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Study of muons from the direction of Cygnus X-3 using an underground proportional-tube array

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From July 1987 through March 1988 an array of proportional wire modules was operated as a muon detector at a depth of 2090 meters water equivalent in the Soudan mine in northern Minnesota. A spatial angular resolution of 1.2° was achieved for muon tracking. A clean sample of 1.02×10^5 muon trajectories recorded underground is used to search for an excess flux of muons from the direction of Cygnus X-3. For muons within the phase interval [0.6, 0.9] of the source's 4.8-h period, 90%-C.L. upper limits for fluxes arriving within 3° and 1.5° half-angle cones centered on the Cygnus X-3 direction are 8.5×10^{11} $cm^{-2}s^{-1}$ and 3.1×10^{-11} $cm^{-2}s^{-1}$, respectively.

INTRODUCTION

Much interest concerning underground muon experiments was stimulated in 1985 by reports of observation of muons from the direction of Cygnus X-3.[1,2] The underground muon flux was reported to be correlated with the 4.8-h period associated with this binary star system. This period is very stable and has been established by numerous observations of the modulation of x rays coming from Cygnus X-3.[3] In the phase interval [0.65, 0.90], corresponding to a fixed portion of the 4.8-h period, the Soudan-1 group observed a 3.6-standard-deviation excess in muon flux. The NUSEX group reported a 5-standard-deviations excess in the phase interval [0.70, 0.80]. Since 1985, other experiments have searched for, but have failed to find an excess muon flux from the direction of Cygnus X-3.[4–7] Meanwhile, the Soudan 1 and NUSEX experiments have been regularly reporting their post-1984 observations.[8,9] In neither experiment do muons recorded underground during 1985 and 1986 show an excess signal correlated with the Cygnus X-3 phase. However, in both experiments, the data collected since 1986 is reported[8,9] to be consistent with the time-modulated enhancement reported in 1985.

We report here on measurements of the underground muon flux from the direction of Cygnus X-3 (declination $\delta=40.8°$, right ascension $\alpha=308°$) using a proportional-tube array deployed in the Soudan-2 cavern on level 27 of the Underground Mine State Park in Soudan, Minnesota. The array provides an effective area of 35 m^2 and a measured effective angular resolution in space of 1.2° for muon tracking. Our motivation for deploying this array was, in part, to explore the capability of an open geometry configuration of proportional-tube detectors for precise measurement of the direction of underground muons. In the course of this study, we obtained data which, although of limited statistical precision, is nevertheless of interest in connection with design and analysis of underground muon experiments. In this paper we summarize the performance of this prototype detector and present an analysis of data obtained with it.

Since Cygnus X-3 passes nearly overhead at the Soudan site, our array has good acceptance for this candidate source. The overburden is nearly uniform within

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the detector acceptance. Our vertical depth is 2090 meters of water equivalent (mwe) which is deeper than, but similar to, the depth of Soudan 1 located on level 23 at 1800 mwe. For the present work, all surveying and all computer codes required for underground muon astronomy were developed independently of the Soudan-1 experiment. Various cross-checks were then made between the two experiments. These checks were facilitated by the fact that the Soudan-1 detector was operated concurrently and was situated within the angular acceptance of our tracking array in the Soudan-2 cavern.

EXPERIMENTAL APPARATUS

Our muon detector, the "Tracker," is an array of 128 7-m-long and 19-cm-wide proportional-tube modules arranged in two horizontal planes separated by a vertical distance of 10 m. Each plane consists of two 32-module layers, designated L1 and L2 for the lower plane and L3 and L4 for the upper plane, as indicated in Fig. 1. The perpendicular alignment of the modules in the adjacent layers provides an x-y measurement in each plane. The sensitive overlap area in each plane is 35 m^2.

Figure 2 shows three proportional-tube modules in different stages of assembly. The cross section of each module is a honeycomb pattern of hexagonal cells arranged in two four-cell rows, with one row immediately above and offset from the other. The sense wires from the cells in each row are connected to form one detection element. An electronics channel is provided for each four-cell row. In effect, each module consists of two independent detection elements with 87% overlap of their sensitive areas.

The proportional-tube modules were operated as threshold devices. An electronics card installed at one end of each module contained two identical circuits, one for each four-cell channel. Each circuit established a 0.6 μA threshold for the sense wire current, and generated a 1.1-μs digital output voltage pulse when the threshold was exceeded. The signals in each channel were sampled at 1 MHz and the results stored for 128 μs awaiting a trigger. The modules were operated with a 95% Ar-5% CO_2 gas mixture at a fixed absolute pressure of 1.12 bar. Measurements in a cosmic-ray test stand at sea level showed that the maximum delay between the passage of a through-going particle and the subsequent response of a four-cell element was 0.8 μs. The efficiency of an element was measured to be 98%; the small inefficiency is due to the insensitive regions within the interior walls of the honeycomb pattern. The design and performance of this proportional-tube array are described in detail elsewhere.[10,11]

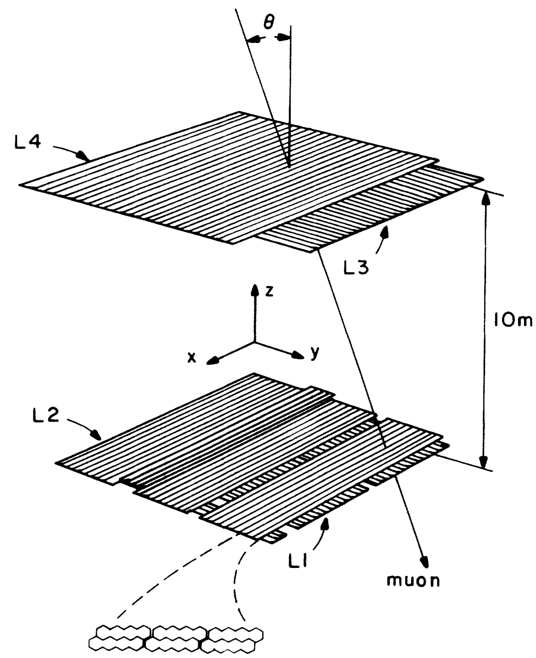

FIG. 1. Layout of the underground muon Tracker. The effective overlap area of the two layers in each plane is 35 m^2.

The Tracker was located at 47.7° N latitude and 92.2°

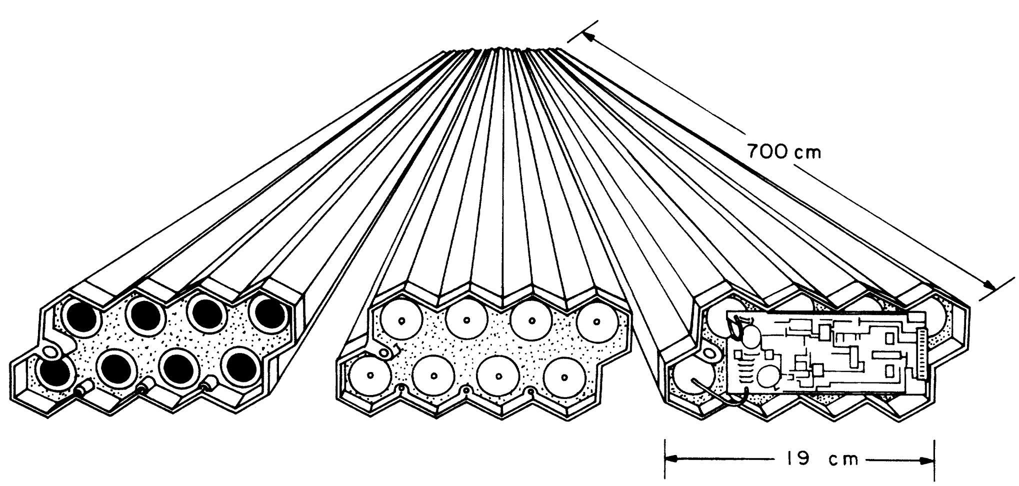

FIG. 2. End view of the eight-cell proportional-tube module at three stages in its construction. From left to right, the modules are shown (i) with end cap, but without wires, (ii) with wires held by crimp pins centered in plastic discs, and (iii) with the two-channel digital-output card mounted.

W longitude at a depth of 715 m. Analysis of rock samples taken at various depths shows the overburden to have an average density of 2.93 g/cm^3 and an average radiation length of 25 g/cm^2. The average density allows us to characterize our vertical depth as equivalent to 2090 meters of water. A muon in the atmosphere must have an energy of at least 0.8 TeV to penetrate to our detector. We estimate that the muons which emerge from the cavern walls on level 27 have a mean energy of 300 GeV and are initiated in collisions of primary cosmic rays of energy greater than 2 TeV with nuclei of the upper atmosphere.

The muon trigger requires that a charged particle pass through the three lowest layers of the Tracker. For each layer the sum S_i of the coincidences between every pair of adjacent channels in that layer was formed. The trigger was then obtained by requiring the coincidence $S_1 \cdot S_2 \cdot S_3$. The rates S_i were measured in the mine to be roughly 100 Hz per layer. This far exceeds the expected muon rate and is consistent with local radioactivity. From the rates S_i we infer that the false trigger rate induced by radioactivity should be small (0.1%) compared to the genuine muon rate, and measurements confirmed this. Coincident activity was observed in L4 for 85% of the $S_1 \cdot S_2 \cdot S_3$ trigger events. A Monte Carlo calculation, based on the geometry of sensitive areas in the four layers of the Tracker, yielded the same percentage.

From the widths of the modules and from the 10-m separation of the two planes, we calculate that the projection of a muon trajectory onto the x-z or y-z plane can be measured with an accuracy (standard deviation) of 0.4°. By studying the relative angles of tracks with two muons observed in the detector, we can obtain an experimental measure of the overall angular resolution. This will include contributions from multiple scattering in the rock, bending in the Earth's magnetic field, and the relative transverse momentum in hadron production and decay, as well as the geometric resolution of the proportional-tube array. For this purpose, we studied a clean sample of 403 events which contained two and only two hits in each of the four layers of the Tracker. Of the two possible associations of hits in each view, we chose the one which produced the more parallel trajectories. The angular separation in space, Δ, of these two trajectories was calculated by adding, in quadrature, their angular separation in the two projections. A signal of parallel muon pairs is seen in Fig. 3 at angular separations smaller than 3°. We infer that our overall spatial angular resolution for single-muon trajectories in the atmosphere is $\sigma_\Delta = 1.2°$, including the effects of both our geometrical resolution and the other contributions listed above.

The vertical direction was determined to an accuracy of 0.05° (after correcting for a 0.1° deflection due to the rotation of the Earth) by measurement of the position of a plumb bob suspended from the upper plane 10 m above. The direction of north was determined to an accuracy of 0.03° by measurements made in the cavern with a gyroscopic theodolite. The event time was derived from the WWVB broadcast of coordinated universal time (UTC) provided by the U.S. National Institute of Standards and Technologies. Our WWVB receiver is specified to maintain UTC to an accuracy of 1 ms.

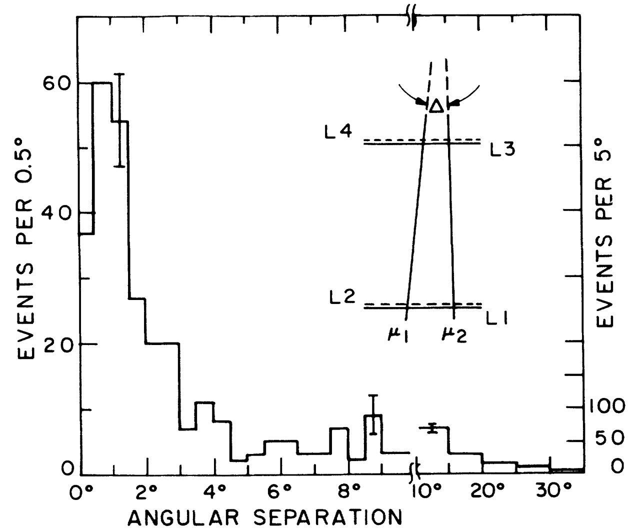

FIG. 3. Histogram of the spatial angular separation Δ of trajectories reconstructed in events with two hits in each layer of the Tracker. A signal of nearly parallel muons is seen at separatons less than 3°.

A check of our determination of the direction of north, the direction of the vertical, and of UTC for our site on level 27 of the Soudan mine, was obtained through comparison of Tracker events with tracks recorded by the Soudan-1 experiment on level 23. The Soudan-1 detector is located 123 m above, 6 m east, and 62 m north of the Tracker, and has its own separate WWVB clock, computer, and local coordinate system. The Tracker survey was independent of the Soudan-1 experiment. We obtained muon track information (α,δ,UTC) from Soudan 1 taken during our July 1987 to March 1988 running period, and searched for a match in time and direction of muon trajectories through the Tracker to muons detected by Soudan 1. Six events, with background less than one event, were isolated. The differences between these Tracker and Soudan-1 muon trajectories were within the timing and angular resolutions of the two detectors. Furthermore, the trajectories lay in the approximate direction between the Tracker and Soudan 1. From our analysis of these six events, we deduce that the differences (Tracker-Soudan 1) in the determination of right ascension and declination are $\Delta\alpha = 1.42° \pm 1.16°$ and $\Delta\delta = -0.41° \pm 0.33°$, respectively. To the extent that these differences are consistent with zero, we infer that there are no gross errors in our determination of equatorial coordinates of muon trajectories.

DATA AND ANALYSIS

The Tracker was operated from July 1987 to March 1988. During that period data were collected with the Tracker performing at full efficiency for a total sensitive time of 159 days. Under these conditions we recorded 153 459 events having coincident hits in all four layers of the Tracker. The above event sample was then studied to see whether any excess fraction of the muons appears to be coming from the direction of Cygnus X-3. A subsample was selected in which there was a single, accurately defined trajectory in the Tracker. Usually, the passage of a muon through a layer of modules caused two adjacent channels to respond. Not infrequently, the number of adjacent channels responding exceeded two. We did not allow the number of adjacent channels responding to be greater than four in any of the four layers. As a result, the sample was reduced to 130 734 events. We further required that there be at most one set of adjacent channels in each layer, so that the reconstructed muon trajectory was unique. This second cut reduced the sample to its final size of 102 187 events.

The reconstructed trajectory was used with the recorded coordinated universal time to calculate the right ascension and declination of its projection onto the celestial sphere (the direction of a hypothesized source of parent particles). For events with trajectories pointing near to Cygnus X-3, we calculated the times of arrival of the particles at the plane containing the solar system barycenter and normal to the direction of Cygnus X-3. The distribution of arrival times at this barycentric plane then corresponds, with a fixed offset, to the hypothesized emission times of the parent particles. These arrival times can then be related to the Cygnus X-3 phase.

Our analysis was performed with two choices for association of muons with the source. We first required that muon trajectories point to within 3° of Cygnus X-3, then repeated the analysis requiring that the trajectories point to within 1.5°. The 3° half-angle cone requirement was chosen to enable comparison to Soudan-1 analyses[1,8] of data obtained at a depth similar to our own. We expect from our measured angular resolution that there will be no loss of signal of atmospheric muons from the direction of Cygnus X-3 due to the 3° requirement. The 1.5° requirement, on the other hand, was chosen to match our angular resolution. We calculate that 20% of the signal will be lost in this case; however, the background should be reduced by a factor of 4, so we may hope to enhance the signal-to-background ratio. This rationale presumes Cygnus X-3 to be, in effect, a point source for muons on the celestial sphere. On the other hand, in both the Soudan-1 and NUSEX experiments the angular distributions of muons associated with Cygnus X-3 are reported to be broader than 1.5°, an effect which is not attributable to instrumental resolution.[2,9,12] Consequently, there remains the possibility that utilization of a 1.5° cone may not improve the signal-to-noise ratio for physics reasons.

The expected background in the source cone was determined by a procedure that required only one assumption: At the Cygnus X-3 declination, the muon flux underground is uniform in time, with the possible exception of time variation caused by Cygnus X-3 itself. The rate at which background muons accumulate in the source cone depends on the hour angle[13] of the source; the rate is greatest when Cygnus X-3 is near zenith, the direction for which the attenuation due to the rock overburden is least. Therefore, to calculate the background muons expected to accumulate in the source cone, we must determine both the rate of background muons within a 3° (1.5°) half-angle cone at the Cygnus X-3 declination, and the distribution of sensitive time of our experiment as a function of Cygnus X-3 hour angle.

To carry out the background determination, an additional 39 background cones were defined, each having the same declination as Cygnus X-3, but centered in right ascension at successive 9° intervals away from Cygnus X-3. The 9° interval ensures no overlap of adjacent cones, even for the larger 3° half-angle cones. By assumption, the muon rate in each background cone is expected to be the same, and equal to the background rate in the source cone. The use of a large number of background cones provides a muon yield that is sufficiently large to determine the assumed common rate accurately.

In a first pass through the data, three distributions were extracted: (i) the yield of muons in each of the 40 cones (Fig. 4), (ii) the total sensitive time as a function of Cygnus X-3 hour angle (Fig. 5), and (iii) the background muon rate, as a function of hour angle, at the declination of Cygnus X-3 (Fig. 6).

The muon yields in each of the forty 3° half-angle cones are displayed as solid circles in Fig. 4. The yield in the Cygnus X-3 cone does not appear to be significantly enhanced in comparison with the yields in the 39 background cones. However, a signal from the source may be obscured by an uneven distribution of sensitive time for which each of the various cones is near zenith. Our background estimation procedure is designed to cope with any such uneven distribution.

The distribution of sensitive time, as a function of hour angle of Cygnus X-3, was determined by tracking the Cygnus X-3 hour angle from the start time to the stop time in each of the data-taking runs. We chose hour angle bins of 3°. After accounting for start and stop times which occur within a bin, and after correcting for the different time scales involved (sensitive times are UTC, whereas hour angle reflects sidereal time), we obtain the sensitive time distribution for the experiment shown in Fig. 5. Note that the total time in this figure is 159 days. The sensitive time distribution for any particular background cone can be obtained from the information in the figure. For example, the time distribution for the background cone 9° greater in right ascension than Cygnus X-3 is simply obtained by shifting the position of zero hour angle three bin widths to the left toward more nega-

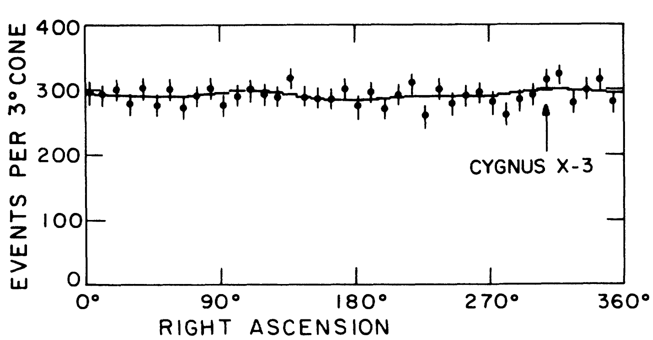

FIG. 4. The number of muons per 3° half-angle cone vs right ascension. The yield expected in each angular cone from the background muon flux is indicated by the histogram.

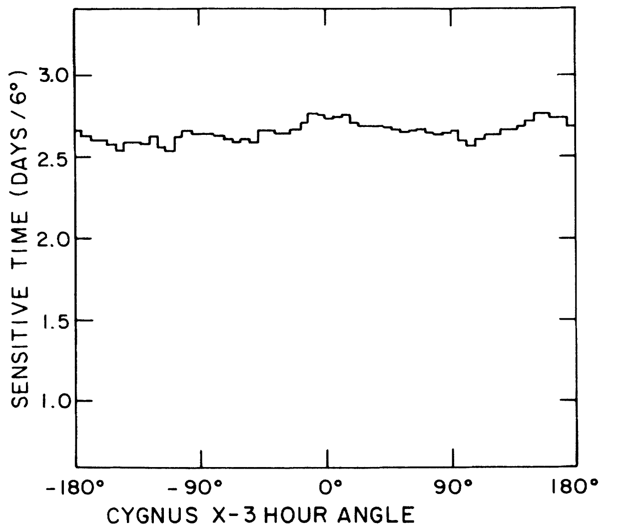

FIG. 5. Variation of the detector sensitive time with hour angle of Cygnus X-3.

tive Cygnus X-3 hour angle.

In the first pass, the distribution in hour angle of the total yield in all 39 background cones was immediately determined. Whenever a muon was found in any one of the background cones, the total yield for the hour angle bin containing the center of that cone was incremented by one. The bin width was chosen to be 3° in order to match the binning for the sensitive time distribution. As shown above, the time distribution in hour angle for each background cone can be determined, therefore the time

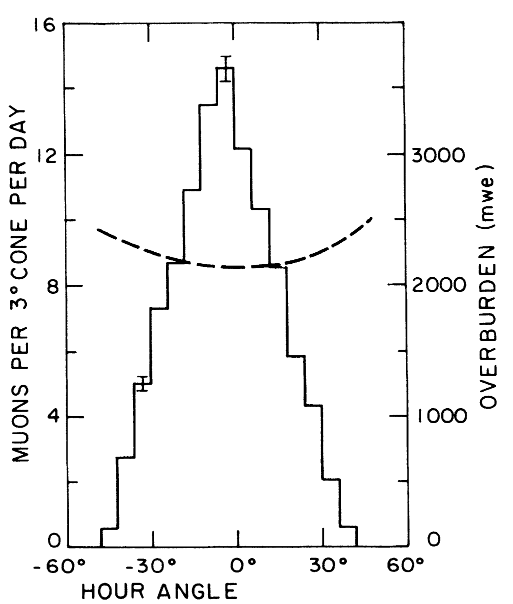

FIG. 6. The histogram shows the dependence on hour angle of the rate of background muons in a 3° half-angle cone centered on the declination of Cygnus X-3. The rate was deduced from an analysis of 39 cones off source in right ascension. Shown by the dashed line is the variation of the overburden with hour angle at the Cygnus X-3 declination.

distribution for the sum of the 39 background cones can also be determined. By forming the ratio bin by bin of the total yield and the total time distributions for the 39 background cones, we obtained our best estimate for the hour angle dependence of the background muon rate in any cone at the Cygnus X-3 declination. Our determination of the background rate is shown (with the bin width doubled to 6°) in Fig. 6. The number of muons used in this measurement of the dependence of the background rate on hour angle is 1.13×10^4. The peak background rate occurs at a slightly negative hour angle because the lower plane of the Tracker was not directly below the upper plane.

Having determined the background muon rate, we calculated the expected number of background muons in the source cone using the known sensitive time for the source cone at each hour angle. The expected number of muons in the 3° half-angle cone is 297 ± 3; the observed number is 315. As gauged by the quadrature sum of the statistical and background errors, the apparent excess of 18 muons in the Cygnus X-3 cone of Fig. 4 is within one standard deviation of our background expectation. For purposes of comparison, the expected yield of muons in each of the 39 3° half-angle background cones was also calculated using the known sensitive time at each hour angle for each of these cones. The differences between observed muon fluxes (solid circles) and background expectations (histogram) for all forty of the 3° cones can be seen in Fig. 4. We find that 5 of the 39 background cones contain muon flux enhancements of significance greater than that observed from the direction of Cygnus X-3. We conclude, for the 3° half-angle cone, that the underground muon flux from the direction of Cygnus X-3 is less than 1.6×10^{-10} cm^{-2}s^{-1} with 90% confidence. For the 1.5° half-angle cone, the expected background was calculated to be 75 ± 1.5 muons; the observed number of muons is 68. With 90% confidence, we find for the 1.5° cone analysis that the flux is less than 2.1×10^{-11} cm^{-2}s^{-1}.

SEARCH FOR A PHASE-CORRELATED FLUX

We searched for a correlation between the time of our muon events and the phase of Cygnus X-3 as inferred from the x-ray light curve. The phase calculations require the use of an accurate ephemeris constructed from the x-ray data. The Soudan-1 and NUSEX analyses of 1985 used the ephemeris of van der Klis and Bonnet-Bidaud published in 1981.[14] The work reported here is based upon the 1988 cubic ephemeris derived by the same authors.[15] An analysis of our data has also been carried out using the 1986 ephemeris of Mason[16] and very similar results were obtained.[11] The usual practice of expressing the phase as a fraction of the period was followed.

Because of the short running time of the experiment, we did not expect that the background in the source cone would be uniformly distributed in Cygnus X-3 phase. Therefore we used our measured background rate and the known pattern of sensitive time to calculate the phase distribution of the expected background in the source cone. A second pass through our data was made in which we referred only to the start and stop times of the various runs. As in our first pass, we tracked Cygnus X-3 in hour angle from start to stop of each run. The phase of Cygnus X-3 was calculated as it enters and leaves each 3° hour angle bin. The background rate at this hour angle was then determined using the information of Fig. 6. This rate was multiplied by the 11.97 min of elapsed time in the 3° traversal to obtain the probability that a background muon would have been detected in the interval. This probability was used to increment the background distribution at this phase. We chose to use twenty bins for the phase distribution. Since the Cygnus X-3 phase changes by 0.042 while it traverses 3° in hour angle, the probability would often have to be alloted between two adjacent bins. In these cases, the probability was divided according to the times spent in each of the phase bins. Necessary modifications were made to the procedure to handle correctly the hour angle bins containing the start and stop times of the run. Proceeding in this way from run to run, we obtained the phase dependence of the background expected in our experiment.

The result of our phase correlation study using the 3° half-angle source cone is shown in Fig. 7. We note that even after 159 deays of sensitive time, there remains a substantial phase variation of the expected background. We emphasize that the background calculated for the Cygnus X-3 cone is determined solely by the muon rate observed in the 39 background cones and by the particular pattern of sensitive times during our nine-month run; it is independent of the muon rate observed in the Cygnus X-3 direction. In Fig. 7, no statistically significant correlation between the muon flux and the Cygnus X-3 period is apparent. We note, however that the largest deviation above the background ($1.5\ \sigma$) occurs in the phase interval [0.6, 0.7]. This interval falls within, or borders on, the phase regions of enhanced muon flux reported by Soudan 1 and NUSEX, respectively. For purposes of quantifying our results, we select the phase range [0.6, 0.9] since it encompasses all phase regions cited by the previous experiments.[1,2,8,9] We find 109 muons in the 0.6-to-0.9 phase interval, whereas 101 ± 1 muons are expected. At the level of 90% confidence, we infer that the excess muon flux from the direction of Cygnus X-3 is less than 8.5×10^{-11} $\text{cm}^{-2}\text{s}^{-1}$. On the other hand, if the observed 8-event excess is taken to be a signal, it would correspond to a 2.9×10^{-11} $\text{cm}^{-2}\text{s}^{-1}$ flux of underground muons. This result is little changed if the phase window is narrowed to [0.6, 0.8]. The 90%-C.L. flux limit is then 9.7×10^{-11} $\text{cm}^{-2}\text{s}^{-1}$; the excess events interpreted as signal would corresond to a muon flux of 4.8×10^{-11} $\text{cm}^{-2}\text{s}^{-1}$. As can be seen in Fig. 5, the variation of overburden within the Tracker's acceptance is small. Consequently, our flux results (at the Cygnus X-3 declination) correspond to a nearly uniform overburden of 2130 mwe, slightly greater than our vertical depth of 2090 mwe.

In a further calculation made to fully utilize the available angular resolution, muons in the data sample were required to fall within a 1.5° half-angle cone centered on Cygnus X-3, and the search for a flux enhancement correlated with the phase was repeated. The phase plot resulting from this 1.5° half-angle search is shown in Fig. 8. The calculated background (solid circles) has a shape similar to the 3° half-angle cone background, since for both the 1.5° and 3° cones the patterns of detector sensitive time are nearly identical. There is no statistically significant evidence for a phase-correlated muon flux in

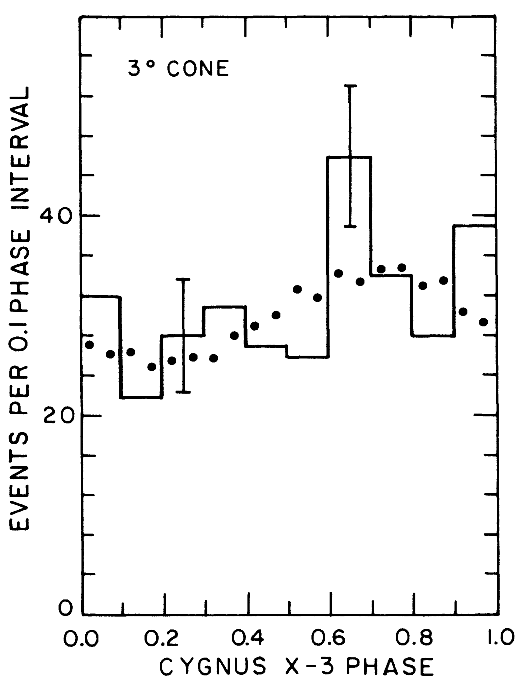

FIG. 7. Phase plot for muons within a 3° half-angle cone centered on Cygnus X-3. The solid circles show the variation of counts from the background muon flux arising from our pattern of sensitive times.

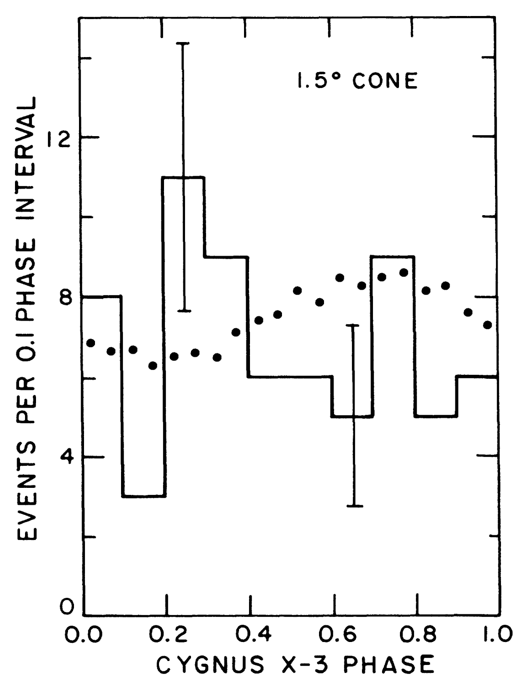

FIG. 8. Phase plot for muons within the 1.5° half-angle cone centered on Cygnus X-3. The solid circles show the number of background muons expected.

Fig. 8. In the phase region [0.6, 0.9] the observed flux is 19 muons, whereas 25.2 ± 0.5 muons are expected from the background. At 90% C.L., the muon flux in the phase interval [0.6, 0.9] is less than 3.1×10^{-11} $cm^{-2}s^{-1}$; in the interval [0.6, 0.8] it is less than 2.0×10^{-11} $cm^{-2}s^{-1}$.

The data in the histogrammed phase distributions of Fig. 7 and 8 has been subjected to a bin-free analysis. That is, the Protheroe statistic[17] and also the Rayleigh statistic[18] were calculated using the individual muon phases and were then compared to the background distributions as shown. Again, no significant signal is seen: The chance probability that the background distribution could account for the observed distribution is 48.6% (44.5%) for the Protheroe (Rayleigh) test of Fig. 7, and 77.5% (83.7%) for the Protheroe (Rayleigh) test of Fig. 8.

SUMMARY

We have reported on analysis of 102 187 muon trajectories recorded from July 1987 to March 1988 at an underground site of vertical depth 2090 mwe. The muons were detected using an open geometry array of porportional wire modules arranged into two *x*-*y* planes separated by a 10-m vertical gap; each plane contained four sampling layers. A spatial angular resultion of 1.2° was achieved for muon tracking. Muons from the direction of Cygnus X-3 have been analyzed for evidence of (i) a steady flux enhancement, and (ii) an enhancement which is time dependent with the 4.8-h period of Cygnus X-3. The data contain no statistically significant muon flux enhancement of either category. For muons within 3° of the Cygnus X-3 direction, we set an upper limit on the flux (90% C.L.) of 1.6×10^{-10} $cm^{-2}s^{-1}$. For muons within a 3° half-angle cone having arrival times coinciding with the Cygnus X-3 phase range 0.6 to 0.9, the upper limit is 8.5×10^{-11} $cm^{-2}s^{-1}$. For muons with phase 0.6 to 0.9 and within a 1.5° half-angle, which is only slightly larger than the detector's angular resolution, the upper limit is 3.1×10^{-11} $cm^{-2}s^{-1}$. The 90%-C.L. upper limits obtained from our 3° and 1.5° half-angle analyses are, respectively, above and below the Cygnus X-3 muon flux signal of $\approx7\times10^{-11}$ $cm^{-2}s^{-1}$ reported by Soudan 1.[1] Their signal was observed in muons pointing to within 3°, with phases 0.65 to 0.9, at depth 1800 mwe, recorded from September 1981 though November 1983. More recently, Soudan-1 data obtained from May 1985 through June 1989 were combined with the earlier data and evidence for a flux range of $(1.5 \text{ to } 3.2)\times10^{-11}$ $cm^{-2}s^{-1}$ was reported.[8] The latter flux range is generally lower than, and hence is compatible with, the Cygnus X-3 muon flux limits obtained by the study reported here.

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