

A STUDY OF CYG X-3, HER X-1, AND THE CRAB NEBULA
FOR GAMMA RAY EMISSIONS ABOVE 7×10^{18} eV

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Abstract

A portion of the Fly's Eye II has been recording Cherenkov flashes since November, 1987, in a declination band which includes these three x-ray sources. The data have been analyzed on a nightly basis in a search for evidence of ultra-high energy (UHE) gamma ray emissions.

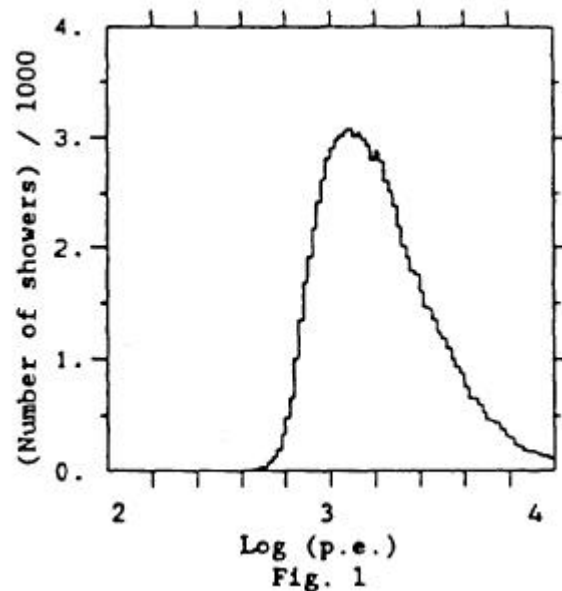
Introduction. Cyg X-3, Her X-1, and the Crab nebula or pulsar have all been reported to be sources of UHE γ -rays. Reviews on Cyg X-3 are Protheroe (1987) and Bonnet-Bidaud and Chardin (1988). Her X-1 reports include Baltrusaitis et al. (1985) and Dingus et al. (1988). UHE emissions from the Crab were reported in Boone et al. (1983) and Dzikowski et al. (1981). We here report results from Cherenkov flash data recorded by the Fly's Eye II detector at Dugway, Utah. The data for each source have been analyzed on a night-by-night basis.

Data acquisition. In order to avoid interfering with the Fly's Eye's principal role of recording scintillation tracks from higher energy showers, the Cherenkov flash data rate has been restricted. Only 9 of the 36 mirror units in Fly's Eye II are set to trigger if a strong pulse is recorded in a single photomultiplier tube (PMT). Those 9 mirrors observe a band of declinations which includes the three candidate sources. The threshold for single-tube triggers is set high in order to limit the detector's dead time and also to avoid triggering on noise from background light. For each trigger, data is stored from every Fly's Eye II PMT which exceeded a low threshold in any of 3 channels with different integration times. Cherenkov flashes are distinguished from airplane strobes, lightning, and other spurious triggers by virtue of their narrow time profile, so the amplitude in the fastest channel is such higher than the amplitude in the slowest channel. Some Cherenkov flashes are detected by more than one PMT. Any PMT is included in the event if it reached threshold almost simultaneously with the highest-amplitude PMT, and if it is contiguous with other PMT's in the event. For each Cherenkov flash event, summary information is stored for subsequent analysis. The stored information includes the number of PMT's in the event, the total photoelectron amplitude, the time of trigger, and the central direction of the PMT with the largest amplitude. (The field of view for each PMT has a radius of 2.6° .)

For each night, a check is made on the relative rate stability in the different mirror units. Bad weather conditions or the onset of twilight can cause severe rate deviations in one or more mirrors. The criteria for acceptable rate behavior have been specified (Baltrusaitis et al. 1987).

From 11-Nov-1987 through 11-Jul-1989, a total of 5.29×10^6 Cherenkov flashes have been recorded during acceptable running conditions on 219 nights. The accepted running time amounts to 4.23×10^9 seconds. The solid angle covered by the 9 mirror units is 0.75 sr.

An energy determination is not possible for an individual event because the distance of the detector from the shower core is unknown. The distribution of photoelectron (p.e.) counts is shown in Fig. 1 (based on a sampling of 6 nights). It shows that the trigger efficiency is low for flashes producing fewer than 1000 p.e. Simulations of the type described in Sommers and Elbert (1987) can be used to determine the energy needed to meet the 1000-p.e. trigger requirement at any given radius from the shower core. The Fly's Eye II cathode efficiency and optical filter transmission have been included as functions of photon wavelength in the simulations. We find that the trigger requires a proton shower to have an energy of at least 60 TeV even near the core, and it needs 100 TeV if the core is 100 m away. For $\tilde{\alpha}$ -ray showers, the corresponding energies are 40 TeV and 70 TeV, respectively.



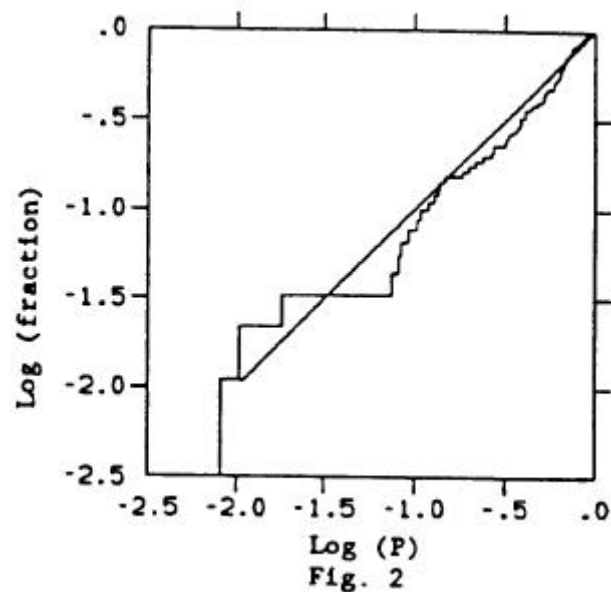
Analysis method. The direction of a recorded Cherenkov flash is taken to be the pointing direction of the PMT with the highest p.e. amplitude. As in previous studies, there is a 3.5° error assigned to each direction because of the angular width of each PMT and the fact that the direction to the point of maximum light emission differs from the shower direction. Accordingly, a disk of 3.5° radius (centered on the sky position of a candidate source) is used to count the number of showers from the source direction.

The number of showers expected in the target disk during a given night (in the absence of a point source) is determined using simulation data sets in which event sidereal times have been scrambled (Cassiday et al. 1989a, 1989b). The underlying assumption is that the sidereal times of events recorded in each PMT can be regarded as having been sampled from one" master sidereal time distribution. (This assumption is valid if the cosmic ray intensity is isotropic and the relative PMT sensitivities are constant, even if the detector is not running continuously or experiences overall variations in sensitivity.) The collection of sidereal event times in the entire detector during the night is used as the master sidereal time distribution. A simulation data set is constructed from the actual data set by keeping the PMT direction for each event, but sampling a different sidereal time for it. The expected number of showers from the source direction is obtained by averaging the numbers obtained from many simulation data sets.

A point source flux should cause the observed number of showers n to exceed the expected number a . The significance of an excess can be measured as the Poisson probability, $P(n, a)$, of observing n or more showers when the expected number is a .

Results for Her X-1. The detector had some exposure to Her X-1 during 94 nights. The numbers of observed showers from that direction sum to 12,698. The sum of expected numbers is 12,767. The total number observed is less than the expected number by 0.610. A 95% confidence level upper limit to the number of source showers in the target disk is 182 (cf. Particle Data Group 1988). Since 309 of source showers are expected to get assigned directions more than 3.5° from the source position, the upper limit for the number of source showers is 260. The effective observing time for Her X-1 is estimated by dividing 12,767 by the detector's rate per sr and multiplying by the solid angle of the 3.5° -radius target disk. Using an effective area of 100-meter radius, the 95% confidence upper limit for flux is $8.1 \times 10^{-13}/(\text{cm}^2\text{s})$.

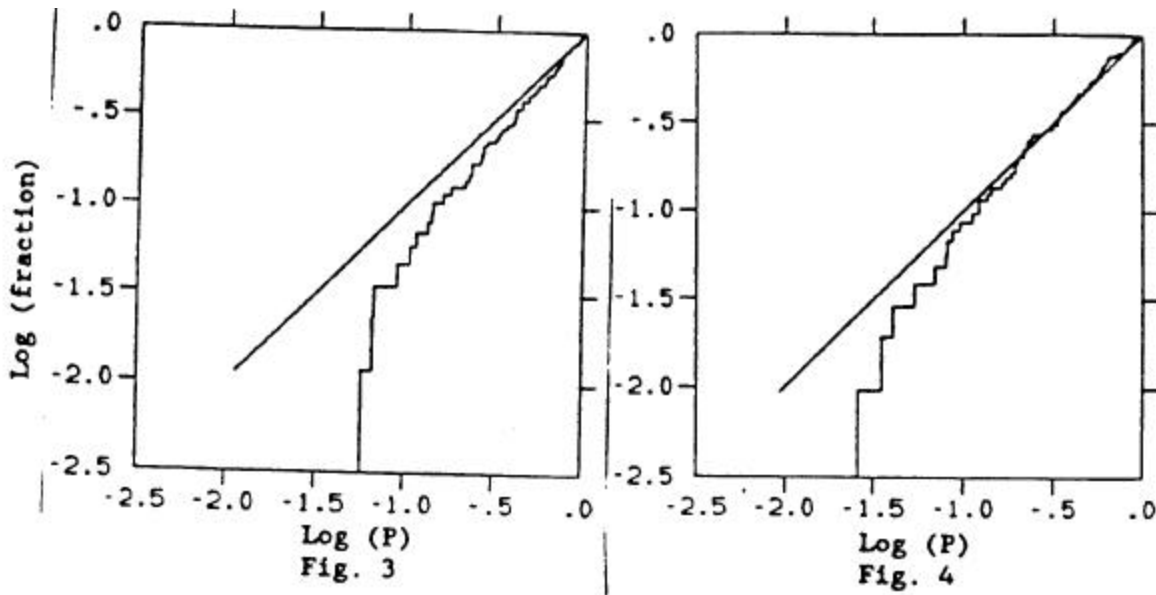
Fig. 2 shows the distribution of probabilities $p(n, a)$ for the 94 nights, the log-log plot emphasizing the low-probability end of the distribution. Plotted versus $\text{Log}(P)$ is $\text{Log}(f)$, where f is the fraction (of 94 nights) for which the Poisson probability is less than P . The diagonal line is the uniform distribution expected in the absence of a source. (It is started at $P = 1/94$ as an indication of where the plot is expected to begin.) Three nights stand out from the others, although probability values that low are to be expected among the 94 trials. Numbers for those nights are tabulated below.



Date (UT)	Number observed	Number expected	Probability
21-Jul-1988	279	245.3	0.0186
16-Aug-1988	252	215.6	0.0083
6-Oct-1988	57	41.0	0.0105

A search for the Her X-1 pulsar periodicity has been performed for each of these three nights. The phase plot has been examined for the x-ray period and for the anomalous period reported at WE and UHE energies (Lamb et al. 1988, Resvanis et al. 1988, Dingus et al. 1988). Rayleigh power has been examined over a broad range of periods surrounding the x-ray period. No statistically significant evidence of pulsar periodicity has been found.

Cyg x-3 results. Exposure to Cyg R-3 occurred during 89 nights. A total of 15,192 showers were observed from that direction with 15,391 expected. That is a 1.66 deficit. The 95% confidence level upper limit on flux from Cyg R-3, calculated as was done for Her X-1, is $5.4 \times 10^{-18}/(\text{cm}^2\text{s})$. The log-log probability distribution in Fig. 3 shows some absence of nights in which the observed number is significantly greater than the expected number.



Crab results. There were 107 nights with exposure to the Crab nebula. Summing the nightly numbers gives 23,428 observed and 23,291 expected, which is a 0.96 excess. The flux upper limit (95% confidence level) is $9.9 \times 10^{-13} / (\text{cm}^2 \text{ s})$. No nightly excess was great enough to produce an anomaly at the low-probability end of the distribution shown in Fig. 4.

Discussion. The results reported here do not help to confirm that these three x-ray sources are UHE $\tilde{\alpha}$ -ray sources. Although an excess has been observed from the Crab, it is not statistically significant. The observed deficit from the Cyg X-3 direction leads to an interesting upper limit on the flux from that source. This upper limit (for a $\tilde{\alpha}$ -ray flux above $7 \times 10^{18} \text{ eV}$) would lie on an integral spectrum of $\tilde{\alpha} E^{-1}$ with $\tilde{\alpha} = 38 \text{ eV}/(\text{cm}^2 \text{ s})$, which is approximately the time-averaged spectrum derived from reported detections.

This is an on-going experiment. More thorough analyses with additional data can be expected in the future.

Acknowledgement. Support has come from NSF grant No. PHY-8720450.

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