A Fly's Eye Search for Point Sources of EeV Air Showers

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ABSTRACT

The Fly's Eye has detected air showers stereoscopically since the end of 1986. That data set is used here in a search for point sources. A survey of the sky in the declination range from -15° to +75° finds a distribution of flux excesses which is consistent with what is expected from statistical fluctuations of the background. Flux limits are derived for Cyg X-3, Her X-1, and the Crab.

The study of air shower arrival directions offers the possibility of a direct identification of EeV cosmic ray sources. Accelerated charged particles can produce neutral particles in collisions with nuclei or photons near the source. At EeV energies (1 EeV = 10^{18} eV), both neutrons and gamma rays could be detected, without magnetic deflection, from distant sources within the Galaxy. A definitive detection of an EeV flux from a compact object would establish such objects as sources of EeV cosmic rays. We have therefore conducted a search for evidence of such point sources in the Fly's Eye data set.

The Fly's Eye is an optical detector which measures the fluorescent light produced by extensive air showers on clear moonless nights at Dugway, Utah. A description of the detector and the methods of shower reconstruction can be found elsewhere (Baltrusaitis *et al*. 1985). Observation of an air shower track from a single site determines the plane which contains the line of the shower axis and the position of the detector site. With stereo observation from two different sites, the shower axis is unambiguously determined by the intersection of the two planes. The present analysis is based on stereo reconstruction of 4773 air showers, detected from 1986 November through 1992 July, whose energies exceed 0.5 EeV

A point source of air showers must be identified by finding a direction from which the flux exceeds, by a statistically significant margin, what is expected from an isotropic intensity of cosmic rays. The method used here is the same as previously reported (Cassiday *et al*. 1989, Cassiday *et al*. 1990). The direction of each shower is represented by a probability distribution on the sky. For some showers, the probability distribution is concentrated in a very small solid angle. For other showers, the distribution may be spread out due to imprecise determination of the shower planes or a small opening angle between them. The mean angular resolution is approximately 2° (cf. Fig. 1). By adding the probability distributions for all recorded air showers, one obtains an observed cosmic ray density function over the sky. It is non-uniform due to the detector's fixed latitude and its intermittent run times. The observed density at any point of the sky must be compared with the density which is expected if the cosmic ray intensity is isotropic. That expected density is computed by averaging simulation data sets. Each simulation data set is constructed from the actual data set by changing each shower's sidereal time of detection to another sidereal time randomly sampled from the collection of actual shower sidereal times.

To assess the statistical significance of sky locations where excesses occur, we begin by examining the function

ó = (actual density - expected density) / (uncertainty in expected density).

at every grid point on the sky. (Grid points are separated by 1° in declination and right ascension.) The "uncertainty in expected density" is the RMS deviation from the mean in the distribution of simulation densities (at each sky point). The distribution of resulting ó-values is shown in Fig. 2. The high-ó values occur at sky locations where one or two highly concentrated air shower probability distributions give big contributions. Fig. 2 also shows that the distribution of observed ó-values agrees with the expected distribution of ó values, which is obtained by averaging the ó distributions which result from many simulation data sets. ,

The peak values of ó are associated with spikes in the ó function on the sky, and a spike is not the expected signature of a true point source from which multiple showers have been detected. The expected functional shape of an excess due to a point source is shown by the broader curve in Fig. 1. The narrower curve in that figure is what would be expected due to the representation of each shower by a probability distribution centered on the source. The broader curve results when the centers of those distributions are displaced from the source location in accordance with the directional uncertainties. A significant excess whose shape on the sky matches the broader curve in Fig. 1 would be the signature of a point source. Therefore, as we have done before (Cassiday et al. 1990), we look for a point source at each grid point by folding the observed ó, function with the expected shape function centered at that point. The resulting significance function is plotted as a contour plot in Fig. 4. The distribution of significance values is shown in Fig. 3 along with the expected distribution derived from applying the same procedures to many simulation data sets. There is no gridpoint of exceptionally high significance relative to the expectations.

The Fly's Eye has good exposure to several a priori candidate point sources. Cyg X-3, Her X-1, and the Crab Nebula warrant special attention. Specific results for these sources are reported in Table 1. The 95% C.L. flux upper limits are derived using simulation data sets in which artificial source showers (with errors sampled from actual shower probability distributions) are added until the density at the source location exceeds the observed density. The upper limit on source showers is that number N such that 95% of the simulations require fewer than N artificial source showers. The flux limit is given by N x I / (*expected density*), where I is the known cosmic ray intensity and the expected density (per unit solid angle) is the expected density at the source location derived from simulation data sets. We have previously reported evidence for an excess from the direction of Cyg. X-3, using data from 1981 November through 1988 May (Cassiday et al. 1989). The stereo data do not offer a means for checking that result since the two data sets have overlapping exposure to Cyg X-3 only in 1987.

In summary, this analysis reveals no evidence for any point source of air showers above 0.5 EeV since the commencement of stereo data at the end of 1986.

TABLE 1: Results for Candidate Sources (E > .5 EeV)

	Expected density (per deg^2)	Percent excess	Chance probability	95% C.L. flux upper limit (cm^{-2}sec^{-1})
Cyg X-3	0.233	-7.73%	0.60	7.0×10^{-18}
Her X-1	0.188	-13.9%	0.69	6.2×10^{-18}
Crab	0.205	-4.92%	0.56	8.0×10^{-18}

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REFERENCES

Baltrusaitis, R.M. et al.: 1985, Nucl. lnstr. Meth., A240, 410
Cassiday, G.L. et al.: 1989, Phys. Rev. Lett., 62, 383
Cassiday, G.L. et al.: 1990, Nucl. Phys. B (Proc. Suppl.) 14A, 291

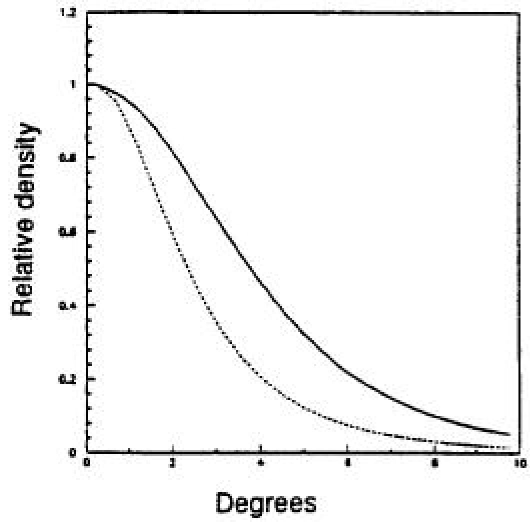

Figure 1. The dashed curve is the expected radial dependence of density excess around a point source due to the solid angle probability distributions for shower directions. The solid curve includes the effect of the solid angles not being centered on the point source.

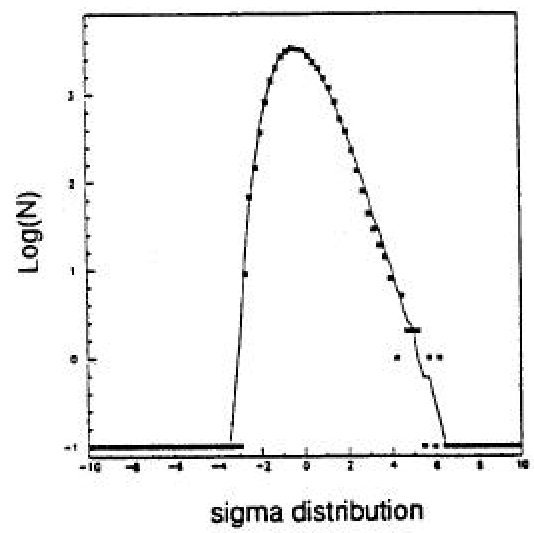

Figure 2. The histogram of ó-values is compared to the expected distribution (solid curve) which is derived from simulation data sets.

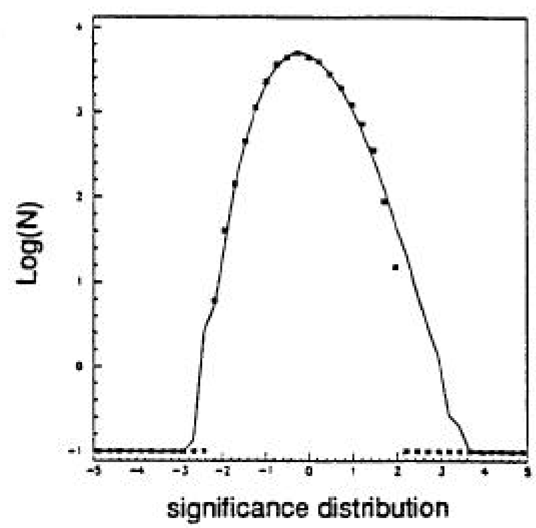

Figure 3. The marks (*) are the histogram of the significance value at each gridpoint which results from folding the o function with the functional shape expected if there were a point source at that location. The solid curve is the expected distribution which is derived from simulation data sets.

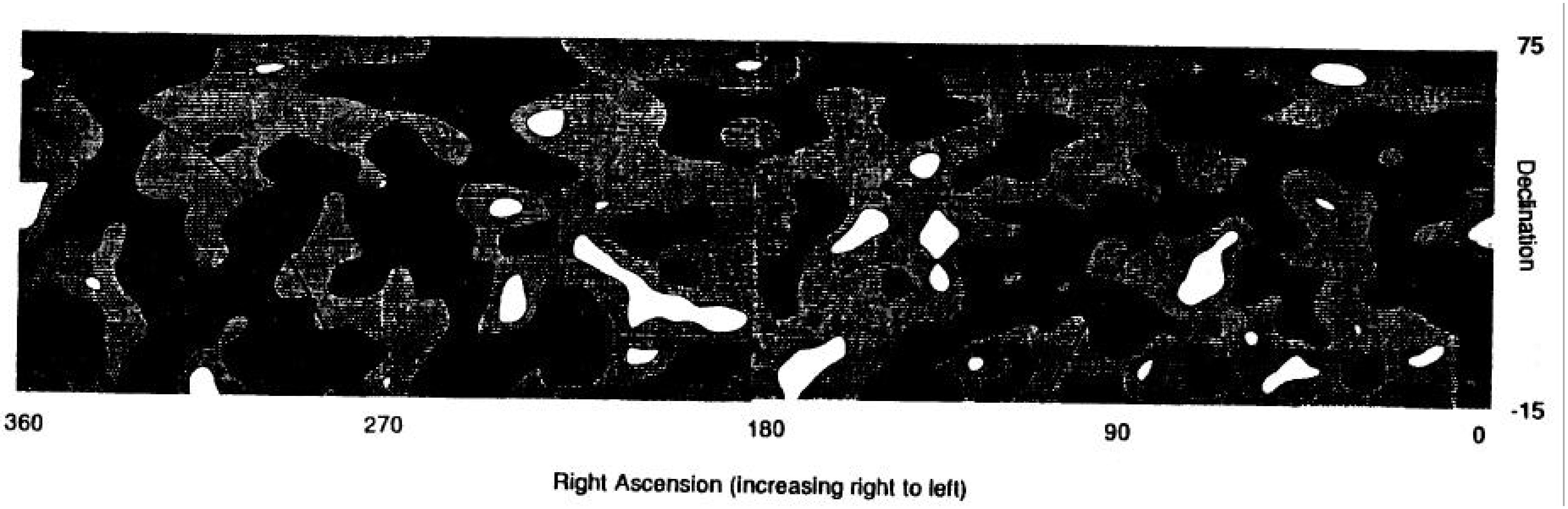

Figure 4. This contour plot represents the statistical significance of density excesses
and deficits as a function on the sky. (See text for the definition of the significance function.) Excesses are denoted by dark grays, deficits by light. Contour lines are at -1, 0, +1. The galactic plane is marked with dots. Stereo showers with energies above 0.5 EeV are used in this data set. In Fig. 3, the histogram of significance values at all gridpoints is compared with the expected histogram derived from isotropic simulations.