Search for \( \gamma \) Rays above 10\(^{14} \) eV from Cygnus X-3 during the June and July 1989 Radio Outbursts

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We have looked for \( \gamma \)-ray emission above 100 TeV from the binary x-ray source Cygnus X-3 during a period of intense radio emission in the summer of 1989. We find no evidence for excess air showers from the direction of the source and the muon content of air showers from this direction is the same as that of ordinary cosmic rays. The flux of \( \gamma \) rays from Cygnus X-3 with energies exceeding 2.1\( \times \)10\(^{14} \) eV is less than \( 5.5 \times 10^{-13} \) cm\(^{-2}\) sec\(^{-1}\) \( (90\% \) C.L.).

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Cygnus X-3 is a powerful radio, infrared, and x-ray source with reported emission of \( \gamma \) rays as high as 5\( \times \)10\(^{13} \) eV.\(^2\) The extrapolated total luminosity is so high that perhaps only a handful of such objects are needed to account for all cosmic rays above 10\(^{16} \) eV.\(^3\)

The radio intensity from this binary system was observed to increase by a factor of more than 100 during the first week of June and again in mid-July 1989,\(^4\) the largest flares since October 1985.\(^5\) Increased production of ultrahigh-energy (UHE, \( E_\gamma > 10^{14} \) eV) \( \gamma \) rays might be expected during such outbursts. Radio-flaring episodes are thought to result after periods of increased mass transfer, perhaps from a nova-like explosive episode as clumps of matter collide with the compact object.\(^5\)

If UHE \( \gamma \) rays result from "beam-dump" interactions of a primary beam (accelerated near the neutron star) with ensheathing or accreting material then it is likely that episodes of enhanced \( \gamma \) emission will be associated with radio flaring.

Many \( \gamma \)-ray observations of Cygnus X-3 above 10\(^{12} \) eV have occurred within days of its peak radio activity.\(^1\) The first reported observation of very-high-energy \( \gamma \) rays took place during a radio outburst in September 1972;\(^6\) the most recent reports were associated with the October 1985 radio flares. These included several observations of \( \gamma \) rays a few days after the radio maximum,\(^1\) enhanced rates of PeV (10\(^{15} \) eV) emission over that month by the Akeno and Haverah Park groups, and detection of PeV \( \gamma \) rays five days after this peak by the Baksan air-shower array.\(^7\)

Muons are copiously produced in hadronic air showers but are relatively rare in \( \gamma \)-ray-induced air showers. Measurements of muons will sensitively discriminate \( \gamma \) rays from the ordinary cosmic-ray background. Some experiments have suggested that the muon content of air showers from the direction of Cygnus X-3 is incompatible with \( \gamma \) rays or any other known neutral primary.\(^8\)

The Utah-Michigan array, located at the site of the Fly's Eye installation at Dugway, Utah (40° N, 112° W, atmospheric depth 870 g/cm\(^2\)), is specifically designed to measure both the electromagnetic and muon components of extensive air showers with energies above 10\(^{14} \) eV. There are 33 surface stations, each with 4 plastic scintillators, arranged over an area of radius 100 m. The muon counters\(^9\) are 2.5-m\(^2\) plastic-scintillator sheets arranged in banks of 64 adjacent counters, buried at a depth of 3 m. The present configuration of 8 banks (512 counters totaling 1280 m\(^2\)) is the largest muon detector of any air-shower array now operating.

Shower calculations indicate that electromagnetic punchthrough to the muon counters is negligible when they are buried to this depth. We have made measurements with a test arrangement of buried counters at two depths to confirm the simulations.

Events are recorded when the surface array is triggered by 7 stations and 15 counters reporting hits within 2 \( \mu \)s. Hit times are digitized for both the surface and buried arrays and the pulse height is recorded for each surface station. The average triggered event recorded 35 muon counter hits and 86 detected electrons. The Universal Time (UT) of the event is recorded (±0.5 ms) from redundant WWVB and GOES satellite receivers.

The location and direction of the shower axis are found by fitting the pulse heights and arrival times of the surface-counter hits. The electron and muon sizes \( N_e \) and \( N_\mu \) are computed from maximum-likelihood fits of surface data by a Nishimura-Kamata-Greisen function\(^10\) and muon-counter hits by a Greisen muon density function.\(^11\)

We define the directional resolution \( \delta \theta \) such that 72% of events from a point source will reconstruct within \( \delta \theta \) of that direction. The resolution is estimated by dividing the array into two parts, fitting each half separately, and comparing the results. For cores within 100 m of the center of the array and \( N_e > 10^4 \), \( \delta \theta = 3^\circ \). The sys-
tematic pointing error is less than 0.3°, determined by
comparison to data obtained by a tracking air-Cherenkov
telescope operated in coincidence with the arrays.

We report here data from the period bracketing the
radio flares from (UT) 17.602 May through 2.470 Au-
gust 1989, during which the array was operative for 65
days. The live time was not continuous as there were occa-
ional periods of detector maintenance. Cygnus X-3
was observable (i.e., within 60° of zenith) for 300 h.
Events with \(3 \times 10^4 < N < 10^6\) are retained for further
analysis.

Events within 3.0° of Cygnus X-3 were admitted as
signal candidates. The expected background is deter-
mined from the data for each run (1 run ≈ 1 day). The
rate of all off-source events in local coordinates is mea-
sured when the source is observable and used to predict
the rate of background cosmic-ray events from the direc-
tion of Cygnus X-3 as it moves across the sky. There is
no evidence in the total data sample for an excess from
the source: A total of 7189 on-source events were
recorded with an expected background of 7215.

The duration of \(\gamma\)-ray emitting episodes is not known,
but previous reports\(^1\) have suggested time scales from 30
min to \(\sim 1\) day. We have searched for rate enhance-
ments in bins of 1 day, 2.4 hr, and 14.4 min. In each
case we compute the significance of the signal in the
presence of the measured background using the prescrip-
tion of Li and Ma.\(^12\) The Gaussian \(\sigma\) is displayed in Fig.
I for intervals of 1 day and 2.4 h.

The frequency of occurrence of excess (and deficient)
rate from the source direction appears to be statistically
distributed. We conclude that there were no observed
episodes of emission on any of the time scales examined.
For possible comparison to other experiments, the most
significant rate enhancements for each time scale are
listed in Table I.

<table>
<thead>
<tr>
<th>Time bin size</th>
<th>Largest excess (1989 UT day)</th>
<th>Observed Bkgd</th>
<th>Significance</th>
<th>Flux (90% C.L.) ((cm^{-2}s^{-1}))</th>
<th>(E_0) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>24 July</td>
<td>137/117</td>
<td>1.8(\sigma)</td>
<td>(&lt; 9.0 \times 10^{-12})</td>
<td>(&gt; 2.1 \times 10^{14})</td>
</tr>
<tr>
<td>2.4 h</td>
<td>31.6 May</td>
<td>9/3.0</td>
<td>2.7(\sigma)</td>
<td>(&lt; 1.6 \times 10^{-11})</td>
<td>(&gt; 7.5 \times 10^{14})</td>
</tr>
<tr>
<td>14.4 min</td>
<td>28.42 May</td>
<td>13/4.9</td>
<td>3.0(\sigma)</td>
<td>(&lt; 9.6 \times 10^{-11})</td>
<td>(&gt; 1.9 \times 10^{14})</td>
</tr>
</tbody>
</table>

FIG. 1. Significance (Ref. 12), \(\sigma\), of the rate of events from Cygnus X-3 when compared to the expected background measured
from off-source data. Upper figure has a bin size of 1 day; lower figure's bins are 2.4 h. Arrows indicate times of peak radio intensi-
ty (Ref. 4).
We find no evidence of anomalous muon content in the on-source data when compared to off-source showers. Calculations predict 98% of γ-ray-induced showers will have less than one-tenth the mean number of muons of hadron showers with similar size (i.e., < −1.0 in the figure; see text). Dashed histogram: events from within 3° of Cygnus X-3; solid histogram: combined off-source events from two regions with same declination as Cygnus X-3 but right ascensions offset by ±6°. Total off-source solid angle accepted here is twice that of the on-source region.

We can compute limits on the γ-ray flux from Cygnus X-3, assuming we have seen no signal. We estimate our triggering efficiency by measuring departures from an assumed power-law \( dN/dN_\gamma \) spectrum. \( N_\gamma \) is converted to primary γ-ray energy \( E_\gamma \) using simulation results for the mean and dispersion in size. The array acceptance is computed for the observed distribution of zenith angles as the source moves across the sky during our live observations of Cygnus X-3. Assuming we have seen no signal, we compute limits on the integral flux of γ rays from the source near the zenith and energies above 2.1 \( \times 10^{14} \) eV.

We have searched the combined data set for periodicity at or near the 4.79-h cycle observed in x rays, presumed to be the orbital period of the binary system. The significance of departures from random arrival times in the on-source data when compared to background was assessed using the Rayleigh statistic. We find no evidence for periodicities in the range 4.6 to 5.0 h.

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Table II gives the average integral flux limits obtained both with and without the \( \mu \)-poor criterion for the various time intervals examined. Limits for the shorter time intervals were computed for the source near the zenith and energies above 2.1 \( \times 10^{14} \) eV.

<table>
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<th>Time bin size</th>
<th>Flux (90% C.L.) (( \text{cm}^{-2} \text{s}^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>(&lt; 4.2 \times 10^{-12})</td>
</tr>
<tr>
<td>2.4 h</td>
<td>(&lt; 4.3 \times 10^{-12})</td>
</tr>
<tr>
<td>14.4 min</td>
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We find no evidence of anomalous energy content in the on-source data when compared to off-source showers. Calculations predict 98% of γ-ray-induced showers will have less than one-tenth the mean number of muons of hadron showers with similar size (i.e., < −1.0 in the figure; see text). Dashed histogram: events from within 3° of Cygnus X-3; solid histogram: combined off-source events from two regions with same declination as Cygnus X-3 but right ascensions offset by ±6°. Total off-source solid angle accepted here is twice that of the on-source region.

The energy threshold is defined here as the energy at which our acceptance for γ showers reaches 25% of its maximum. Integral flux limits (90% C.L.) are obtained in the usual way, assuming the background and signal obey Poisson statistics. Table I gives the flux limits obtained for the particular intervals listed. Note that the rate and threshold energy of the array have a strong zenith-angle dependence. Table II gives the average integral flux limits obtained both with and without the \( \mu \)-poor criterion for the various time intervals examined. Limits for the shorter time intervals were computed for the source near the zenith and energies above 2.1 \( \times 10^{14} \) eV.

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K. J. Johnston (private communication); E. B. Walton, R. L. Fiedler, and K. J. Johnston, International Astronomical Union Circulars No. 4798 and No. 4817 (1989); K. J. Johnston, Mostra d'Oltremare, Padova 20, 80125 Napoli, Italy.

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![Table II. Mean γ-ray integral flux limits for searches on three time scales. The acceptance for intervals shorter than 1 day are computed for data near the zenith; all limits here are for \( E_\gamma > 2.1 \times 10^{14} \) eV. Shown are limits obtained for all the data and for showers selected as \( \mu \)-poor (having less than one-tenth the expected number of muons).](image-url)


