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EVIDENCE FROM THE SOUDAN 1 EXPERIMENT FOR UNDERGROUND MUONS ASSOCIATED WITH CYGNUS X-3

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ABSTRACT

The Soudan 1 experiment has yielded evidence for an average underground muon flux of $\sim 7 \times 10^{-11}$ cm^{-2} s^{-1} which points back to the x-ray binary Cygnus X-3, and which exhibits the 4.8 h periodicity observed for other radiation from this source. Underground muon events which seem to be associated with Cygnus X-3 also show evidence for longer time variability of the flux. Such underground muons cannot be explained by conventional models of the propagation and interaction of cosmic rays.

1. Introduction. At the 1983 ICRC, the Kiel group[1] reported that extensive air showers associated with Cygnus X-3 had muon contents approximately equal to those of most other extensive air showers. At the same meeting, the Soudan group[2] showed evidence that multimuon events observed deep underground were anisotropic. One particularly active direction was centered about 20° from the x-ray binary Cygnus X-3.

In this paper, I summarize the analysis of the single-muon data[3,4] obtained from the Soudan 1 experiment during the same two-year exposure as the the multiple-muon data presented in Ref. 2. These data indicate that the muon flux from the direction of Cygnus X-3 exhibits the 4.8 h "orbital" period[5] characteristic of that source. The magnitude of the muon flux associated with Cygnus X-3 is similar to the reported flux of cosmic-ray air showers from Cygnus X-3.[1,6,7] Finally, the data suggest a longer term variability in the muon flux, in addition to the 4.8 h period. Knowledge about all levels of time variation is important for flux comparisons with surface detectors.

The reports of the Kiel,[1] Soudan,[2-4] and NUSEX[8] groups that a large muon flux is associated with Cygnus X-3 have been challenged[9] as being inconsistent with current understanding of the propagation and interaction of primary cosmic radiation. By flux arguments, the maximum primary energy that can be observed by an 8 m^2 detector like Soudan 1 in one year is $\sim 10^{16}$ eV. The primary energy associated with any statistically significant effect must be at least an order of magnitude lower. Because of the galactic magnetic fields, charged particles at energies of 10^{15} eV cannot travel more than about 1 pc without being homogenized in time and direction. Thus, any radiation associated with a source like Cygnus X-3, which is at least 10 kpc from the earth,[10] must be uncharged.

Known neutral primaries, however, cannot account for underground muon production related to Cygnus X-3. Neutrons can produce muons, but at the relevant energies, neutrons from Cygnus X-3 will decay before reaching the earth. Neutrinos also produce muons, but they interact at such a low rate that enormous fluxes would be required. Photons are very

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inefficient producers of muons, because the inelastic photoproduction cross section is about 1/300 of the pair-production cross section. A secondary muon flux similar to that produced by hadron primaries is not consistent with known photon shower mechanisms.

2. The Underground Muon Data. The Soudan 1 proton-decay detector is described in detail in Ref. 11. The detector consists of an array of 3456 proportional tubes, each 2.8 cm in diameter, arranged in 48 layers of 72 tubes each. Alternate layers are rotated by 90° to provide two orthogonal views of each event. Figure 1 shows a typical cosmic-ray muon track in the detector. The experiment is located in the Soudan iron mine in northeastern Minnesota (48° N. latitude, 92° W. longitude) at a depth equivalent to 1800 m of water.

The current data sample consists of 784,456 single muon events recorded during a live time of 0.96 yr, between September 1981 and November 1983, and is the same one discussed in Refs. 3 and 4. Each event was required to consist of a single straight track, and to have a minimum of eight proportional-tube hits in each view. The most probable number of proportional-tube hits per view was sixteen, which yields an average angular resolution of ± 25 mrad. We estimate a ± 25-mrad uncertainty in the absolute orientation of the detector in the horizontal plane. We identify the observed tracks as muons both because of their depth underground and because of their passage through the detector in a straight line without substantial interaction. Tracks satisfying a 16-hit minimum (summing both views) penetrate at least 115 g cm^{-2} of material within the detector.

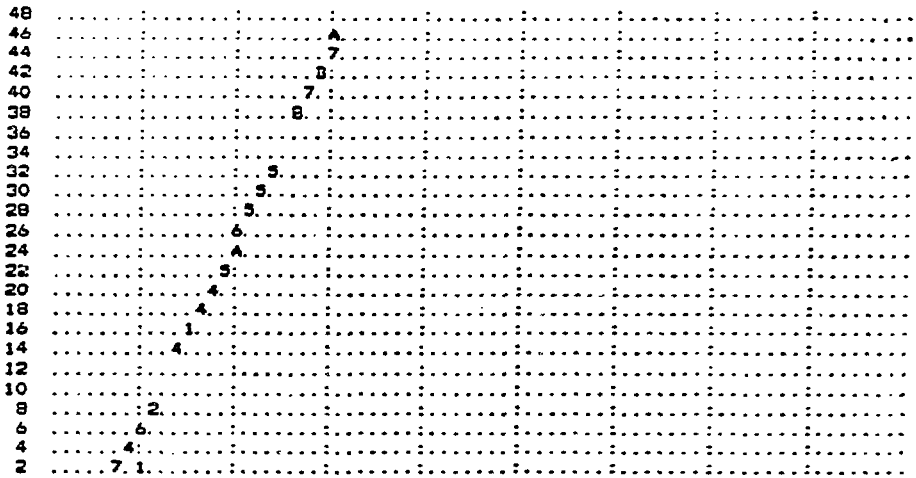

Fig. 1. One of two orthogonal views of a single-muon event in the Soudan 1 detector. Numbers and letters indicate observed pulse height, and dots show the positions of proportional tubes with no signals.

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 keV x-ray data.[5] The flux modulation of Cygnus X-3 at high energies according to the same ephemeris has been observed in air showers.[7] The peak flux of TeV air showers, which may or may not produce the $\gtrsim$ 650 GeV muons that we detect, has been observed[6] since 1980 at phases in the range 0.60 to 0.73.

Using the angular resolution of the detector described above, we have selected those events whose 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 exact ephemeris of Ref. 5 (t_o = JD2440949.8986, p_o = 0.1996830 d, $\dot{p} = 1.18 \times 10^{-9}$), we calculate the Cygnus X-3 phase for each of these 1183 events. These phases are histogrammed in Fig. 2(a). The peak between phases of 0.65 and 0.90 contains 60 $\pm$ 17 events, using a background level determined from off-source directions. Figures 2(b) and 2(c) show the background distributions from nearby off-source directions, chosen at the same declination as Cygnus X-3 in order to have the same counting rate.

We have traced the dependence of the events-minus-background value for the phase plot as a function of right ascension and declination, as shown in Fig. 3. Since each point has been calculated by the use of all events within a 3° half-angle cone, nearby points are not statistically independent. The most probable right ascension is within our pointing accuracy of the nominal position of Cygnus X-3. The preferred declination is about 2.7° north of Cygnus X-3's nominal position. This discrepancy is slightly larger than our estimated pointing error, and its origin is unclear. The phase plot in Fig. 2(a) differs slightly from the similar plot in Ref. 3 because here we have selected the nominal direction of Cygnus X-3 rather than the one 2.7° from the nominal, which yields about a 30 percent higher signal.

Within statistics, the ratio of intensity within the phase peak to intensity outside the phase peak does not vary as a function of zenith angle. Thus, the local zenith-angle distribution of the events in the phase peak is similar to that of ordinary muons from hadronic interactions in the atmosphere. In particular, we can completely reject the hypothesis of an isotropic zenith-angle distribution, as would be expected if the signal muons were produced by neutrino primaries. This result is illustrated in Fig. 4, which shows the phase plot for events within the 3° half-angle cone which $\Theta_z > 66°$ ($\cos\Theta_z < 0.4$). Our measured flux at small slant depths predicts a signal of 18 events in the 0.65 - 0.90 phase bin if the muons are produced by neutrinos interacting in the earth, to be compared with zero events shown in Fig. 4.

3. Statistical Analysis. We have used several alternate methods[4] to estimate the statistical probability that Fig. 2(a) represents a random fluctuation of a uniform background. Ref. 3 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.[4] In the case of the moment (or generalized Rayleigh) analysis, a particularly powerful

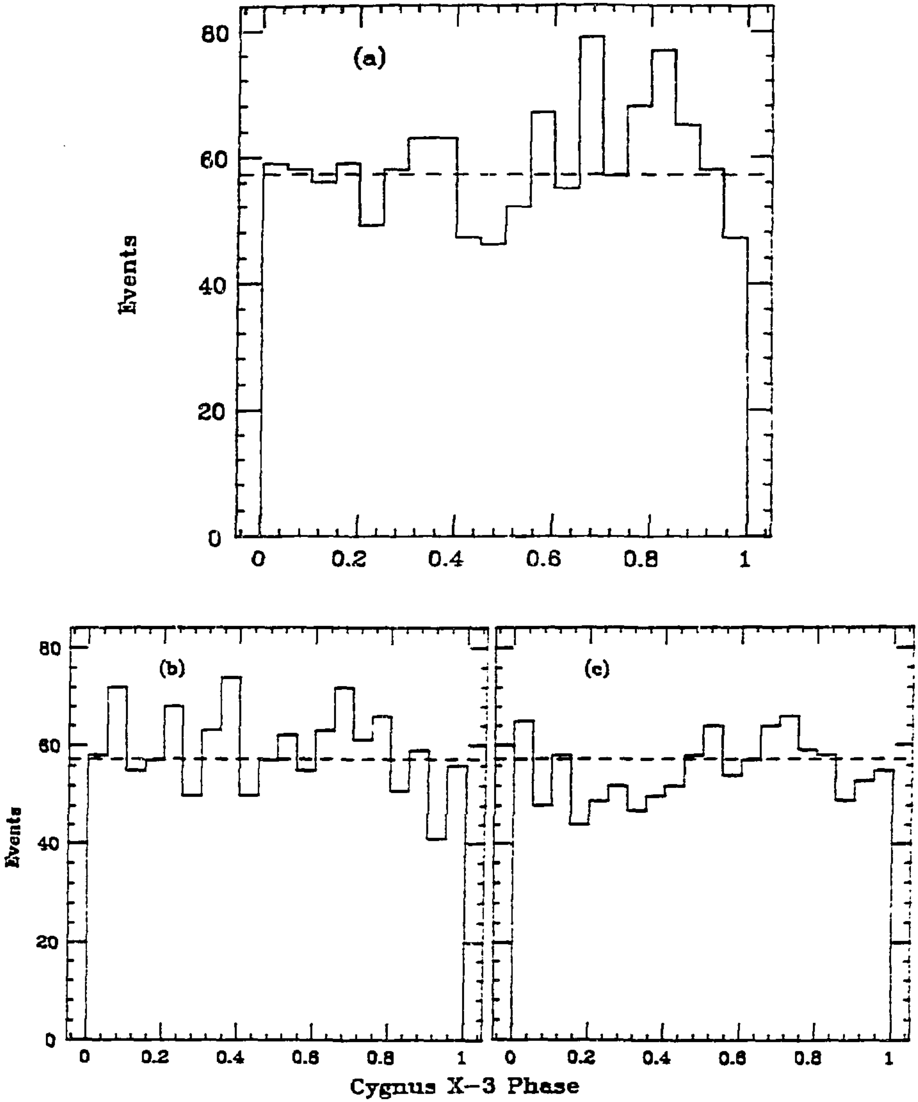

Fig. 2. (a) Cygnus X-3 phase plot for events within 3° of the nominal direction of Cygnus X-3. (b) and (c) Similar phase plots for events within a 3° half-angle cone centered at $\alpha = 297.6°$ and $\alpha = 317.6°$, respectively, and the same declination as Cygnus X-3. The dashed line shows the estimated background from a random source.

constraint can be imposed by using 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 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 data samples.*

For Fig. 2(a), the results of our statistical analyses can be summarized as follows: A peak-over-background analysis using the 60 ± 17 event effect noted above (3.5 σ) yields a probability of ~ 2×10^{-4} of it being a random background fluctuation. If the background is determined

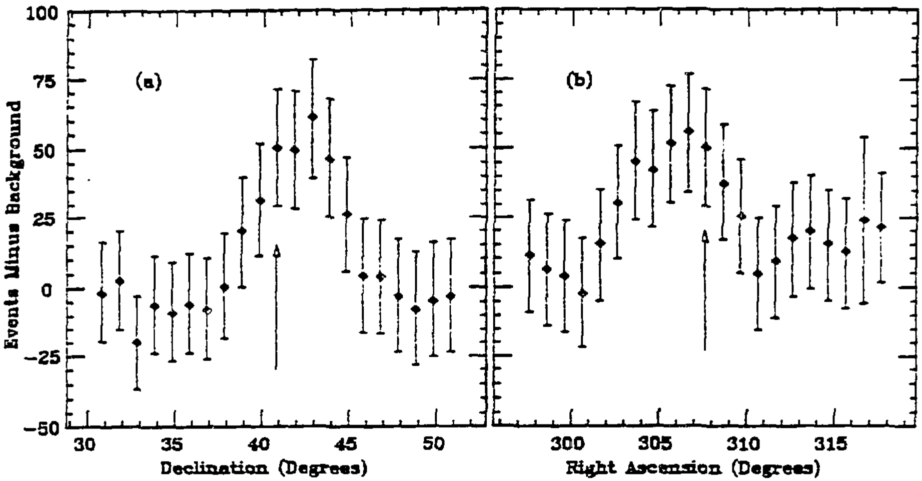

Fig. 3. Events-minus-background distribution for the phase plot as a function of (a) declination, and (b) right ascension. Note that nearby points are not statistically independent. The vertical arrows indicate the position of Cygnus X-3.

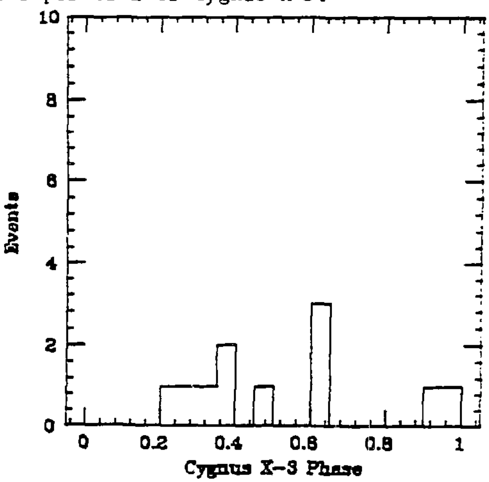

Fig. 4. Cygnus X-3 phase plot for events with zenith angles greater than 66°, and within 3° of the nominal direction of Cygnus X-3.

from all events in Fig. 2(a) (including the peak), the signal is 10 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.

4. Long-time Flux Variablity. The air Cerenkov data indicate that Cygnus X-3 is not a constant source.[12] Such episodic behavior suggests that the signal-to-background-ratio in Fig. 2(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 5(a) shows such a plot where the mean phase is plotted for each pair of consecutive events which occurred 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 this estimate has been derived from Figs. 5(b) and 5(c), which show similar plots for nearby off-source directions. The results of a background-independent moment analysis of Fig. 5(a) indicate an unconstrained probability of a random fluctuation generating the plot as $\sim 3 \times 10^{-4}$. The constrained probability using knowledge of 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. 5(a) compared to that in Fig. 2(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 1 contains further information on this question. Listed there are the number of Cygnus X-3 cycles observed with n muons in a 1.2 hour (1/4 cycle) period. Data are shown on and off the phase peak for both on- and off-source directions.

We have fit the off-source (background) data in Table 1 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 when Cygnus X-3 is not directly overhead. The model fits the background data well. The χ^2 for each of the background distributions is shown in the table. The fits are likely, except for the signal region, 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 1 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^{-1} during the active quarter-period and a (source-overhead) background rate described above of 0.42 ± 0.03 muons h^{-1}.

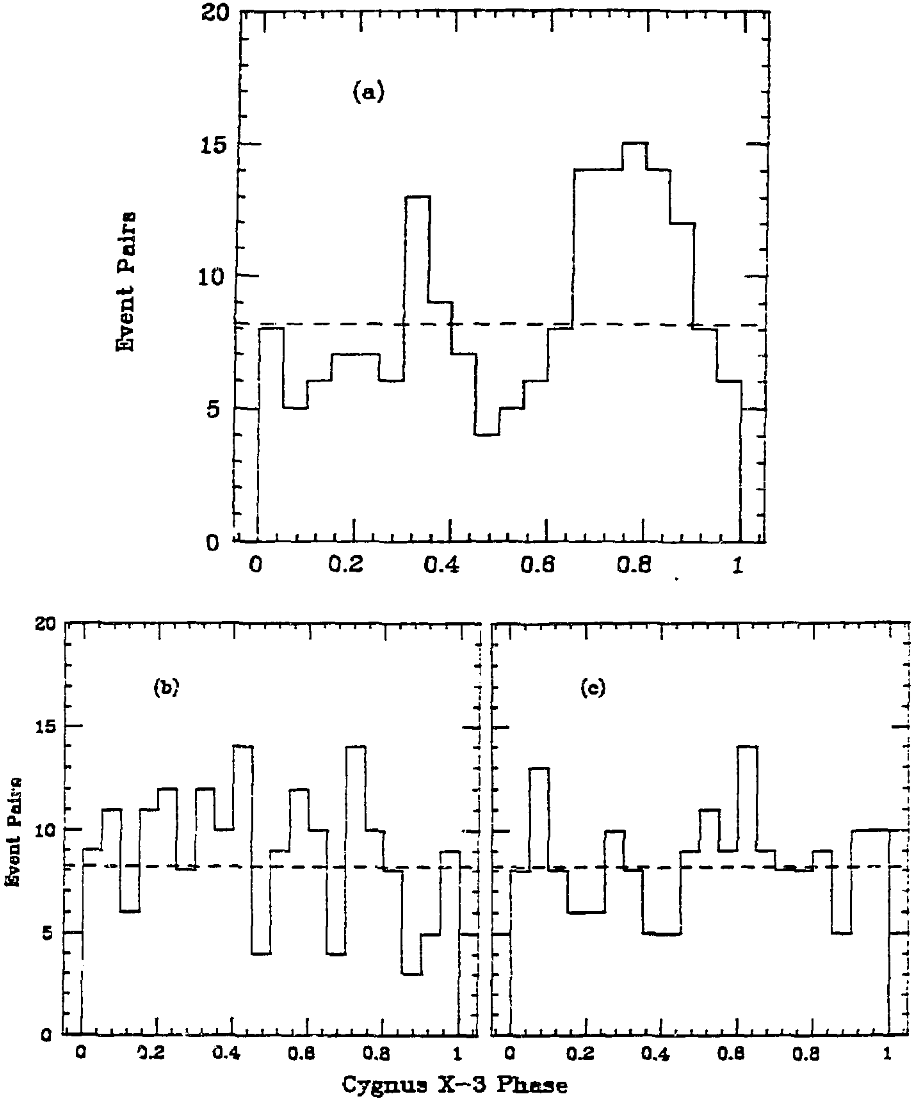

Fig. 5. (a) The Cygnus X-3 phase plot showing the mean phase for pairs of events arriving within 0.5 h, from within 3° of the nominal direction of Cygnus X-3. (b) and (c) Similar phase plots for pairs of events within a 3° half-angle cone centered at $\alpha = 297.6°$ and $\alpha = 317.6°$, respectively, and the same declination as Cygnus X-3. The dashed line shows the estimated background from a random source.

Table 1. Number of Cygnus X-3 Cycles in Which n Muons Are Observed in 1.2 h From Within 3° of On- and Off-source Directions.

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	

From the ~ 8 m^2 area of the Soudan 1 detector and the 0.96-year live time, we can use the above model to estimate the following fluxes of muons from Cygnus X-3 with energy $\gtrsim$ 650 GeV:

(a) Average detected flux for the entire observation period: ~ 2.5×10^{-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 (assuming a $\cos^3 \Theta_z$ dependence): ~ 7.3×10^{-11} cm^{-2} s^{-1}.

(The following flux values are for the directly-overhead geometry.)

(c) Average flux during all potentially active times with phase between 0.65 and 0.90: ~ 2.9×10^{-10} cm^{-2} s^{-1}.

(d) Flux during "on" times with phase between 0.65 and 0.90, with 7 percent of cycles "on": ~ 4.2×10^{-9} cm^{-2} s^{-1}.

(e) Flux averaged over entire 4.8 h period during 7 percent of time source is "on": ~ 1.0×10^{-9} cm^{-2} s^{-1}.

The uncertainty in these fluxes is estimated at +50,-25 percent.

These fluxes may be compared with fluxes attributed to Cygnus X-3 by air Cerenkov experiments at similar energies. Reference 12 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." Reference 13 reports a flux averaged over the 4.8 h cycle of ~ 8×10^{-11} cm^{-2} s^{-1} at a threshold energy of 500 GeV. Our muon fluxes are apparently larger than the fluxes reported from air Cerenkov measurements at similar energies. However, deducing 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 3 or 4 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[14] a 34.1 d period for the flux variation of Cygnus X-3. Figure 6 shows a 34.1 d phase plot for the nine times listed above, using an arbitrary t_0 of 18.04 January 1981. Note that the absolute phase has been selected using these data, and that it differs from the one in Ref. 14 by almost half a period. A Rayleigh analysis indicates a probability of about one percent that this plot is consistent with a random fluctuation of a uniform background. The plot additionally shows the phases of air shower bursts observed[15] on 20 January and 21 November 1981 and radio outbursts observed[16] on 27 September 1982 and 1 and 8 October 1983. These data are clearly anecdotal, but their near-zero phase suggests that a more systematic analysis is warranted.

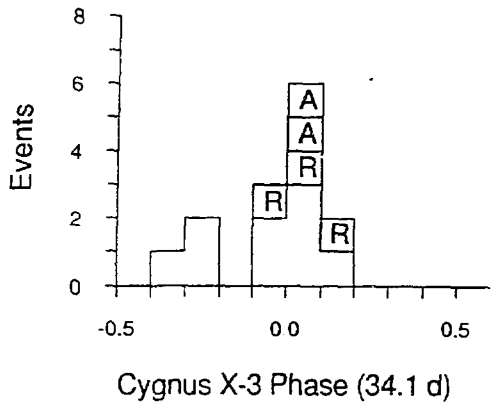

Fig. 6. The 34.1 d period phase plot for high-rate periods as defined in the text, using the ephemeris given in the text. The symbol A indicates air shower bursts described in Ref. 15. The symbol R indicates radio outbursts described in Ref. 16.

5. Conclusions. Our evidence for an underground muon flux related to Cygnus X-3 seems unlikely to be a statistical fluctuation. The data indicate that Cygnus X-3 is an episodic source, as has been previously reported from air Cerenkov 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. 6 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 we have previously reported on multimuon events in a nearby direction[2], although we have not found a connection between the two phenomena.

These data are difficult to explain in terms of conventional ideas about cosmic-ray propagation and interaction. Our results yield a muon flux several orders of magnitude larger than that expected from inelastic photoproduction by photons from Cygnus X-3. The most likely possibilities are either that high energy photons have new type of interaction that leads to direct or indirect muon production, or that the muons are produced by a new type of stable, neutral particle coming from Cygnus X-3. Further observations will be required to confirm and explore this effect.

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