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ARRIVAL DIRECTIONS OF COSMIC RAYS OF $E > 0.4$ EeV

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ABSTRACT

The arrival directions of cosmic rays observed by the Utah Fly's Eye detector have been studied in an effort to find the sources of this high-energy radiation. No statistically significant departure from isotropy has been observed for energies greater than 0.4 EeV (1 EeV = 10^{18} eV).

Subject heading: cosmic rays: general

I. 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 with 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 fitted to two different models for Galactic latitude dependence: (1) An excess f 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 (Wdowczyk and Wolfendale 1984); and (2) A gradient s with respect to Galactic latitude of the form $I_{(b)} = I_0(1 + sb)$, where b is the Galactic latitude in degrees.

II. DESCRIPTION OF ANALYSIS

We report here the arrival directions of extensive air showers observed by the Utah Fly's Eye detector, situated at 41° north latitude, between 1981 November and 1985 May. A detailed description of the detector is reported elsewhere (Baltrusaitis *et al.* 1985*a*). Only data recorded on clear nights with no clouds higher than 20° above the horizon were accepted. The total live time corresponding to these "weather cuts" is 60.08 days. Further cuts on the data were made to ensure well-measured tracks with good control over the error in arrival direction: the average error in zenith angle after cuts is $\sigma = 3^\circ\!.8$. Events passing all cuts were then binned in Galactic coordinates for four energy intervals:

0.4–1.0 EeV, 1.0–3.0 EeV, 3.0–10.0 EeV, and $E > 10$ EeV.

All distributions were made in equal-area bins of 5° in Galactic longitude versus 0.04 in sin (latitude). We restrict our present analysis to Galactic coordinates, since that system is best matched to most recent models of production of ultra–high energy cosmic rays.

Since the detector does not see each part of the sky for the same amount of time or with the same efficiency, we must now calculate the distribution of events expected given isotropic arrival directions. The absolute start and stop times for each data run have been recorded. For each 15 minute interval of

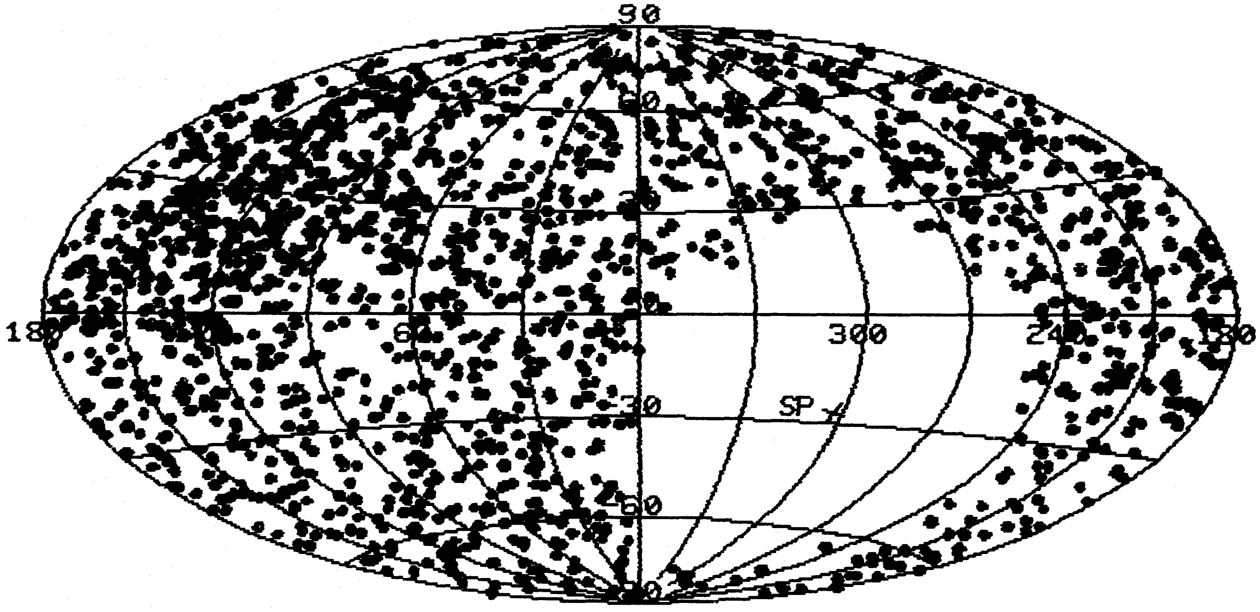

FIG. 1.—Acceptance of the Fly's Eye in Galactic coordinates

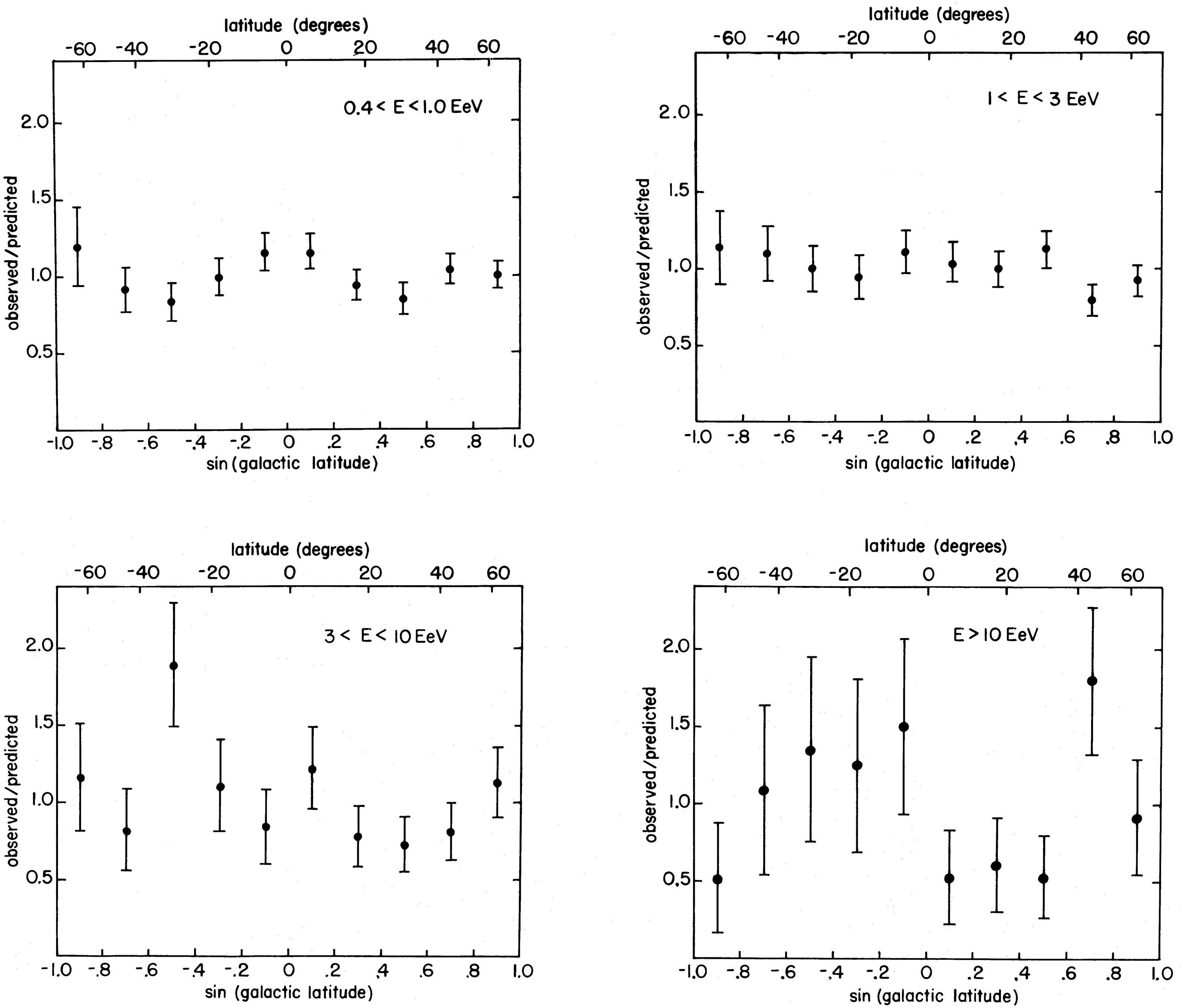

FIG. 2.—Observed rates as a function of Galactic latitude

detector ON-time, the zenith θ_z for each bin of Galactic coordinates is computed. The effective live time for each pair of Galactic coordinates is then the sum of each 15 minute interval weighted by the acceptance of the detector at the corresponding zenith angle. Two different techniques have been used to find the acceptances as a function of zenith angle. The first is to use a 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. A uniform acceptance gives a flat distribution in cos θ_z, so measuring the deviation from a constant 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, $(1 + sb)$ 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 distribution given the expected 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.

III. RESULTS AND DISCUSSION

Figure 1 shows our acceptance in Galactic coordinates from Monte Carlo events between 3 and 10 eV. Note that the region between Galactic longitude 240° and 0° and Galactic latitude $+30°$ and $-90°$ 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. Since both the data and the expected distributions are binned in two dimensions, we can search for clustering of events, perhaps indicating sources. The largest deviation observed (seven events seen with 1.76 expected) has a probability of 1.8×10^{-3} of being due to statistical fluctuations: in the 50 bins used in that plot, the probability of such a fluctuation is 9%. We conclude that there is no significant two-dimensional clustering observed in our data.

TABLE 1

GALACTIC LATITUDE FITS

Energy (EeV) (1)	$\langle E \rangle$ (EeV) (2)	Number of Events (3)	Slope s ($\times 10^3$ deg^{-1}) (4)	Galactic Plane Excess f (5)
0.4–1.0	0.64	791	-0.1 ± 1.6	0.06 ± 0.20
1.0–3.0	1.7	621	-1.5 ± 1.7	0.15 ± 0.21
3.0–10.0	5.0	217	-1.5 ± 3.0	0.1 ± 0.3
>10.0	18.8	54	0.6 ± 6.0	$0^{+0.5}_{-1.0}$

The ratios of events observed to events expected as a function of Galactic latitude are shown in Figure 2. Table 1 gives the results for the two Galactic models considered. Column (4) shows fits to a latitude gradient s of the form $(1 + sb)$; column (5) 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. 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.

IV. 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" extragalactic protons, then the observed uniformity of arrival directions would be reasonable. Since the energy spectrum observed by the Fly's Eye (Baltrusaitis *et al.* 1985*b*) gives some evidence for extragalactic origin of the highest energy cosmic rays, the isotropy observed in the same data tends to favor a universal extragalactic source.

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