Underground search for muons correlated with Cygnus X-3

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We have examined muon data collected with the IMB (Irvine-Michigan-Brookhaven) proton-decay detector in search of a muon flux associated with the x-ray binary Cygnus X-3. A sample of 3.6×10^4 muons from the direction of Cygnus X-3 during the period September 1982 until April 1984 shows no evidence of its characteristic 4.8-h periodicity. In the phase interval 0.65 to 0.90 where a signal has been reported by other workers at a similar depth we obtain a 90%-confidence-level limit to the flux of 6.9×10^{-11} cm^{-2}sec^{-1} for a depth of 1800 m water equivalent. This limit does not conflict with the reported signal. Three subsets of the data taken during Cygnus X-3 radio bursts have been separately analyzed. We find some evidence for an excess in the phase interval 0.50–0.60 at the time of the October 1983 outburst. We examine this excess in detail.

INTRODUCTION

Two experiments[1–4] have recently reported underground muons from the direction of Cygnus X-3 (right ascension 20.5 h, declination 40.9°) that exhibit its characteristic 4.8-h x-ray period.[5] Although Cygnus X-3 has been observed above ground in air showers at TeV and PeV energies,[6] the reported underground muon flux is not consistent with the flux and assumed γ-ray origin of these showers. If confirmed, the underground results would indicate new physics, such as a new neutral particle or unexpected interactions of a known neutral. The variability of Cygnus X-3 observed by the surface experiments apparently also extends to the underground signal.[2] Thus, although the Kamioka[7] and Fréjus[8] experiments have reported upper limits that are below the fluxes found by the Soudan and NUSEX nucleon-stability experiments, these limits apply to a later time and so do not preclude, for example, a variable source that may have been mostly in a low state since late 1983. The on time of the IMB (Irvine-Michigan-Brookhaven) experiment has a better temporal overlap with both of the experiments that have reported positive results. We have data at depths similar to both the Soudan and NUSEX experiments. We examine these data for evidence of a signal at the corresponding phases.

The Soudan group has also reported[9] a burst of muons occurring at the time of a large radio outburst of Cygnus X-3 in October 1985. Although we have no data from the period, we use data taken at the times of three previous radio outbursts to search for muon bursts at those times.

DATA ANALYSIS

The IMB proton-decay detector[10] is located in the Morton-Thiokol salt mine near Fairport Harbor, Ohio (41.7 °N, 81.3 °W) at a depth of 1570 m water equivalent (mwe). The detector is a rectangular tank ($22.5\times17\times18$ m^3) filled with 8000 metric tons of purified water. At the time these data were taken 2048 5-in. photomultipliers (PM's) were arrayed on the six sides of the tank on a $\sim$1-m grid. These PM's provide both pulse-height and timing information.

After cuts on the number of triggering PM's, the directions of through-going muons were determined by identifying the cluster of early triggering PM's as the muon entry point and the cluster of brightest PM's as the exit point. The fit is further constrained by the PM times in both clusters. A fiducial cut is made requiring the point of closest approach to the center of the detector to be at least 2 m inside the detector from the PM planes. This fitting procedure has an 80% efficiency for saving through-going single muons which satisfy the fiducial requirement. The final sample is predominantly single muons of energy greater than 2 GeV at the detector. The angular resolution of the fitter was determined by first applying the fitter to Monte Carlo–generated data. This result was then calibrated by a comparison of the difference between the muon directions obtained by pairs of different fitters when applied to both Monte Carlo and real data. A 7° angular cut is used in the analysis presented here. This value gives the optimal signal-to-noise ratio for a point source of muons and has a 70% acceptance efficiency for such a point source. Both the Soudan[11] and NUSEX (Ref. 3) results indicate that the excess muons may be scattered by up to 5° about the source direction. This would reduce the efficiency of 7° cut by an amount dependent on the exact distribution of the muons. Using the NUSEX data as a guide we estimate that the loss in efficiency is $\lesssim 5\%$. Additional small losses of efficiency are due to the accuracy of the detector alignment, systematic errors in fitting the muon direction, and uncertainties in the local source coordinates due to absolute timing uncertainties, each of which is $\lesssim 1°$.

During normal data taking we use on-line cuts designed to reject the majority of the cosmic-ray muons which trigger the detector at ~ 2.7 Hz. In this mode muons may be saved for several reasons: (1) one event in 64 is saved as a random sample (referred to as the random-save sample), (2) an on-line algorithm is used to save up-going and large zenith angle down-going muons, and (3) events occurring within 10 msec of each other are saved (the 10-msec sample). This last sample has not been analyzed in full. In addition, data are taken without cuts for a nominal one day per week. This "uncut" data provide our largest data sample for the present analysis.

The on-source muons, i.e., those with directions within 7° of Cygnus X-3, are binned according to their phase in the 4.8-h Cygnus X-3 orbital period using the ephemeris of van der Klis and Bonnet-Bidaud.[5] To obtain the expected phase distribution in the absence of a source, the muon rate as a function of local coordinates was tabulated using all the muons in the relevant data sample. This produces a table of the muon rates that takes into account the detector angular response, the cosmic-ray muon flux, and any variations in the overburden. Then, at fixed intervals during the on-time, the position of Cygnus X-3 was determined and the number of muons expected from that direction was obtained from the rate table and added to the background phasogram at the appropriate phase. The effective off-source to on-source exposure ratio is $\sim 10{:}1$ for the uncut sample for which the analyzed data sets were preferentially chosen to have Cygnus X-3 at high altitudes, and $\sim 20{:}1$ for the other samples. The same muon data sample (i.e., directions and times) was passed through a second, independently written, analysis as a check for possible error.

RESULTS AT 1570 mwe

The IMB detector, at a depth of 1570 mwe, is slightly shallower than the 1800 mwe of the Soudan experiment. For the period September 1981–November 1983 Soudan,[2] using an on-source sample of 1183 single muons, found an excess flux within 3° of Cygnus X-3 in the phase interval 0.65–0.90, corresponding to an average flux over the whole 4.8-h period of 7.3×10^{-11} cm^{-2} sec^{-1} ($^{+50}_{-25}\%$) for the source at a constant effective depth of 1800 mwe. The flux is higher if the muons are at angles out to 5° from the source direction. The IMB uncut sample contains 36 046 on-source muons, obtained in 655 h live time from September 1982–April 1984 with an average on-source detector area of 265 m^2. The mean depth penetrated by these muons is 1800 mwe. The phase distribution of these muons and the calculated background is shown in Fig. 1. There is a slight net excess of 1.8σ. We find no significant excess in the phase interval 0.65–0.90 (8749 observed, 8704 expected) and obtain a corresponding upper limit at the 90% confidence level (C.L.) of 5.6×10^{-11} cm^{-2} sec^{-1} for depths greater than 1570 mwe. To convert this to a flux at a fixed depth requires a knowledge of the zenith angle (θ_z) distribution of the Cygnus X-3 muons. The Soudan flux was obtained assuming a $\cos^3\theta_z$ dependence,[2] this being approximately the distribution of the cosmic-ray muon flux out to $\sim 60°$. Under the same assumption our flux limit is 6.9×10^{-11} cm^{-2} sec^{-1} at 1800 mwe. If we limit the data to that which overlaps the Soudan data (i.e., through November 1983) we obtain a less stringent limit of 8.6×10^{-11} cm^{-2} sec^{-1}.

The flux limits derived from the uncut data strictly apply only to a nonvariable source because of the poor total

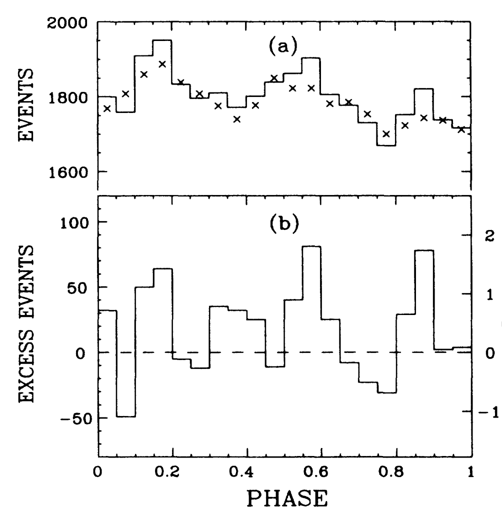

FIG. 1. (a) The phase distribution of muons with directions within 7° of Cygnus X-3 from the uncut sample (solid histogram), and the expected distribution in the absence of a source (crosses). The data are from 655 h live time between September 1982 and April 1984. (b) The background-subtracted phase distribution. The right-hand scale is in approximate standard deviations (S.D.).

time coverage of the sample. The random-save muon sample is much smaller than the uncut sample but is more continuous (~ 360 live days from September 1982 through June 1984). The background subtracted phasogram for the 3902 on-source muons in this sample is shown in Fig. 2. The 90%-C.L. flux limit for phases 0.65–0.90 is 1.8×10^{-10} cm^{-2} sec^{-1}.

RESULTS AT 4600 mwe

The large-zenith-angle sample consists of muons whose fit directions are between 70° and 80°. The slant depth of the IMB detector at 70° is 4600 mwe, which is close to the minimum depth of the NUSEX detector. From June 1982 through January 1985 the NUSEX group, using an on-source sample of 151 muons, found an excess in the phase interval 0.7–0.8 corresponding to a flux of 8.5×10^{-12} cm^{-2}sec^{-1} at 4600 mwe (Ref. 4). Figure 3 shows the phase distribution of our 222 on-source muons recorded in 490 h that Cygnus X-3 was between 70° and 80° from March 1983 through June 1984. The average on-source area is 254 m^2. Because part of the on-source cone does not overlap the 10° band, the zenith-angle constraint reduces the efficiency of the 7° cut around the source from 70% to 52% averaged over the band. In addition, the efficiency of the on-line algorithm is 55%. In the phase interval 0.7–0.8 we have 14 events whereas the calculated background is 22.2. This gives a 90%-C.L. flux upper limit of 5.1×10^{-12} cm^{-2}sec^{-1} for depths greater than 4600 mwe. The equivalent flux limit at 4600 mwe is 1.7×10^{-11} cm^{-2}sec^{-1}. Hence the IMB 90%-C.L. limit is a factor of ~ 2 above the measured NUSEX flux and so does not contradict it.

CORRELATIONS WITH RADIO OUTBURSTS

The Soudan group interprets the arrival-time distribution of their on-source, in-phase muons in terms of a

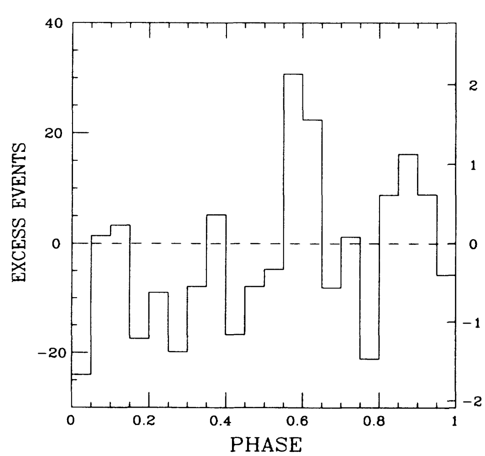

FIG. 2. The on-source background-subtracted phase distribution for the random-save muons. The effective live time for this sample is $\frac{1}{64}$ of 360 days between September 1982 and June 1984.

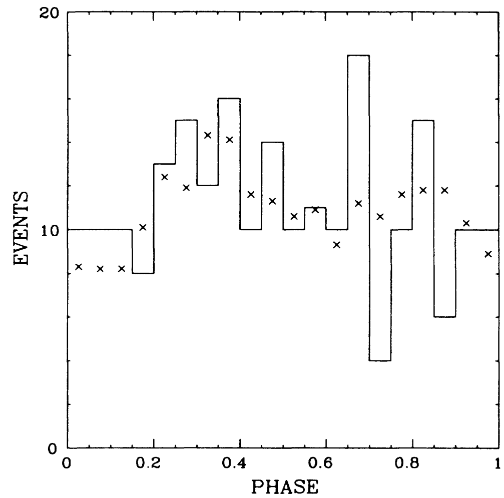

FIG. 3. The phase distribution for on-source muons for 490 h when Cygnus X-3 was between zenith angles of 70° and 80°, from March 1983 until June 1984.

long-term variability of the source which is active for only $\sim 7\%$ of the time.[2] During these active times the flux would be $\sim 10^{-9}$ cm^{-2}sec^{-1}. That group has also recently reported observing a burst of muons from the direction of Cygnus X-3 near a phase of 0.7, coincident with a major radio outburst of the system in October 1985 (Ref. 9). The muon burst is spread over ~ 4 weeks. This suggests that other muon-burst periods may also coincide with radio outbursts. We have examined data from around the times of three previous radio outbursts[12,13] for which we have data. Because we do not know the exact nature of any correlation between the radio outbursts and muon bursts we use data from two weeks before and after the radio-outburst times. Although the Soudan muon burst in October 1985 occurred in a small range near phase 0.7, the other bursts might not be at the same phase. The radio outbursts for which we have data occur during the period of the earlier Soudan observations, and so we again look for an effect in the phase interval 0.65–0.90.

For the outburst of 28 September 1982 we use 55 h of uncut data taken on 16, 17, and 23 September and 3–8 October. We obtain an upper limit of 1.7×10^{-10} cm^{-2}sec^{-1} for this period in this phase interval (0.65–0.90). For the burst of 16 February 1983 we use 36 h of data from 1, 2, 15, 21, 24, 25, and 28 February and 1 March, obtaining a corresponding limit of 2.0×10^{-10} cm^{-2}sec^{-1}. For the bursts of 1–11 October 1983 we use 71 h of data from 16, 21, and 22 September and 12, 24, 25, 26, and 27 October to give a corresponding limit of 1.9×10^{-10} cm^{-2}sec^{-1}. The background-subtracted phasograms for these times are shown in Fig. 4.

The phase distributions for the random-save sample at these times are shown in Fig. 5. The flux limits for the phase interval 0.65–0.90 are 1.1×10^{-9} cm^{-2}sec^{-1} for September/October 1982, 2.1×10^{-9} cm^{-2}sec^{-1} for February 1983, and 7.2×10^{-10} cm^{-2}sec^{-1} for September/October 1983.

The September/October 1983 random-save data [Fig. 5(c)] does show a large excess (4.2σ) in the phase interval 0.50–0.65 and we have examined this more closely. To determine how this excess varies with time we plot the cumulative excess in a given phase interval as a function of the total number of expected events for that interval; i.e., observed minus expected events versus expected events, both summed from the beginning of the data sample in September 1982 until a given date. The abscissa is expected events rather than the more convenient date, because the former is the relevant parameter which allows for such things as variations in live time and source position. An approximate time scale is included in the plots but it is nonlinear and will vary slightly between phase bins. Figure 6 shows full cumulative excess plots for the three phase bins from 0.50–065, while the region corresponding to September/October 1983 is shown in more detail in Fig. 7. From these two figures it can be seen that for September/October 1983 the excess between phases 0.60 and 0.65 does not obviously display any unusual behavior. On the other hand, the other two phase bins (0.50–0.60) show an unusually rapid accumulation of excess at this time, beginning in both cases on about 1 October and extending until ~15 October in the 0.50–0.55 bin, and until ~10 October in the 0.55–0.60 bin. For comparison, Fig. 8 shows the gross features of the radio

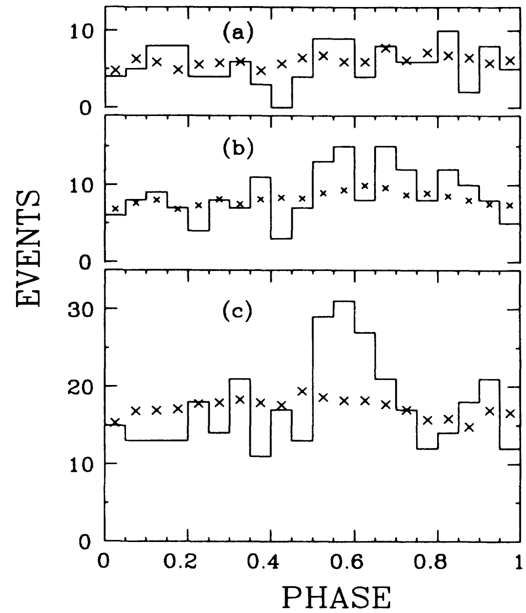

FIG. 5. The phase distributions of the random-save muons at Cygnus X-3 radio flare times. The solid histograms are the observed distributions, crosses are the expected. (a) 280/64 h live time from 14 September until 8 October 1982; (b) 403/64 h live time from 2 February until 3 March 1983; (c) 690/64 h live time from 17 September until 31 October 1983.

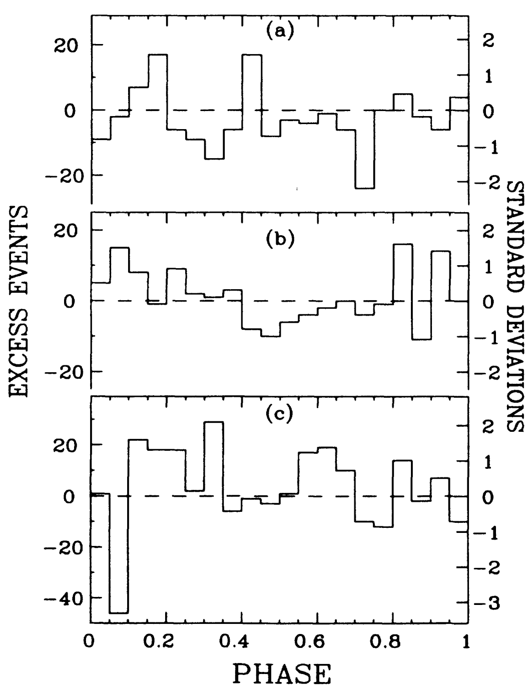

FIG. 4. Background-subtracted phase distributions of the uncut sample for times around reported radio outbursts of Cygnus X-3. (a) 55 h live time on 16, 17, and 23 September, and 3, 4, 5, 6, 7, and 8 October, 1982; (b) 36 h live time on 1, 2, 15, 21, 24, 25, and 28 February and 1 March, 1983; (c) 71 h live time on 16, 21, and 22 September and 12, 24, 25, 26, and 27 October 1983.

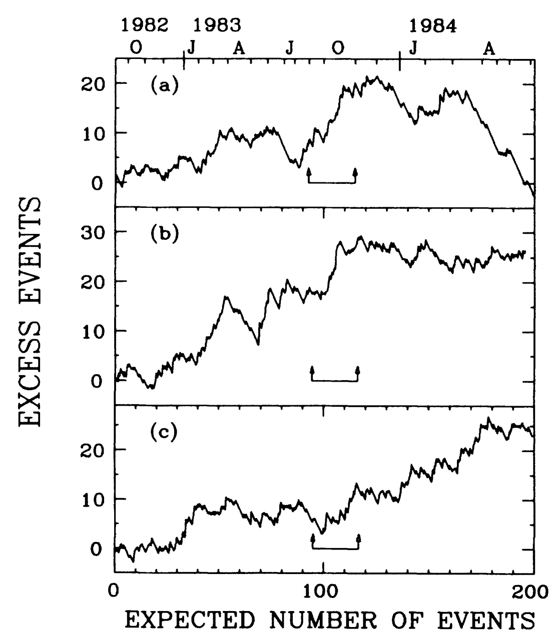

FIG. 6. Cumulative excess plots for the random save muons between phases 0.50 and 0.65. These plots show how the excess, which can be negative, varies with time. For phases (a) 0.50–0.55, (b) 0.55–0.60, and (c) 0.60–0.65. The arrows indicate the regions shown in more detail in Fig. 7.

flux from Cygnus X-3 over the same period.[13] The apparent temporal correlation of the excess muons with the radio flare is interesting, but lacking a model we are unable to assign a statistical significance to it.

Because the Cygnus X-3 period is indistinguishable from one-fifth of a day over such short periods of time, we investigate the possibility of a diurnal origin of the excess by dividing the data into two 12-h periods each day. To maximize the statistics we use data from 1 to 12 October and 10 phase bins. These phase distributions (Fig. 9) show that both halves of the day contribute to the excess. This is not consistent with a diurnal origin which would give an excess in only one of two halves.

As a further check we analyzed events that were saved because their trigger occurred within 10 msec of a previous trigger, for September and October 1983. This provides a second independent sample of about the same size as the random-save sample. The phase distribution for these events from 1 to 12 October [Fig. 10(a)] shows only a slight excess (2.2σ) at 0.50–0.60. The cumulative excess plot [Fig. 11(b)], while reflecting this marginal significance, shows a similarity to the plot for the previous sample [Fig. 11(a)]. The phase distribution and cumulative excess plot for the sum of the two samples are shown in Figs. 10(b) and 11(c), respectively. From Fig. 11(c) it appears that the excess occurs in two distinct episodes, the first from about 2–5 October and the second from 9–11 October. It should be noted, however, that the sample does not include data from 28 September to 1 October, or from 6 October. Also, the only uncut data we have close

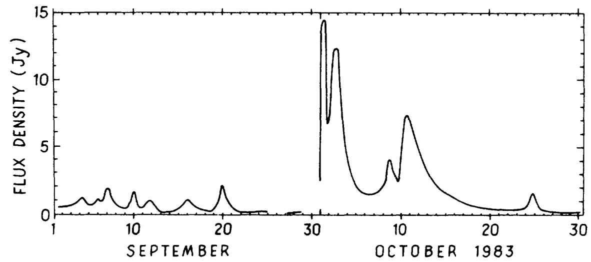

FIG. 8. The radio flux from Cygnus X-3 during September and October 1983. This is based on the observations at 3.75, 6, and 11 cm reported in Ref. 13.

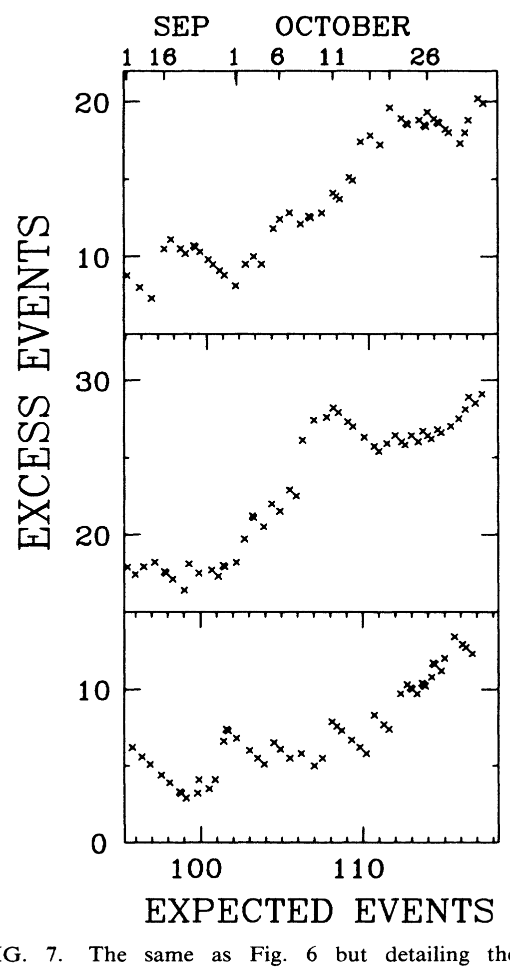

FIG. 7. The same as Fig. 6 but detailing the period September/October 1983. The horizontal axes have been shifted slightly so that the three plots are aligned by date. Each point represents one data tape.

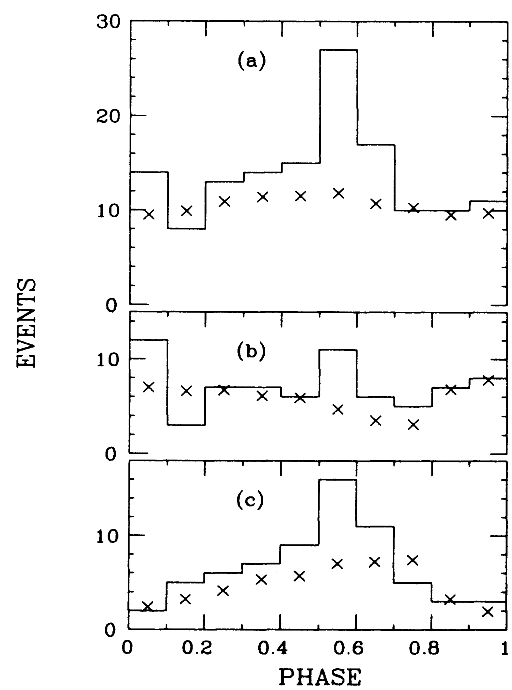

FIG. 9. The phase distribution for the random save muons for 1–12 October 1983. The solid histogram is the observed distribution, the crosses the expected. (a) No restriction on time of day (203 h on-time); (b) for data between 0030 and 1230 UT (101 h); (c) for data between 1230 and 0030 UT (102 h).

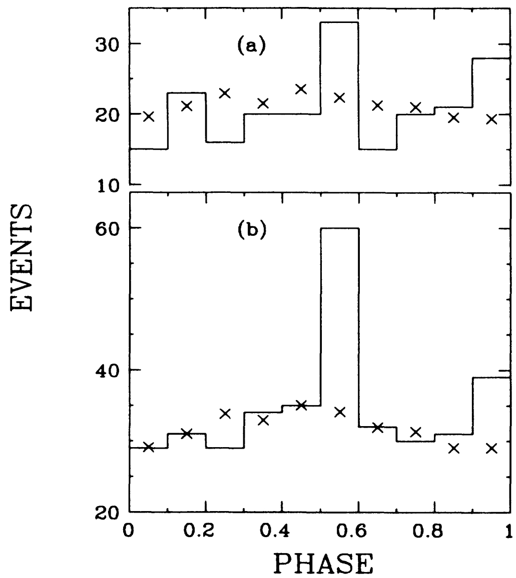

FIG. 10. (a) The phase distribution for the 10-msec sample between 1 and 12 October 1983. (198 h on-time.) (b) The sum of the distributions in Figs. 9(a) and 10(a).

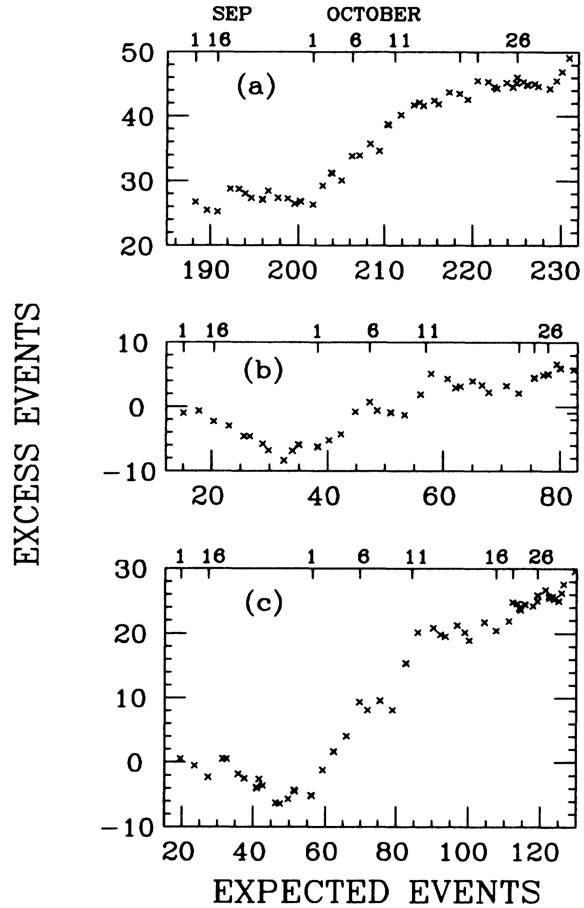

FIG. 11. Cumulative excess plots for September/October 1983 and phase 0.50–0.60. (a) The random-save muon sample. The zero on both scales is in September 1982. (b) The 10-msec sample. This is a limited sample beginning in August 1983. (c) The sum of (a) and (b). The zeros for this plot are the same as for (b).

to this time is on 12–13 October. The absence of an excess in the uncut sample [Fig. 4(c)] is not then in conflict with excess in the random and 10-msec samples [Figs. 5(c) and 10].

The excess between phases 0.50 and 0.60 in Fig. 10(b) is 4.3σ. The statistical significance is reduced by the *a posteriori* choice of the final data subset and of the phase bin. This excess would correspond to an average flux over the twelve days of 1.0×10^{-9} $cm^{-2}sec^{-1}$ at 1800 mwe.

TABLE I. A summary of the Cygnus X-3 muon flux limits (90% C.L.) obtained with the IMB detector. The results of the two groups that have reported positive results are shown for comparison. For the IMB random-save sample only $\frac{1}{64}$ of the events are saved, so the total exposure is reduced by this factor.

Data sample		Observation period	On-time (h)	Flux (limit) ($cm^{-2}sec^{-1}$)
Soudan (Ref. 2)[a]		Sept. 1981–Nov. 1983	8400	7.3×10^{-11}
IMB[a]	Uncut	Sept. 1982–April 1984	655	$\leq 6.9\times10^{-11}$
	Random	Sept. 1982–June 1984	8200	$\leq 1.8\times10^{-10}$
	Uncut	14 Sept.–8 Oct., 1982	55	$\leq 1.7\times10^{-10}$
	Random		280	$\leq 1.1\times10^{-9}$
	Uncut	2 Feb.–3 March, 1983	36	$\leq 2.0\times10^{-10}$
	Random		493	$\leq 2.1\times10^{-9}$
	Uncut	17 Sept.–31 Oct., 1983	71	$\leq 1.9\times10^{-10}$
	Random		690	$\leq 7.2\times10^{-10}$
NUSEX (Ref. 4)[b]		June 1982–Jan. 1985	16000	8.5×10^{-12}
IMB 70°–80°[b]		March 1983–June 1984	490	$\leq 1.7\times10^{-11}$

[a]For these results the flux (limit) is for orbital phase 0.65–0.90, and for a depth of 1800 mwe.
[b]For phase 0.70–0.80 and depth 4600 mwe.

SUMMARY

We find no evidence of a muon flux associated with Cygnus X-3 at the phase at which the Soudan experiment found an excess. The upper limit from our total data sample is similar to the flux measured by Soudan but is not in conflict with it. Using large zenith-angle muons we have looked for a signal at slant depths corresponding to the NUSEX experiment. In this case our upper limit is a factor of 2 above the reported flux. We have also searched for a signal at the times of the three Cygnus X-3 radio bursts. Once again we find no evidence for an excess in the phase interval 0.65–0.90. These results are summarized in Table I. We have found an interesting correlation between a 4σ excess phase 0.50–0.60 and the October 1983 radio outburst. We know of no other reported underground effects which might be associated with this observation.

ACKNOWLEDGMENTS

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