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UNDERGROUND MUONS FROM THE DIRECTION OF CYGNUS X-3*

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We report on 3.2 years live time of underground muon observations taken between 1981 and 1989 using the Soudan 1 proportional tube detector, located at a depth of 1,800 m water equivalent. The post-1984 observations are consistent with our earlier data on an excess signal apparently correlated with the Cygnus X-3 orbital period. The signal-to-background ratio in the entire data sample is 1 to 3 percent, depending on phase width.

Introduction. For the past several years, we have continued utilizing the Soudan 1 detector to record and analyze data on underground muons from the direction of the x-ray binary Cygnus X-3 (Cyg X-3). The goal of this effort is the collection of data which might assist in determining the correctness of the independent 1985 reports by us¹ and the NUSEX collaboration², which suggested a modulation in the underground muon flux from the direction of Cyg X-3 at the 4.79 h orbital period of that binary. These reports have elicited considerable skepticism³, both because of possibly contradictory evidence from other detectors and because such modulation cannot result from known physical mechanisms.

Data Analysis and Observations. The methodology for this analysis has been fixed⁴, in order to reduce bias from methodology changes based on the data themselves. We reconstruct all single muon events observed in the 8 m² Soudan 1 proportional tube detector, which is located at 48° N. latitude, 92° W. longitude at a depth of 590 m (1800 m water equivalent). Events which have valid arrival time data and which traverse at least 1 m of the detector with at least 6 proportional tube hits are saved for further analysis.

Despite a detector angular resolution determined as ± 25 mr by an analysis of multimMuon events, we select events with muons located within a 3° half-angle cone centered on the 1987 coordinates of Cyg X-3 ($\alpha = 308.00^\circ$, $\delta = 40.92^\circ$) for analysis as the Cyg X-3 sample. We simultaneously choose events as background samples, which are pointed within 35 other 3° half-angle cones centered at the same declination as Cyg X-3, but at right ascensions spaced at 10° intervals. This large angular cut has no *a priori* rationale, other than it enhanced the effect observed in Ref. 1 and an even larger angular cut relative to detector resolution was chosen in Ref. 2, presumably for similar reasons.

The data reported here consist of 1,195 events (called Data I) containing single tracks within the 3° half-angle Cyg X-3 cone selected from a total of 780,485 events passing cuts during a detector live time of 1.02 years between September 1981 and November 1984 and 2,480 events (called Data II), also with single tracks within the same cone, selected from 1,583,922 events passing cuts during 2.20 years of live time between May 1985 and June 1989. The Data I sample here differs somewhat from Ref. 1, principally because of a 2° change in detector azimuthal alignment relative to north and the use of a newer ephemeris.

As in Ref. 4, the analysis reported here consists of both a time-independent, integrated flux

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analysis and a time-dependent, Cyg X-3 phase-related analysis. This investigation of time-dependence relates only to the Cyg X-3 orbital phase and not to possible flux "bursts." For the phase-dependent analysis, we have used the 1988 van der Klis and Bonnet-Bidaud cubic ephemeris⁵ (vdKBB-88). The principal hypothesis in both these analyses is that in the absence of a signal, the total number of events in any 3° half-angle cone fluctuates only statistically from the expected value. We further hypothesize that the expected number of events in any cone is a smooth function of right ascension, (presumably due to varying exposure), and that the events in any 3° half-angle cone are uniformly distributed with respect to Cyg X-3 orbital phase.

We have tested all of these assumptions in the following manner: We binned the events in each of the 35 3° half-angle cones into 20 Cyg X-3 phase bins, a total of 700 background bins. We have fit the contents of all 700 background bins with a single function $x_1 + x_2 \cos(\alpha + x_3)$, where α is the right ascension and the x_i are determined by minimizing the χ^2 of the fit. The values of χ^2 determined by this procedure are 691.0 for Data I, 705.0 for Data II and 715.4 for Data I and Data II combined. Since there exist 697 degrees of freedom in each case, the probabilities for such χ^2 values using our hypotheses are all between 0.25 and 0.75. We therefore conclude from the off-source data that our assumptions about the detector are correct and that we may proceed to analyze the data for the Cyg X-3 direction.

The right ascension analysis described above for the on-source and the 35 off-source directions indicate that the Cyg X-3 direction contains 3,675 events while 3,639 events are expected in this direction from the background fit. A possible interpretation of this analysis is the hypothesis of a signal at a level of (1.0 ± 1.7) percent of the background. We note that a true signal of, for example, 2 percent (which is consistent with the analysis described below) implies that a century's data with a detector the size of Soudan 1 would be required to obtain a 4σ result by this type of d.c. analysis.

A phase-dependent analysis offers the possibility of a significant improvement in the signal-to-background ratio. We have already demonstrated from the off-source data the validity of the expectation that all phase bins are uniformly populated under the assumption of no source. Fig. 1 shows the phase plot for the Cyg X-3 direction for Data I, Data II and Data I and Data II combined. The expected contents for each bin from the off-source analysis is also shown.

Hypothesis Testing and Flux Measurements. There are several questions that we may attempt to answer from the data in Fig. 1. Are the distributions shown consistent with uniformity, that is, no signal? What is the time dependence of the signal (if any) over the interval 1981-1989? There is no single statistical test which best answers such questions. Tests which assume no particular model for a signal are generally not very powerful; that is, they do not distinguish well between the signal and non-signal hypotheses in cases such as that illustrated in Fig. 1 where the signal-to-background ratio (if there is a signal) is small and the number of events is limited. Tests which presume a specific form for a signal are more powerful, but the biases involved in determining the model are difficult to determine and the choices made in this procedure are hard to enumerate.

Examples of general tests are the χ^2 and the Rayleigh statistics. Using the off-source determined expectation values, the χ^2 statistics for Fig. 3 (all with 20 degrees of freedom) are 23.1 (probability for uniformity .28) for Data I, 25.2 (probability for uniformity 0.20) for Data II and 30.7 (probability for uniformity 0.06) for Data I and Data II combined. The χ^2 statistic that Data I and Data II are consistent is 17.9 (probability for consistency 0.60). The Rayleigh statistics are 2.55 (probability for uniformity 0.08) for Data I, 0.92 (probability for uniformity 0.40) for Data II, and 2.37 (probability for uniformity 0.09) for Data I and Data II combined.

It would be possible to develop more powerful tests if we knew *a priori* the phase dependence of the signal. In Table 1, we list the parameters of excesses corresponding to several different definitions of the signal phase region. The broadest definition described there is the region 0.60 to 0.90, which is roughly comparable to the phase region defined in Ref. 1, using an

Fig. 1. The number of muon events as a function of Cyg X-3 orbital phase for the Data I, Data II and combined samples. The lines indicate the expected values obtained from the fit described in the text.

Fig. 2. The cumulative number of excess events as a function of Julian Day for the phase range 0.70-0.75 (filled squares) and 0.60 to 0.90 (open squares). Data I is to the left and Data II is to the right of the gap.

earlier ephemeris. A second definition, 0.60 to 0.75, is motivated by several reviews⁶ of air shower data (translated to the vdKBB-88 ephemeris) presumably related to radiation from Cyg X-3 during the interval 1981-1989. A third possibility is intuitively motivated by the data in Fig. 1, which show a narrow phase peak in the range 0.70 to 0.75. Table I indicates that for all three such definitions, the probability for uniformity is of order 10^{-3} , which shows the power of specific tests.

It is important to emphasize that the Soudan 1 data themselves do not distinguish among these or similar hypotheses for the phase dependence of the signal, if any. This difficulty also carries to the evaluation of a flux from the phase-dependent analysis. The data in Table 1 yield a factor of two variation in flux, depending on the phase range definition for the signal. The flux associated with the narrowest signal, 43 excess events, agrees best with the d.c. excess of 36 events, but the uncertainties in the latter mean that the 90 excess events associated with the broadest signal are also in reasonable agreement with the d.c. excess.

Thus, we can only give a range of fluxes. The overall time-averaged flux is $(5.3 \text{ to } 11) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, which (assuming a $\cos^3 \theta_z$ zenith angle dependence) yields a flux of $(1.5 \text{ to } 3.2) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, if Cyg X-3 were constantly overhead, that is, corresponding to a depth of 1800 m water equivalent. The peak fluxes, those are the fluxes during the phase region in which Cyg X-3 is emitting, corrected as if Cyg X-3 were always overhead, are $(1.1 \text{ to } 3.0) \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$. These fluxes assume no "burst" modulation of emission from the source.

Using these phase ranges for the signal, we can compare the fluxes implied by the Data I and Data II samples. Fig. 2 shows the time development of the apparent flux excess for the phase ranges 0.60 to 0.90 and 0.70 to 0.75. (The intermediate phase range data are omitted to simplify the graph.) The wide phase range data show apparent intervals of relative inactivity prior to the beginning of 1983 and from November 1985 to February 1987. The excess flux by this phase definition for Data II is thus about 2/3 of the flux for Data I. (Because of systematic improvements in the analysis procedures, the Data I fluxes listed here are smaller than the fluxes listed in Ref. 1). Thus, the wide phase range case is consistent with the interpretation by Bhat⁷ indicating that emission of radiation by Cyg X-3 has decreased in recent years. For the

narrowest phase range, the fluxes for Data I and Data II appear approximately constant. However, in all cases, the signal strengths in Data I and Data II are statistically consistent with each other. The consistency hypothesis is supported with a probability of >40 percent for all three phase regions.

Conclusion. Continued observations with the Soudan 1 detector since mid-1985 continue to confirm the earlier evidence for a modulation of the underground muon flux from the Cyg X-3 direction at the orbital period of that binary. The data collected since 1985 (Data II) are predicted in a statistical sense by the pre-1985 data (Data I). For the selected phase ranges, both data sets are inconsistent with the hypothesis of no signal. However, the statistical significance of the combined result continues to grow more slowly than might be expected from the pre-1985 data set. The overall signal level, if a signal exists, is not more than a few percent. This level is small enough that a detector much larger than Soudan 1 will be required to determine with a high level of confidence whether underground from the direction of Cyg X-3 are modulated by the Cyg X-3 4.79 h orbital period.

References

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- ¹ M. L. Marshak et al., Phys. Rev. Lett. 54, 2079 (1985) and 55, 1965 (1985).
- ² G. Battistoni et al., Phys. Lett. 155B, 465 (1985).
- ³ For a review, see J.-M. Bonnet-Bidaud and G. Chardin, Phys. Reports 170 (1988) 325.
- ⁴ K. Johns, et al., Proceedings of the XXIV Conference on High Energy Physics Munich 1988, ed. by R. Kotthaus and J. Kuhn (Springer-Verlag, 1989), pg. 1307.
- ⁵ M. Van der Klis and J. M. Bonnet-Bidaud, Astronomy and Astrophys. 214 (1989) 203.
- ⁶ D. E. Nagle et al., Ann. Rev. Nucl. Sci. 38 (1988) 609; T. Weekes, Phys. Reports 160 (1988) 1; R. J. Protheroe, Proc. 20th Intl. Cosmic Ray Conf. 8 (1988) 21.
- ⁷ C. L. Bhat et al., Astrophys. J. 306 (1986) 587.
- ⁸ Y. Oyama et al. Phys. Rev. Lett. 56 (1986) 991.
- ⁹ Ch. Berger et al. Phys. Lett. B 174 (1986) 118.
- ¹⁰ R. M. Bionta et al. Phys Rev. D 36 (1987) 30.

Table 1. The number, number of standard deviations and probability for fluctuation from a uniform background of the excess muon or "signal" events observed in the Soudan detector from the Cygnus X-3 direction for the Data I (1981-1984), Data II (1985-1989) and Data I and II combined samples for differing phase region definitions.

Phase Range	Data I	Data II	Data I + II
0.60-0.90	37.1 1.97 σ p<0.025	49.2 1.80 σ p<0.036	90.2 2.73 σ p<0.0032
0.60-0.75	12.3 0.93 σ p<0.18	54.2 2.81 σ p<0.0025	68.1 2.91 σ p<0.0018
0.70-0.75	14.0 1.82 σ p<0.034	28.4 2.56 σ p<0.0052	43.0 3.19 σ p<0.0007