Time Distributions for Underground Muons from the Direction of Cygnus X-3

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Analysis of underground muon events from the direction of Cygnus X-3 shows evidence for large time variability of the flux in addition to the 4.8-h modulation. Our data support earlier suggestions that high fluxes occur with a 34.1-d cycle. Events measured during high-rate periods show increased statistical support for the hypothesis linking underground muons with this x-ray binary.

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We have recently reported evidence[1] from the Soudan-1 detector[2] for underground muons apparently correlated with the x-ray binary Cygnus X-3. The measured, time-averaged flux was $\sim 7\times 10^{-11}$ cm^{-2} s^{-1} at a depth of 1800 m water equivalent. A similar observation has also been reported in data from the NUSEX (nucleon-stability experiment) detector under Mt. Blanc.[3] These muon signals, if confirmed, may indicate either that high-energy photons or neutrinos have previously unknown interactions which produce muons with a high probability or that a new type of stable neutral particle is emitted by Cygnus X-3.

In this paper, we extend our analysis of the underground-muon data presented in Ref. 1. We show that these data imply that the muon flux from Cygnus X-3 has a longer-term variability, in addition to the 4.8-h orbital period. This longer-term modulation provides additional evidence for the existence of a source. Knowledge about all time variations is important for flux comparisons with surface detectors. Such comparisons are needed to test proposed mechanisms for the production of underground muons by radiation from Cygnus X-3.

The ability of a detector to separate the signal of an x-ray binary from a random background is considerably enhanced by the source periodicity. For Cygnus X-3, both the 4.8-h period and the absolute phase are accurately known from kiloelectronvolt x-ray data.[4] The flux modulation (pulsed emission) of Cygnus X-3 at high energies according to the same ephemeris has been observed in air showers.[5] Arrival times for air showers with primary energy ~ 1 TeV have been observed to cluster about two particular phases: 0.60 to 0.73, which dominates at teraelectronvolt energies, and 0.25, which is more common at higher energies. It is not clear what relation, if any, may exist between these air-shower data and observations of underground muons.

Our data sample contains 784 000 muon events with at least eight proportional-tube hits in each of two orthogonal views. This 0.96-yr live-time sample is the same one discussed in Ref. 1. For 1183 events, the direction of arrival points within 3° of the nominal direction (declination $\delta = 40.8°$, right ascension $\alpha = 307.6°$) of Cygnus X-3. Using the ephemeris of Ref. 4 [$t_0 =$ JD2 440 949.8986 (JD denotes Julian day), $p_0 = 0.199\,6830$ d, $\dot{p} = 1.18\times 10^{-9}$], we calculate the Cygnus X-3 phase for each of these events. These phases can be histogrammed to produce the plot in Fig. 1(a). The peak between phases of 0.65 and 0.90 contains 60 ± 17 events, with use of a background level determined from off-source directions. The phase plot in Fig. 1(a) differs slightly from a similar plot in Ref. 1 because here we have selected the nominal direction of Cygnus X-3 rather than one about 2° off nominal, which yields about a 30% higher signal.

We have used several alternative methods[6] to estimate the statistical probability that Fig. 1(a) represents a random fluctuation of a uniform background. Reference 1 relied principally on a χ^2 analysis. More specific tests for the presence of a Cygnus X-3 signal include a peak-over-background analysis, a Fourier-coefficient analysis, and a first- and second-moment analysis.[7] In the case of the moment (or generalized Rayleigh) analysis, a particularly powerful constraint can be imposed by use of projections of the moments in directions specified by previous high-energy data on Cygnus X-3 (such as the 0.65-phase-peak direction). This method, which may be affected by systematic uncertainties concerning the relationship between air-shower and underground-muon data, yields the phase-constrained probabilities discussed below. We have made empirical checks on the validity of these methods using both data from regions of the sky away from Cygnus X-3 and Monte Carlo–generated, simulated data samples.

For Fig. 1(a), the results of our statistical analyses can be summarized as follows: A peak-over-

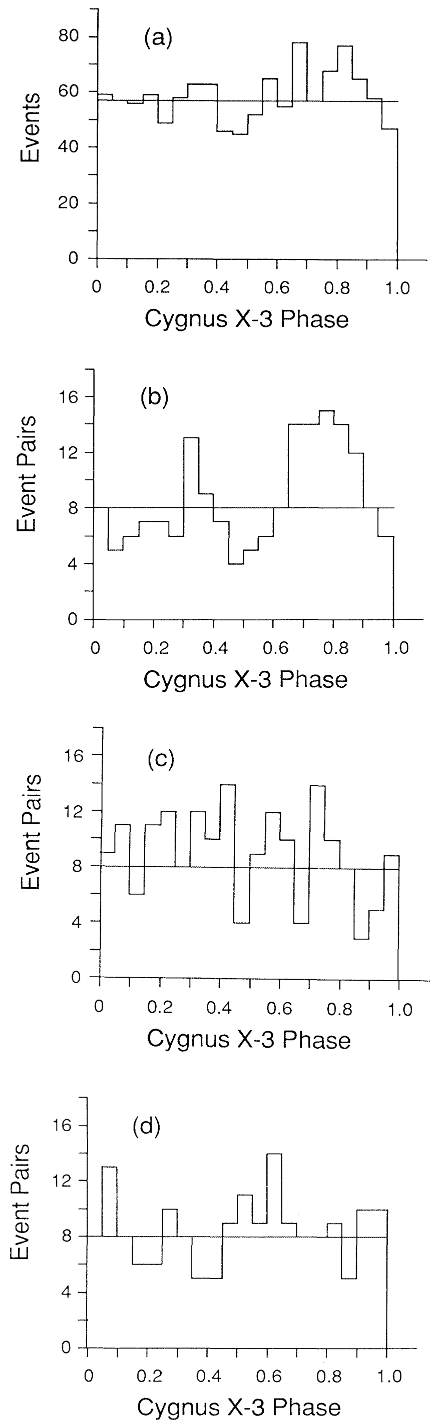

FIG. 1. (a) Cygnus X-3 phase plot for all muon events arriving within 3° of the nominal direction of Cygnus X-3. (b) The same plot showing only the mean phase for pairs of events arriving within 0.5 h. (c),(d) Similar pairs-of-events phase plots for events within a 3° half-angle cone centered at $\alpha = 297.6°$ and 317.6°, and the same declination as Cygnus X-3. The horizontal line represents the estimated background from a random source.

background analysis using the (60 ± 17)-event effect noted above (i.e., 3.5σ) yields a probability of $\sim 2\times 10^{-4}$ of it being a random background fluctuation. If the background is determined from all events in Fig. 1(a) (including the peak), the signal is ten events smaller, and the corresponding probability is $\sim 4\times 10^{-3}$. These probabilities would increase by about an order of magnitude if a phase peak at any location were accepted. A moment analysis which uses neither *a priori* expectations nor off-source background information gives a random fluctuation probability of ~ 0.02. Constraining the flux to be large near a phase of 0.65 and small near phases of 0.0 and 0.5, as might be expected from the air-shower data for radiation from Cygnus X-3, reduces this probability by a factor of 10 to 20.

The air Cherenkov data indicate that Cygnus X-3 is not a constant source.[8] Such episodic behavior suggests that the signal-to-background ratio in Fig. 1(a) may be enhanced by plotting the phases of pairs of events which occur within a short period of time, i.e., those events associated with high-rate periods. Figure 1(b) shows such a plot where the mean phase is plotted for each pair of consecutive events which occur within 0.5 h of each other. The signal in this plot for phases between 0.65 and 0.90 includes 29 ± 6 event pairs above background. The background for these estimates has been derived from Figs. 1(c) and 1(d), which show a similar plot for nearby off-source directions (but at the same declination to keep the counting rate constant). The results of a background-independent moment analysis of Fig. 1(b) indicate an unconstrained probability of a random fluctuation generating the plot as $\sim 3\times 10^{-4}$. The constrained probability using expectations concerning the absolute phase dependence of Cygnus X-3 high-energy emission is again 10 to 20 times smaller.

The larger signal-to-background ratio in Fig. 1(b) compared to that in Fig. 1(a) shows that much of the excess flux in the phase region of 0.65 to 0.90 occurs in bursts of two or more events occurring close together in time. Table I contains further information on this question. Listed there are the number of Cygnus X-3 cycles observed with n muons in a 1.2-h ($\frac{1}{4}$ cycle) period. Data are shown on and off the phase peak for both on- and off-source directions.

We have fitted the off-source (background) data in Table I with a Monte Carlo model, which uses a detection efficiency varying as $\cos^3\theta_z$, where θ_z is the local zenith angle. This zenith-angle dependence approximates the attenuation observed for single-muon events due to the higher muon threshold energy required when Cygnus X-3 is not directly overhead. The model fits the background data well. The value of χ^2 for each of the background distributions is shown in the table. The fits are likely, except for the signal re-

TABLE I. Number of Cygnus X-3 cycles in which n muons are observed in 1.2 h from within 3° of $\delta = 40.8°$ and α as specified.

Direction	Phase	n = 1	2	3	4	χ^2
On-source	0.15–0.40	206	38	2	1	2.5
	0.40–0.65	198	28	3	0	2.3
	0.65–0.90	218	49	7	2	13.6
	0.90–0.15	222	23	3	0	7.4
$\alpha = 297.6°$	0.15–0.40	203	45	5	1	3.8
	0.40–0.65	202	33	5	1	0.6
	0.65–0.90	218	36	5	1	2.3
	0.90–0.15	203	38	1	0	3.7
$\alpha = 317.6°$	0.15–0.40	166	29	6	0	7.4
	0.40–0.65	198	36	5	0	0.6
	0.65–0.90	207	32	7	1	2.2
	0.90–0.15	199	34	4	0	0.6
Fit in text		199.5	34.5	4.6	0.5	

gion, which has a χ^2 probability of ~ 0.01.

Our data do not uniquely determine the functional form of the source modulation. To investigate this time dependence further, we have chosen a simple model where, in addition to the background, a source may be "on" during the quarter period with phase between 0.65 and 0.90. This signal is turned on only for a certain percentage of the Cygnus X-3 4.8-h cycles. The signal events are also modulated by the zenith-angle dependence described earlier. The data in Table I are fitted well with an on fraction of 0.07 ± 0.04 of the active-phase quarters, a (source-overhead) signal rate when on of 1.3 ± 0.7 muons/h during the active quarter period, and a (source-overhead) background rate described above of 0.43 ± 0.03 muons/h.

From the $\sim 8\text{-m}^2$ area of the Soudan-1 detector and the 0.96-yr live time, we can use the above model to estimate the following fluxes of muons from Cygnus X-3 with energy $\gtrsim 650$ GeV [the flux values for (c)–(e) are for the directly overhead geometry]: (a) average detected flux for the entire observation period, $\sim 2.5 \times 10^{-11}$ cm^{-2} s^{-1} (i.e., 60 events during 0.96 yr); (b) same as (a) if Cygnus X-3 were always directly overhead (with the assumption of $\cos^3\theta_z$ dependence), $\sim 7.3 \times 10^{-11}$ cm^{-2} s^{-1}; (c) average flux during all potentially active times with phase between 0.65 and 0.90, $\sim 2.9 \times 10^{-10}$ cm^{-2} s^{-1}; (d) flux during on times with phase between 0.65 and 0.90, with 7% of the cycles on, $\sim 4.2 \times 10^{-9}$ cm^{-2} s^{-1}; (e) flux averaged over the entire 4.8-h period during 7% of the time that source is on, $\sim 1.0 \times 10^{-9}$ cm^{-2} s^{-1}. The uncertainty in these fluxes is estimated as $^{+50}_{-25}$%.

These fluxes may be compared with fluxes attributed to Cygnus X-3 by air Cherenkov experiments at similar energies. Reference 8 reports a peak pulsed flux (measured over about 0.5 h) of $(5.1 \pm 1.1) \times 10^{-10}$ cm^{-2} s^{-1} for a threshold energy of 800 ± 400 GeV. That experiment observed no significant signal a month later, indicating that this flux corresponded to a time when the source was on. Lamb *et al.*[9] report a flux averaged over the 4.8-h cycle of $\sim 8 \times 10^{-11}$ cm^{-2} s^{-1} at a threshold energy of 500 GeV. Our muon fluxes are apparently larger than the fluxes reported from air Cherenkov measurements at similar energies. However, deduction of a primary flux from the secondary muon flux requires a knowledge of the number of muons per primary which reach the Soudan-1 depth. Because this quantity is not known, a direct flux comparison is not possible.

Our results imply that other detectors should also observe a modulation in addition to the 4.8-h period in the Cygnus X-3 flux. In particular, the times at which we observed three or four muons in the 1.2-h phase peak during one Cygnus X-3 cycle are (Universal Time) 29.82 December 1981, 30.78 January 1982, 4.39 June 1982, 19.98 October 1982, 27.94 October 1982, 23.87 December 1982, 3.86 January 1983, 17.50 April 1983, and 19.46 May 1983.

X-ray observations have suggested[10] a 34.1-d period for the flux variation of Cygnus X-3. Figure 2 shows a 34.1-d phase plot for the nine times listed above with use of an arbitrary t_0 (which differs from the one in Ref. 10) of 18.04 January 1981. A Rayleigh analysis indicates a probability of about 1% that this plot is consistent with a random fluctuation of a uniform background. The plot additionally shows the phases of air-shower bursts observed[11] on 20 January and 21 November 1981 and radio outbursts observed[12] on 27 September 1982 and 1 and 8 October 1983.

We conclude that the result which we reported earlier,[1] indicating an underground-muon flux related to Cygnus X-3, is unlikely to be the result of a statistical fluctuation. The data indicate that Cygnus X-3 is an episodic source, as has been previously reported from

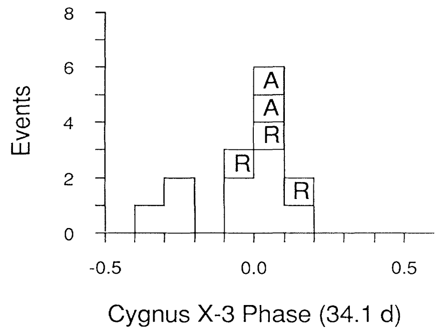

FIG. 2. 34.1-d-period phase plot for high-rate periods as defined in the text using the ephemeris given in the text. The symbol A indicates air-shower bursts described in Ref. 11. The symbol R indicates radio outbursts described in Ref. 12.

air Cherenkov measurements. Our observations support a 34.1-d variation in the flux. This result can be checked by other experiments with accumulated data. The apparent correlation in Fig. 2 of underground-muon flux maxima with peaks in radio and air-shower activity from Cygnus X-3 further supports the identification of muons with this particular source. This long-term episodic behavior is similar in some respects to observations that we have previously reported on multimuon events in a nearby direction,[13] although we have found no direct connection between the two phenomena.

The data reported here do nothing to resolve the dilemma of the nature of the primary particles discussed in our earlier report. The muon flux variations reported here increase the discrepancy between our results and the muon flux which would be expected from inelastic photoproduction in showers originated by photons from Cygnus X-3.

We note that observations of underground muons associated with Cygnus X-3 have also been reported by Battistoni *et al.*[3] Although the substance of their effect seems similar to the one described here, the data differ in several important respects, notably absolute flux, signal-to-background ratio, width of the phase peak, and angular width of the signal. Some of these differences may derive from the order-of-magnitude difference in minimum muon energy for the two experiments; others seem more difficult to explain. The data here also differ somewhat from air-shower measurements in the width and absolute position of the phase peak.

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