ARRIVAL DIRECTIONS OF COSMIC RAYS OF E > .4 EeV

Baltrusaitis, R.M., Cady, R., Cassiday, G.L., Cooper, R., Elbert, J.W.,
Gerhardy, P.R., Ko, S., Loh, E.C., Mizumoto, Y., Salamon, M.,
Sokolsky, P., Steck, D.

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

ABSTRACT

The anisotropy of cosmic rays observed by the Utah Fly's Eye detector has been studied. Emphasis has been placed on examining distributions of events in galactic coordinates. No statistically significant departure from isotropy has been observed for energies greater than 0.4 EeV (1 EeV = 10^{18} eV). Results of the standard harmonic analysis in right ascension are also presented.

1. Introduction. At the highest energies, the arrival directions of cosmic rays are expected to begin to reveal their origins. In this analysis the observed number of events is compared to the number predicted for an isotropic distribution as a function of both galactic longitude and sin (galactic latitude) for each energy interval, so searches can be made for clustering in two dimensions. The event distributions have also been fit to two different models for galactic latitude dependence: 1. An excess of events from the general direction of the galactic plane of the form $I_{(b)} = I_0[(1 - f) + f \exp(-b^2)]$ where b is the galactic latitude in radians (1), and 2. A gradient with respect to galactic latitude of the form $I_{(b)} = I_0(1 + s \cdot b)$, where b is the galactic latitude in degrees. A similar analysis of the data is performed in the two-dimensional celestial coordinates, and fits have been made to the amplitude A and phase α_0 of the first harmonic of the form $I_{(\alpha)} = I_0(1 + A \cos(\alpha - \alpha_0))$, where α is the right ascension.

2. Description of Analysis. We report here the arrival directions of extensive air showers observed by the Utah Fly's Eye detector, situated at 41°N latitude, between the dates of Nov. 1981 and April 1985. A detailed description of the detector is reported in ref. 2. Only data recorded on clear nights with no clouds higher than 10° above the horizon were accepted. The total live time corresponding to these "weather cuts" is 58.2 days. Further cuts on the data were made to ensure well-measured tracks with good control over the error in direction: the average error in zenith angle after cuts is $\sigma = 3.8°$. Events passing all cuts were then binned in both galactic and celestial coordinates for four energy intervals: 0.4 - 1.0 EeV, 1.0 - 3.0 EeV, 3.0 - 10.0 EeV, and > 10 EeV. All distributions were made in equal-area bins of 5° in galactic longitude (or right ascension) versus 0.4 in sin latitude (or sin declination).

Since the Fly's Eye can only operate on clear moonless nights, the irregular pattern of observation times precludes the assumption of uniform acceptance in right ascension made by experiments running continously. The procedure used to calculate the number of events expected as a function of galactic longitude and sin(latitude) from an isotropic distribution is outlined in this section. The distribution in celestial coordinates follows exactly the same prescription.

The absolute start and stop times for each data run have been recorded. For each 15 minute interval of detector on-time, the zenith angle for each bin of galactic coordinates is computed. Since the distribution in azimuth is uniform, the detector acceptance in zenith angle is the only quantity necessary to compute the acceptance times live-time product at each time interval and each pair of coordinates. Two different techniques have been used to find the acceptance as a function of zenith angle. The first is to use the Monte Carlo simulation of the detector. In principle, this allows an absolute rate determination in galactic coordinates, although only the relative rate was used for this analysis. The second technique uses the measured zenith angle distribution of the data itself to get the relative acceptance. An acceptance of 1 gives a flat distribution in $\cos(\theta_Z)$, so measuring the deviation from a fixed number gives the θ_Z dependence. The relative acceptance in zenith angle calculated directly from the data agrees very well with that predicted by the Monte Carlo simulation: the results reported here were shown to be insensitive to the distribution used.

The acceptance-weighted live times thus generated give the relative rates expected in each bin of galactic coordinates. The absolute normalization is then fixed by demanding that the total number of events predicted be equal to the total number of events observed in each energy interval. Deviations in the data from isotropy should then appear as local excesses (or deficits) of events compared with the number predicted.

Given the number of events observed and predicted in each bin, fits to various models for a possible anisotropy can be made. The number of events expected is weighted by the appropriate model-dependent factor (for example, $(1 + s \cdot b)$ to fit for a galactic latitude gradient s), the "expected" array is renormalized to preserve the same total number of events, and the joint probability for the observed to predicted distribution is calculated. Maximizing the probability with respect to variation in the parameters of the model (for example, s) gives the best fit to the data as well as the associated errors on the best-fit values of the parameters.

3. Results and Discussion. Figure 1 shows our acceptance in galactic coordinates from Monte Carlo events between 3-10 EeV. Note that the region between galactic longitude 240° to 0° and galactic latitude +30 to -90° are not visible to the Fly's Eye. Observed rates projected onto a single axis must, of course, be evaluated with this fact in mind.

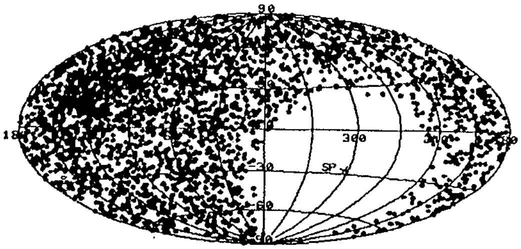

Fig. 1. The Fly's Eye Acceptance.

The ratio of events observed to events expected as a function of galactic latitude are shown in Fig. 2. Table 1 gives the results for the two galactic models considered. Column a) shows fits to a latitude gradient s of the form $(1 + s\cdot b)$; column b) shows the fits to a galactic plane excess $(1 - f + fe^{-b^2})$ with b in radians. No statistically significant deviations from isotropy are observed, although the trend in the latitude gradient agrees with that observed by other experiments (3). The data disagrees mildly with the analysis presented in ref. (1) for the galactic plane excess model, at about 1 σ level. However, our inability to see a rather large region of the galactic disk, in particular the galactic center, should be kept in mind when interpreting these results.

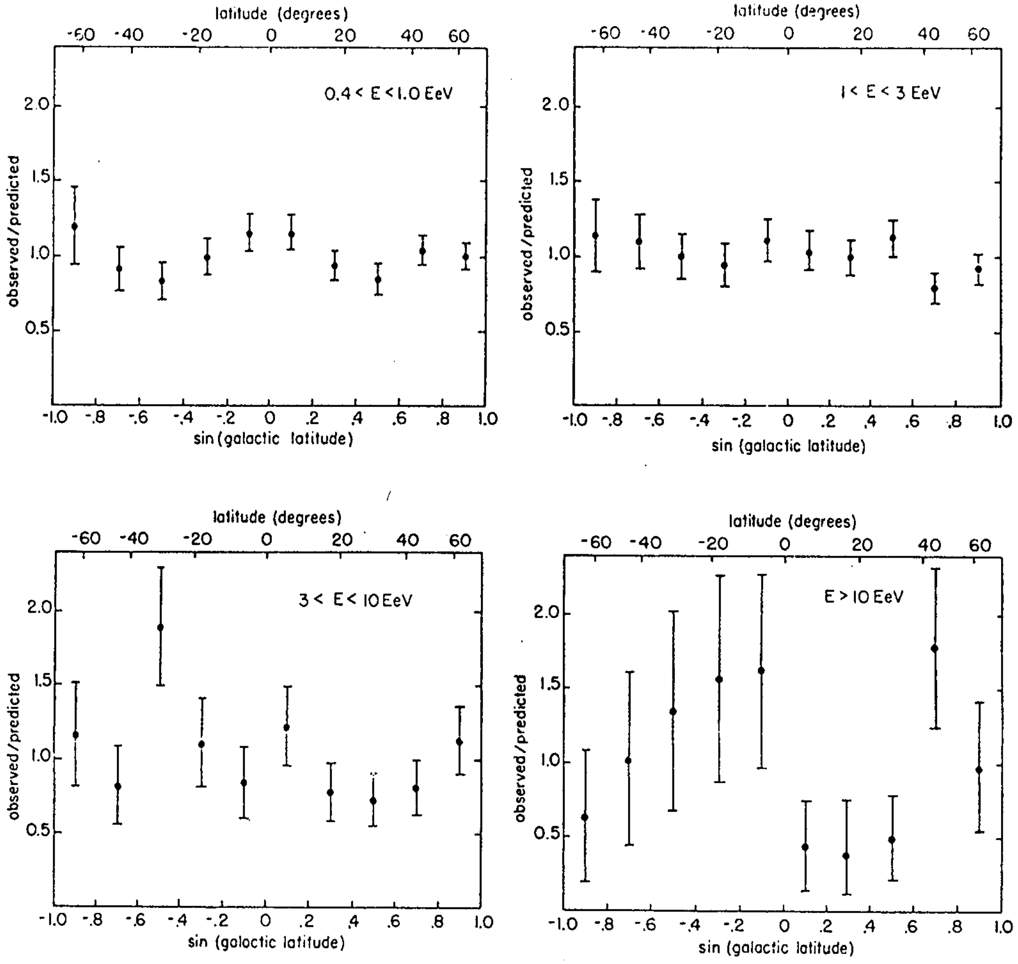

Fig. 2. Observed rates as a function of galactic latitude.

Table 1. Galactic latitude fits

Energy (EeV)	<E> (Eev)	Number of Events	a) Slope $s(10^{-3}/deg)$	b) Galactic Plane Excess f
0.4-1.0	.64	760	-0.1 ± 1.6	0.06 ± 0.20
1.0-3.0	1.7	575	-1.5 ± 1.7	0.15 ± 0.21
3.0-10.0	5.0	170	-1.5 ± 3.0	0.0 ± 0.3
>10.0	18.8	45	0.6 ± 6.0	$0^{+.5}_{-1.0}$

In celestial coordinates, the fits were made to the amplitude and phase of the first harmonic in right ascension, and are shown in Table 2. Here, there is some evidence for non-zero anisotropy, again in agreement with other experiments.

Table 2. First harmonic in right ascension

Energy (EeV)	Amplitude A	Phase α_0 (degrees)
0.4-1.0	.15 ± .08	300 ± 30
1.0-3.0	.07 ± .08	25 ± 80
3.0-10.0	.25 ± .16	350 ± 40
>10.0	.34 ± .34	290 ± 60

4. Conclusions.

If we believe that the cosmic rays above 1 EeV are predominantly protons from our own galaxy, then it is perhaps surprising that there is no evidence in our data for an enhancement from the general direction of the galactic disk. Certainly, more evidence on the composition of cosmic rays at this energy will be crucial to a real understanding of production sources and mechanisms. If a significant fraction of the observed cosmic rays are in fact galactic iron, or are "universal" extra-galactic protons, then the observed smoothness of the data would be reasonable.

Acknowledgment

This work was supported by the U.S. National Science Foundation under grant PHY-8201089.

References

1. Wdowczyk, J. and Wolfendale, A.W., J. Phys. G: Nucl. Phys. 10 (1984) 1453.
2. Baltrusaitis, R.M. et al., The Utah Fly's Eye Detector, submitted to Nucl. Inst. Meth.
3. Astley, S.M. et al., Proc. Int. Conf. on Cosmic Rays (Paris) 2, 156, 1981.