to the Backward-Forward axis. One might also expect variation with the angle measured with respect to the Anticenter-Center axis (Cassiday *et al.* 1990a). A previous search for these angular dependences has been described elsewhere (Cooper *et al.* 1991). For each plot of the type shown in Figure 1, the angular dependence is summarized by doing a fit with Legendre polynomials through order 2. A non-zero value of the order-1 coefficient a_1 indicates a gradient from one hemisphere to the other. A non-zero value of the order-2 coefficient a_2 is a

TABLE 1: Results from Sky Lobes

Log(E) range	Lobe	Number observed	Excess	"Sigma"
1 .5-18	North	2855	-0.86%	-0.54ó
	South	682	1.11 %	0.33ó
	Center	481	-0.78%	-0.19ó
	Anticenter	2928	-1.41 %	-0.87ó
	Forward	4276	1.65%	1.47ó
	Backward	84	-7.13%	-0.72ó
18-18.5	North	942	-3.11 %	-1.13ó
	South	362	5.50%	1.21ó
	Center	270	4.09%	0.73ó
	Anticenter	1087	3.49%	1.35ó
	Forward	1404	-2.83%	-1.48ó
	Backward	78	6.81 %	0.64ó
18.5-19	North	267	6.45%	1.20ó
	South	90	-6.11 %	-0.68ó
	Center	68	-10.43%	-1.03ó
	Anticenter	251	-8.42%	-1.65ó
	Forward	380	1.85%	0.50ó
	Backward	39	54.6%	2.99ó
> 19	North	59	-9.10%	-0.84ó
	South	33	13.0%	0.83ó
	Center	20	-16.7%	-0.93ó
	Anticenter	71	2.28%	0.22ó
	Forward	91	0.31 %	0.04ó
	Backward	14	43.69%	1.52ó

measure of polar or mid-plane excess (positive for a polar excess, negative for a midplane excess). The statistical significance of a non-zero coefficient is determined by comparison with simulation data sets. In an ensemble of simulations, the mean values for a_l and a_2 are zero, but each has a distribution of values, and the RMS width of the distribution is taken to mean " 1ó ". The plots in Figure 1 are for all showers with energies greater than $10^{17.5}$ eV. Table 2 summarizes results for the 4 separate energy bands.

Wdowczyk and Wolfendale have used a slightly different functional form for studying equatorial or polar excesses. In their revised version (Chi, Wdowczyk, and Wolfendale 1992), they find the parameter f_E for which $f_E(1.4\exp(-b^2) - 1)$ gives the best fit to the fractional excess as a function of galactic latitude b in radians. This functional form which multiplies f_E differs very little from $-.85P_2$, where $P_2 = (3\sin^2 b - 1) / 2$ is the order-2 Legendre polynomial. To a good approximation, therefore, the coefficient a_2 is proportional to f_E. Including the conversion from percentage excess to fractional excess, the relation is $f_E = -a_2/85$.

<u>3. Harmonic analysis</u>. For any declination range, one can examine whether or not the distribution of right ascensions deviates from what is expected for an isotropic cosmic ray intensity. The procedure, as summarized by Linsley (Linsley 1975) is straightforward if a detector has uniform exposure in sidereal time. The Fly's Eye has an irregular run schedule, and its distribution of recorded sidereal times is not quite uniform. To achieve uniformity, showers from each hour bin are subject to a probability of rejection such that the expected number which survive is the same for all hour bins. To minimize fluctuations from the rejection procedure, the process is repeated many times.

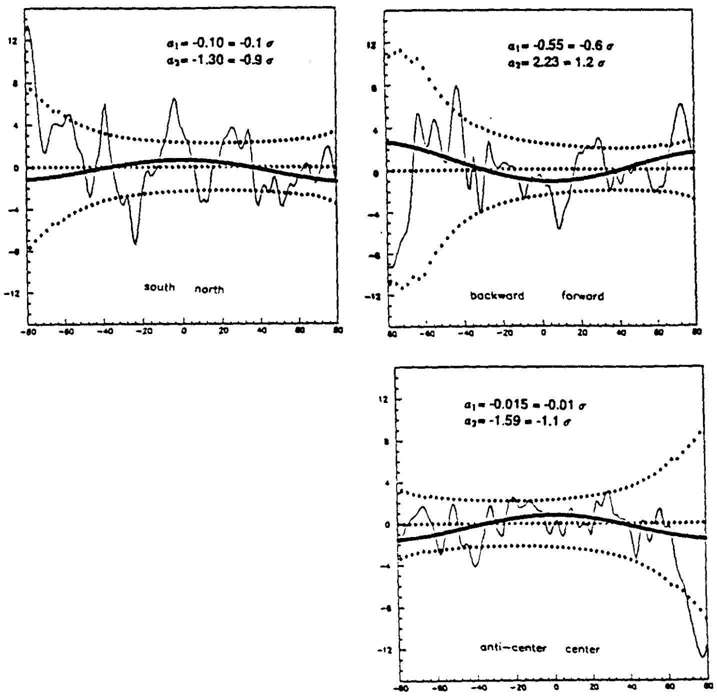

Figure 1. The percentage excess is shown as a function of angle from the planes perpendicular to the 3 galactic axes. Diamonds indicate the "1-sigma" variation in simulations. The heavy curve is the Legendre polynomial fit, whose coefficients are displayed.

TABLE 2: Angular Dependence Results

Log(E) range ~	Axis	Coefficient a,	_ Coefficient a2
17.5-18	South-North	0.10 = 0.08 ó	-0.64 = -0.33 ó
	Anticenter-Center	0.14 = 0.10 ó	-2.93 = -1.38 ó
	Backward-Forward	-0.50 = -0.44 ó	2.13 = 1.04 ó
18-18.5	South-North	3.16 = 1.15 ó	-2.68 = -0.70 ó
	Anticenter-Center	-2.22 = -0.80 ó	5.64 = 1.41 ó
	Backward-Forward	-1.77 = -0.71 ó	-2.85 = -0.66 ó
18.5-19	South-North	5.23 = 1.07 ó	5.38 = 0.82 ó
	Anticenter-Center	1.77 = 0.38 ó	-11.5 = -1.85 ó
	Backward- Forward	-4.76 = -1.19 ó	4.82 = 0.67 ó
> 19	South-North	-14.4 = -1.54 ó	9.97 = 0.80 ó
	Anticenter-Center	-4.42 = -0.47 ó	-11.91 = -0.94 ó
	Backward-Forward	5.15 = 0.67 ó	11.03 = 0.86 ó

The results in Table 3 are based on the mean Rayleigh vector and the mean number of showers surviving the rejection. First and second harmonics are given for 3 declination bands in each of the four energy ranges. Note that the chance probability of obtaining an anisotropy percentage greater than or equal to the measured value is given by exp($-k_0$). For small probabilities, the phase uncertainty (in radians) is given by 1 / ($2k_0$) for first harmonics and 1 / ($8k_0$) for second harmonics.

4. Sky maps. In a separate paper in the OG section of these proceedings (Corbato *et al.* 1993), we present an analysis of cosmic ray density excesses and deficits (relative to

TABLE 3: Harmonic Analysis Results

Log(E) range	Declination band (deg.)	First harmonic	Phase (deg.)	k_0	Second harmonic	Phase (deg.)	k_0
17.5-18	10-30	0.69%	234	0.03	4.11 %	13	0.98
	30-50	2.82%	301	0.48	5.23%	137	1.64
	50-70	5.20%	314	1.18	4.09%	82	0.73
18-18.5	10-30	7.11 %	52	0.97	5.09%	108	0.50
	30-50	4.15%	52	0.33	10.1 %	89	1.95
	50-70	1.79%	298	0.05	9.90%	54	1.43
18.5-19	10-30	12.1 %	103	0.69	8.39%	176	0.33
	30-50	21.8%	281	2.15	7.93%	49	0.28
	50-70	5.30%	180	0.11	8.94%	139	0.30
> 19	10-30	16.2%	333	0.32	16.6%	82	0.34
	30-50	26.2%	26	0.63	25.8%	5	0.61
	50-70	10.2%	142	0.12	39.9%	58	1.91

isotropy) over the exposed sky in a search for point sources. No large-scale pattern of excesses or deficits is obvious in the contour plot. Moreover, the histogram of excesses and deficits is shown to match what is expected due to statistical fluctuations of an isotropic intensity. It is not broadened by large regions of greater-than-average intensity and large regions of less-than-average intensity.

Caveat. Some loss of sensitivity is implicit in all of these methods. There is no attempt here to evaluate the expected sidereal time distribution from the detector's run times and variations in its sensitivity (although such work is in progress). The simpler methods adopted here implicitly assume that the non-uniform sidereal time distribution is due to detector exposure rather than cosmic ray anisotropy. Numerical simulations with artificial anisotropy show that the loss of sensitivity can be as much as 1 /3. For example, a true intensity excess of 15% from the North sky lobe might be measured as only a 10% excess.

Summary. The studies reported here do not reveal any statistically significant cosmic ray anisotropy. The absence of evident anisotropy argues against models in which the EeV cosmic ray intensity is dominated by protons accelerated in the galactic disk and bound only by a magnetic field in the disk of the Galaxy. Work is in progress to evaluate quantitatively the impact of these null results on various models of the cosmic ray source distribution, composition, and propagation.

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