

A SEARCH FOR 10^{18} eV POINT SOURCES, INCLUDING CYGNUS X-3

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Abstract

We have analyzed the cumulative Fly's Eye data for point sources of air showers. Due to the detector's angular resolution, a signal from a point source is spread over a finite solid angle and must be distinguished from a chance clustering of cosmic rays. We describe our methods and report results of a search for point sources between declinations -15° and 75° . Evidence for a signal from Cyg X-3 is summarized.

Introduction. Cosmic rays with energies up to 10 EeV ($1 \text{ EeV} = 10^{18} \text{ eV}$) may be predominantly of galactic origin (Fichtel and Linsley 1986). Based on reported PeV $\tilde{\alpha}$ -ray fluxes from Cyg X-3 (Samorski and Stamm 1983; Lloyd-Evans et al 1983), Hillas (1984) showed that Cyg X-3 could account for much of the Galaxy's cosmic ray production at energies near 0.1 EeV. It is therefore plausible to suppose that Cyg X-3 and other compact objects are galactic accelerators of cosmic rays up to 10 EeV. If adequate numbers of neutral particles are also produced near such sources (Sommers and Elbert 1989), it should be possible to detect EeV point sources using EAS detectors. An analysis of the Fly's Eye data through 1987 Hay indicated the presence of a neutral particle flux from the direction of Cyg X-3 (Cassiday et al 1989x). An analysis of Haverah Park data has yielded a counter-indication (Lawrence et al 1989). We here report further analysis of the Fly's Eye data through 11-Jun-1989.

In addition to Cyg X-3, we report results for 57 other candidate source locations. These secondary candidates include known x-ray sources (Bradt and McClintock 1983), $\tilde{\alpha}$ -ray sources (Hermsen 1981), and fast pulsars (period $< 0.01 \text{ s}$) with declinations between -15° and 75° .

The data set. Showers have been detected since 1981 November by the Fly's Eye (Baltrusaitis et al 1985). For showers with energies above 0.5 EeV, the median measured depth of maximum is 700 gm/cm^2 . In this search for point sources of neutral particles, only showers with maxima deeper than 700 gm/cm^2 have been used. This cut should help to exclude showers initiated by heavy nuclei without discarding many $\tilde{\alpha}$ -ray or neutron showers. A total of 11,202 showers have been well-reconstructed and pass the depth-of-maximum cut. Directions for 12% of them have been determined stereoscopically. Because of variability in the detector's angular aperture for showers near its threshold energy, showers with energies below, 0.5 EeV are suppressed in this analysis. Each shower is weighted by the probability that its energy exceeds 0.5 EeV, with the probability based on the measured shower energy and its uncertainty.

Analysis procedures. A description of the techniques has been presented; elsewhere (Cassiday et al 1989b). Briefly, the idea is to smear each shower's direction into a 2-dimensional Gaussian density function on the sky whose peak is at the shower's most likely direction of origin and whose

widths are given by uncertainties in that direction. Summing the density functions for all detected showers gives a celestial density function of cosmic rays measured by the detector. A search for point sources of neutral particles can be performed by looking for small sky regions where this observed density significantly exceeds the expected density. The expected density function is evaluated using simulation data sets based on the hypothesis of isotropy. Each simulation data set is constructed from the actual data set by simply changing each shower's sidereal time of detection to another time randomly sampled from the other detection times. (If the detector is responding to an isotropic particle intensity, then the flux from any detector direction should be constant. In that case, the shape of the expected sidereal time distribution for any detector direction should be the same as that for the entire detector.) An ensemble of simulation data sets provides a distribution of density values for any point X of the sky. The distribution's mean is the expected density at X. The distribution also gives the probability (assuming an isotropic particle intensity) for the occurrence at X of a density greater than or equal to the density measured at X.

The hypothesis of a point source at X can be tested not only by checking for an excess at the point X, but also by comparing the behavior of the excess in a neighborhood of X with what is expected from a point source, given the angular resolution of the detector. This comparison is achieved by folding the density with a normalized function which describes the density function expected from a point source at X. Monte Carlo simulations show that a width of $s = 3.8^\circ$ gives the best Gaussian fit to the expected point source function. Each shower's density function can be folded analytically with the 3.8° Gaussian centered at X, so that summing over all showers gives the folded total density at X. This folded density at X is used to test for the presence of a point source at X. A simulation data set can be counted as a "success" if it gives a folded density at X greater than or equal to the value computed using the actual data set. Dividing the number of "successes" by the number of tried simulation data sets gives the probability that a chance clustering of cosmic rays would cause a folded density at X greater than or equal to the measured value. This probability can be evaluated at any sky point X and provides a quantitative test of the hypothesis that a detectable point source is located at X.

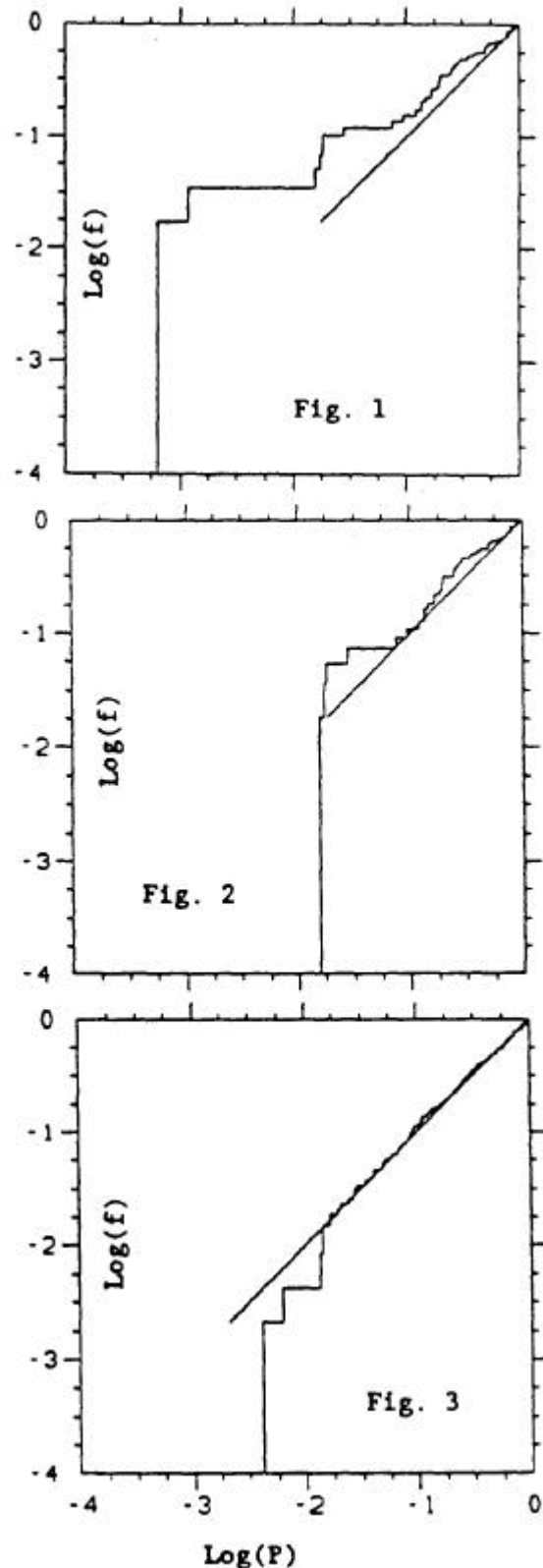
Evaluating the chance probability at each point X require considerable computer time if the probability is low enough that a large number of simulation data sets must be tried before enough 'successes occur to give a valid estimate of the probability. And in order to make maps like Fig. 4 it is necessary to evaluate the significance, at a large number of grid points. Instead of evaluating the chance probability directly, an expedient alternative is to quantify the significance of a density by how much it exceeds the expected density in units of RMS deviations. A relatively small number of simulation data sets suffices to determine both the seen value and the RMS deviation from the mean for the distribution of folded densities at X. If the simulation data sets produce a normal distribution of density values, then this measure of significance is the "number of σ " excess at each point X.

Results. The chance probability (defined above) has been evaluated for the 58 candidate source positions. The resulting distribution of probabilities is shown in a Log-Log plot in Fig. 1. The abscissa is $\text{Log}(P)$ and the ordinate is $\text{Log}(f)$, where f is the fraction of points with probabilities

less than P . The 45° line (starting at $P = 1/58$) represents the expected distribution for a random set of probabilities. The candidate source with the lowest chance probability (6.4×10^{-4}) is Cyg X-3. The second lowest probability occurs for the $\tilde{\alpha}$ -ray source at ($\tilde{\alpha} = 40$, $\tilde{\alpha} = 305$), which is close enough to Cyg X-3 that it is part of the same density peak. Since the expected point source function has a Gaussian width of 3.8° , the effects of a point source at Cyg X-3 should be mostly excluded by eliminating all points within 7.6° of Cyg X-3. The probability distribution for the remaining SS candidate sources is shown in Fig. 2. The chance probability is 0.094 for Her X-1 and 0.35 for the Crab nebula.

Fig. 3 shows the probability distribution for an array of 474 points spread over the portion of the sky for which $-15^\circ \leq \alpha \leq 75^\circ$. With closest neighbors separated by at least 7.5° , these points represent 474 nearly-independent trials. (Points within 7.6° of Cyg X-3 have been excluded.) The distribution is consistent with a uniform probability distribution, and none of the array positions gives a probability as low as at Cyg X-3.

These results suggest that the density excess from the Cyg R-3 direction is the most significant excess in the Fly's Eye data. The following table shows the Cyg X-3 chance probability for each calendar year. In 1985 there was very little exposure to Cyg X-3 because the detector was not operated June-October in order to retrofit optical detectors. The 1989 entry is based on data through July 11, with Cyg X-3 exposure predominantly in June and July, near the times of radio outbursts. No EeV neutral particle outburst is apparent.



Calendar year:	1982	1983	1984	1986	1987	1988	1989
Data set number of showers:	454	456	524	1633	3212	3739	774
Cyg X-3 chance probability:	.14	.024	.23	.026	.0048	.34	.72

Fig. 4 shows a contour map of the " σ significance" (described above) in a sky region which includes Cyg X-3. The plot is centered on ($b = 0^\circ$, $l = 80^\circ$) with galactic latitude ranging vertically from -10° to 10° and longitude (increasing leftward) from 70° to 90° . The + marks the location of Cyg X-3. A point source at + would be expected to produce a density excess centered at + and with a Gaussian width of $s = 3.8^\circ$. Since, for each point X, the density function has been folded with a Gaussian of that width, the expected folded density excess (and hence the σ significance function also) should have a Gaussian width of $2 \cdot 3.8^\circ = 5.4^\circ$. In Fig. 4, the peak of 3.896 occurs at ($b = 4.1^\circ$, $l = 82.2^\circ$). The contour lines are drawn for $\sigma = 3.77, 3.43, 2.93, 2.36, 1.78$, and 1.26 . For a Gaussian of central amplitude 3.89 and width S, these would be the function values at distances $.25S, .5S, .75S, S, 1.25S$ and $1.55S$, respectively. The positions of the plotted contours suggest that $S = 7.6^\circ$, somewhat broader than the 5.4° expected for a point source. The central peak is offset from Cyg X-3 by 0.55.

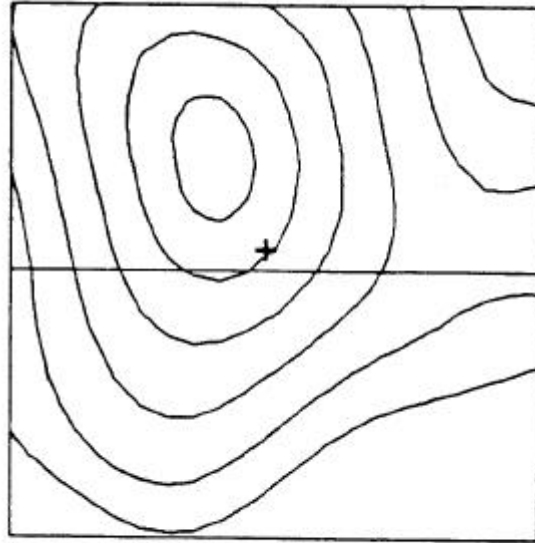


Fig. 4
(see text)

Conclusion. This analysis of the cumulative Fly's Eye data has produced no compelling evidence for an EeV point source at any position other than that of Cyg X-3. The chance probability at Cyg X-3 is 6.4×10^{-4} .

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

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