Search for γ 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 γ-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 γ rays from Cygnus X-3 with energies exceeding 2.1×10^{14} eV is $<5.5\times10^{-13}$ $\mathrm{cm}^{-1}\mathrm{sec}^{-1}$ (90% C.L.).

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Cygnus X-3 is a powerful radio, infrared, and x-ray source with reported emission of γ rays as high as 5×10^{17} eV.[1,2] 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. Increased production of ultrahigh-energy (UHE, $E_\gamma > 10^{14}$ eV) γ rays might be expected during such outbursts. Radio-flaring episodes are thought to result after periods of increased mass transfer, perhaps from novalike explosive episodes as clumps of matter collide with the compact object.[5] If UHE γ rays result from "beam-dump" interactions of a primary beam (accelerated near the neutron star) with enshrouding or accreting material then it is likely that episodes of enhanced γ emission will be associated with radio flaring.

Many γ-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 γ 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 TeV γ 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 γ 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 γ-ray-induced air showers. Measurements of muons will sensitively discriminate γ 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 γ rays or any other known neutral primary.[1,8]

The Utah-Michigan array, located at the site of the Fly's Eye installation at Dugway, Utah (40° N, 112° W, atmospheric depth 870 $\mathrm{g/cm^2}$), 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 μs. 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_μ 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 $N_e > 10^4$, $\delta\theta = 3°$. The sys-

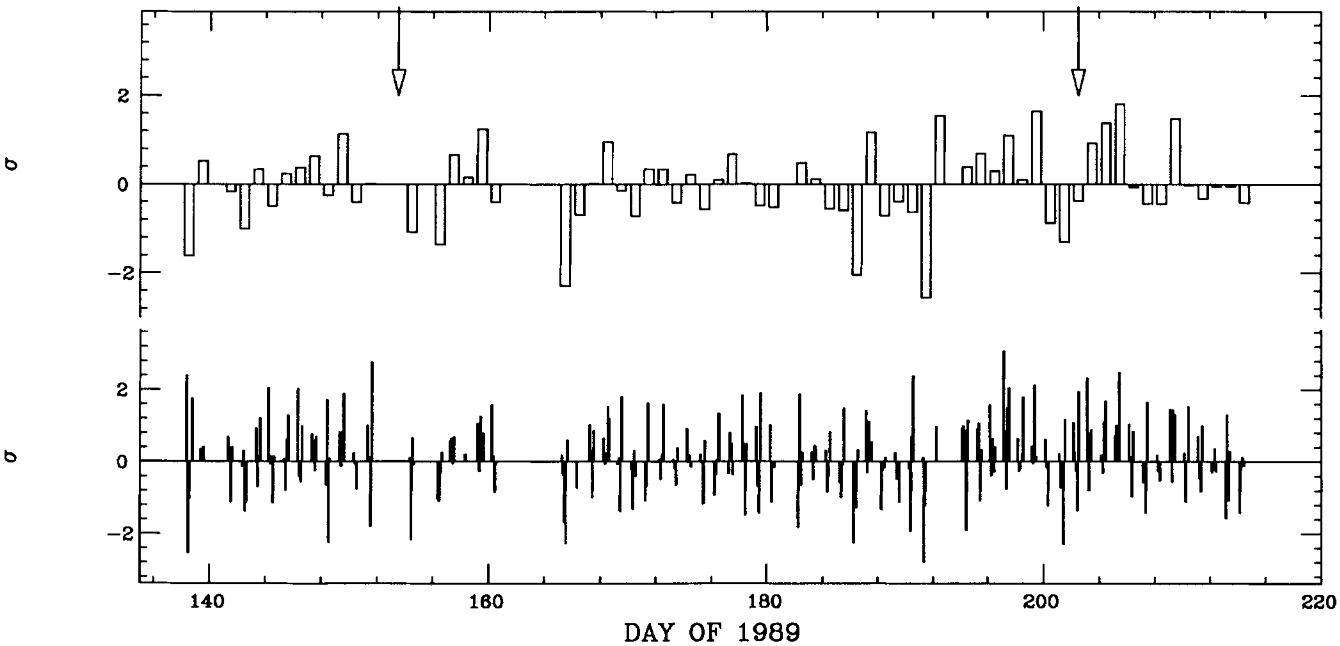

FIG. 1. Significance (Ref. 12), σ, of the rate of events from Cygnus X-3 when compared to the expected background measured from off-source data. Upper figure has a bin size of 1 day; lower figure's bins are 2.4 h. Arrows indicate times of peak radio intensity (Ref. 4).

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 August 1989, during which the array was operative for 65 days. The live time was not continuous as there were occasional periods of detector maintenance. Cygnus X-3 was observable (i.e., within 60° of zenith) for 300 h. Events with $3\times10^4 < N_e < 10^6$ are retained for further analysis.

Events within 3.0° of Cygnus X-3 were admitted as signal candidates. The expected background is determined from the data for each run (1 run $\approx$ 1 day). The rate of all off-source events in local coordinates is measured when the source is observable and used to predict the rate of background cosmic-ray events from the direction 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 γ-ray emitting episodes is not known, but previous reports[1] have suggested time scales from 30 min to ~1 day. We have searched for rate enhancements 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 prescription of Li and Ma.[12] The Gaussian σ is displayed in Fig. 1 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 I. Most significant episodes of excess events from Cygnus X-3 for three time scales. Column 3 shows observed events (those within 3° of Cygnus X-3) compared to expected background. The significance is expressed as a Gaussian σ, according to Ref. 12. The calculated backgrounds, energy thresholds, and integral flux limits depend strongly on the zenith angle of the source during the particular time interval (see text).

Time bin size	Largest excess (1989 UT day)	Observed Bkgd	Significance	Flux (90% C.L.) ($cm^{-2}s^{-1}$)	E_0 (eV)
1 day	24 July	137/117	1.8σ	$<9.0\times10^{-12}$	$>2.1\times10^{14}$
2.4 h	31.6 May	9/3.0	2.7σ	$<1.6\times10^{-11}$	$>7.5\times10^{14}$
14.4 min	28.42 May	13/4.9	3.0σ	$<9.6\times10^{-11}$	$>1.9\times10^{14}$

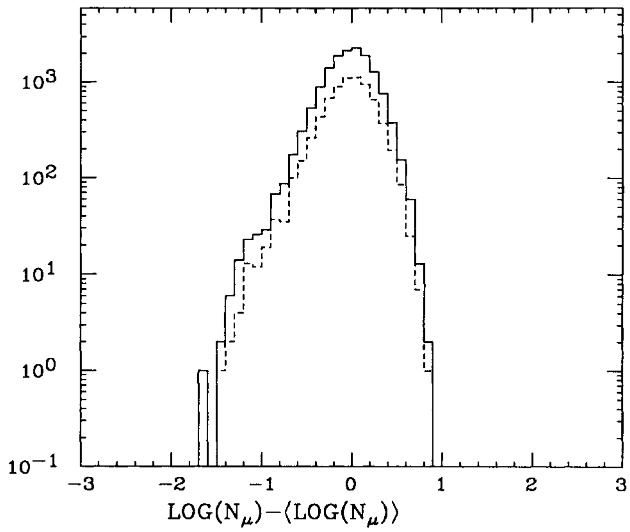

FIG. 2. Distribution of the relative muon content of showers, corrected for zenith angle and N_e. γ showers should have less than one-tenth the expected mean number for hadron showers of similar size (i.e., < -1.0 in the figure; see text). Dashed histogram: events from within 3° of Cygnus X-3; solid histogram: combined off-source events from two regions with same declination as Cygnus X-3 but right ascensions offset by $\pm 6°$. Total off-source solid angle accepted here is twice that of the on-source region.

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 N_e and zenith angle. Of the 7189 on-source events, only 40 satisfy this "muon-poor" criterion and appear to be distributed randomly in time. Figure 2 shows the relative muon sizes for showers from the direction of Cygnus X-3 and for off-source showers.

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_e spectrum. N_e is converted to primary γ-ray energy E_γ 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 periods. Our acceptance depends weakly on the spectral index of γ rays from the source. We have used $dN/dE_\gamma \propto f(E_\gamma)E_\gamma^{-2}$ based on fits of previous, lower-energy observations of Cygnus X-3.[1] The factor $f(E_\gamma)$ accounts for depletion of the γ-ray beam by absorption on the 3-K microwave background over the 10-kpc distance to the source.

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,[13] assuming the background and signal obey Poisson statistics. Table I shows 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 indicates the average integral flux limits obtained both with and without the μ-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 2.1×10^{14} eV.

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 $E_\gamma > 2.1\times10^{14}$ eV. Shown are limits obtained for all the data and for showers selected as μ poor (having less than one-tenth the expected number of muons).

Time bin size	Flux (90% C.L.) ($cm^{-2}s^{-1}$) all	μ poor
1 day	$<4.2\times10^{-12}$	$<5.5\times10^{-13}$
2.4 h	$<4.3\times10^{-12}$	$<1.1\times10^{-12}$
14.4 min	$<2.0\times10^{-11}$	$<9.3\times10^{-12}$

We have searched the combined data set for periodicity at or near the 4.79-h cycle observed[1] 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.[14] We find no evidence for periodicities in the range 4.6 to 5.0 h.

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[1]For reviews, see W. Hermsen *et al.*, Astron. Astrophys. **175**, 141 (1987); R. J. Protheroe, in *Proceedings of the Twentieth International Cosmic Ray Conference, Moscow, 1987,* edited by V. A. Kozyarivsky *et al.* (Nauka, Moscow, 1987), Vol. 8, p. 21.

[2]G. L. Cassiday *et al.*, Phys. Rev. Lett. **62**, 383 (1989).

[3]A. M. Hillas, Nature (London) **312**, 50 (1984).

[4]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, E. B. Walton, R. L. Fiedler, and J. H. Spencer (to be published).

[5]E. R. Seaquist, Astrophys. J. **207**, 88 (1976); W. T. Vestrand, Astrophys. J. **271**, 304 (1983).

[6]B. M. Vladimirsky *et al.*, in *Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, California, 1985*, edited by F. C. Jones, J. Adams, and G. M. Mason (U.S. GPO, Washington, DC, 1985), Vol. 1, p. 456.

[7]V. V. Alekseenko *et al.*, in *Proceedings of the Twentieth International Cosmic Ray Conference, Moscow, 1987*, edited by V. A. Kozyarivsky *et al.* (Nauka, Moscow, 1987), Vol. 1, p. 229; V. S. Berezinsky, Nature (London) **334**, 506 (1988).

[8]M. Samorski and W. Stamm, in *Proceedings of the Eighteenth International Cosmic Ray Conference, Bangalore, India, 1983*, edited by N. Durgaprasad *et al.* (Tata Institute of Fundamental Research, Bombay, 1983), Vol. 11, p. 244; M. Drees and F. Halzen, Phys. Rev. Lett. **61**, 275 (1988).

[9]D. Sinclair, Nucl. Instrum. Methods Phys. Res., Sect. A **278**, 583 (1989).

[10]K. Greisen, Prog. Cosmic Ray Phys. **3**, 1 (1956); E. J. Fenyves *et al.*, Phys. Rev. D **37**, 649 (1988).

[11]K. Greisen, Annu. Rev. Nucl. Sci. **10**, 63 (1960).

[12]T. P. Li and Y. Q. Ma, Astrophys. J. **272**, 317 (1983).

[13]O. Helene, Nucl. Instrum. Methods Phys. Res. **A212**, 319 (1983); Particle Data Group, R. Gatto *et al.*, Phys. Lett. B **204**, 81 (1988).

[14]K. V. Mardia, *Statistics of Directional Data* (Academic, London, 1972), p. 133ff.