Evidence for Muon Production by Particles from Cygnus X-3

M. L. Marshak, J. Bartelt,[a] H. Courant, K. Heller, T. Joyce, E. A. Peterson, K. Ruddick, and M. Shupe
School of Physics, University of Minnesota, Minneapolis, Minnesota 55455

and

D. S. Ayres, J. Dawson, T. Fields, E. N. May, L. E. Price, and K. Sivaprasad[b]
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
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We have observed underground cosmic-ray muons, corresponding to a secondary flux of $\sim 7\times 10^{-11}$ cm^{-2} s^{-1}, at a depth of 1800 m water equivalent, which appear to be initiated by Cygnus X-3. This identification is based on both direction and phase coherence. The existence of such secondary muons conflicts with the current understanding of photon cascades and/or the nature and location of Cygnus X-3.

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Several observers have reported[1-3] air showers originated by 10^{12}–10^{15}-eV cosmic-ray primaries from the direction of the x-ray binary Cygnus X-3 (declination $\delta = 40.8°$, right ascension $\alpha = 307.6°$). The identification of Cygnus X-3 as the source relies on both the shower arrival direction and the observation of a flux enhancement in a phase plot made with use of Cygnus X-3's characteristic 4.8-h period.[4]

The phase coherence over a distance of more than 10 kiloparsecs[5] indicates that the primaries have a velocity within 10^{-9} of c. The directionality of the showers, their energy, and the existence of a galactic magnetic field indicate that the primaries must be electrically neutral. For these reasons and because Cygnus X-3 is a known kiloelectronvolt x-ray emitter,[6] these high-energy primaries have been assumed to be photons.

Photons incident on the atmosphere should be very inefficient at producing high-energy muons.[7] Hadronic photoproduction, which would produce muons via pion decay, is suppressed by a factor of about 300 from e^+-e^- pair production at 100 GeV and rises only logarithmically with energy. Direct muon production has an even smaller probability. In contradiction to these considerations, surface detector data[8] have indicated that air showers initiated by primaries from Cygnus X-3 have only a slightly lower muon content than hadronic showers. A recent analysis[7] finds such a result to be unlikely for photon-initiated showers and concludes that the observation may be caused by a misidentification of secondary shower particles as muons.

We have recently reported evidence from the Soudan-1 proton-decay detector[9] for unexpected inhomogeneities in the underground muon flux. These data concern multimuon events in which two or more parallel, time-coincident muons were observed in a detector 2.9 m by 2.9 m horizontally by 1.9 m high. Although one of the observed source regions was in a direction centered about 20° from Cygnus X-3, the characteristic 4.8-h period of this source was not apparent. Multimuon events were chosen for that analysis because they result from higher-energy primaries than single-muon events.

We have now analyzed single-muon data from this same detector during the same data-collection period of September 1981 through November 1983. Here we present results concerning single-muon events arriving from the direction of Cygnus X-3. The observation of deep underground muons related to Cygnus X-3 at a flux similar to or greater than that previously identified as photons could indicate a misidentification of the primaries, which would have considerable astrophysical or particle physics implications. Alternatively, it could signal a new mechanism for muon production in ultra-high-energy photon cascades, which would have important particle physics consequences.

The Soudan-1 proton-decay detector and the data-collection and analysis procedures are described in Ref. 9. 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. The detector is located at a depth equivalent to 1800 m of water.

The current data sample consists of 784 456 events recorded during a live time of 0.96 yr. These events were selected by the requirement of a single straight track within the detector resolution. Each event was required to have a minimum of eight proportional-tube hits in each of the two orthogonal views. 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.

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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.

Determining the background distributions, i.e., those events that would be seen from a constant, isotropic source distribution, is important for this analysis. We have calculated the backgrounds using the data themselves. The method was as follows: We considered each event in detector coordinates. We paired with each event ten event arrival times selected at random from the entire data sample. The local coordinates (zenith and azimuth) of the original event and the ten event times were used to generate ten fake events for the background ensemble. The celestial coordinates for these ten events were then calculated. The background ensemble thus contained 10 times as many events as the real data. We applied similar cuts to the real and background data and divided numbers of the latter by 10 for presentation in the figures.

As in previous experiments, showing a relationship between our observations and Cygnus X-3, relies on the demonstration of phase coherence with the 4.8-h period of the source. These data are given in Fig. 1 for events whose arrival directions lie within 3° of $\delta = 43.50°$, $\alpha = 306.74°$. This direction has been chosen to maximize the observed signal as discussed below. We have used a quadratic ephemeris consistent with Ref. 4, namely, $t_0 = \mathrm{JD}\,2\,440\,949.8986$ (JD denotes Julian day), $p_0 = 0.199\,683\,15$ d, and $\dot{p} = 1.18 \times 10^{-9}$. The plot shows the event arrival times modulo the 4.8-h period, expressed as a fraction of the period. The background in Fig. 1 is approximately flat as would be expected from a complete absence of correlation between the detector efficiency and the period of Cygnus X-3. The χ^2 for agreement between the observed data and the background is 54.5 for twenty degrees of freedom. The χ^2 for agreement between the observed data and the observed data mean is 49.5 for nineteen degrees of freedom, a probability of < 0.0002. (This latter χ^2 test for the null hypothesis is used in the remainder of this paper.) The major phase enhancement in Fig. 1 extends from a phase of 0.65 to a phase of 0.90 and consists of 84 ± 20 events, which is equivalent to a secondary flux of $\sim 7 \times 10^{-11}$ cm^{-2} s^{-1} integrated over the entire period.

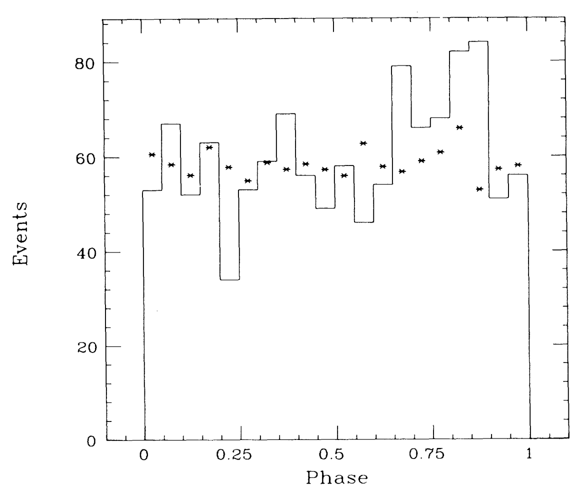

FIG. 1. Phase plot for events within 3° of the observed position of Cygnus X-3. The solid histogram shows the observed data. The points represent the expected number of events for a constant, isotropic source.

This phase enhancement can be compared to previous aboveground observations over a range of energies. At kiloelectronvolt energies,[4] the enhanced phase ranges from 0.18 to 0.78. Most results at teraelectronvolt energies are consistent with Ref. 1 (see also review in Ref. 3), which shows an enhancement of width of 0.2 centered at 0.73. The enhancement narrows even more at 10^{15}-eV energies, ranging from 0.225 to 0.250 in one observation[3] and from 0.20 to 0.30 in the other[2] (after correction[3] for the ephemeris used here[4]). Our observed secondary flux is equal to the primary flux attributed to photons[3] from Cygnus X-3 at an energy of $\gtrsim 1$ TeV.

We have performed several checks on the data presented here including tracing the dependence of the χ^2 for the phase plot as a function of declination, right ascension, and period, as shown in Fig. 2. Since each point has been calculated by use of 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; it is not clear whether the difference is an instrumental effect.

Other checks on these results included a systematic search of the sky with 900 $6° \times 6°$ bins using the ephemeris of Cygnus X-3. The χ^2 distribution for the phase plots for these bins was consistent with the distribution expected from a random background. The largest observed χ^2 away from the Cygnus X-3 was 44, which has a probability of $< 10^{-3}$.

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 (for example, from neutrino primaries). However, there is some evidence that the

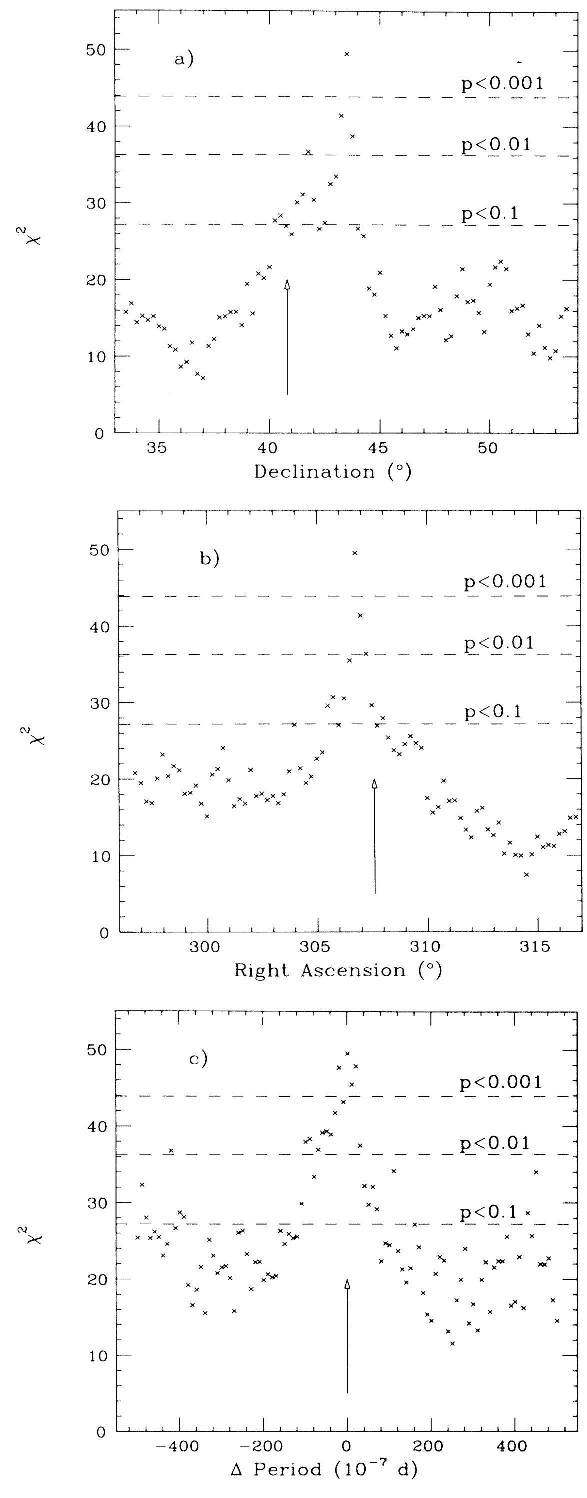

FIG. 2. χ^2 distribution for the phase plot as a function of (a) declination, (b) right ascension, and (c) the difference in the period from the value in Ref. 4. As indicated in the text, nearby points are not statistically independent. The dashed lines indicate probability levels of 0.1, 0.01, and 0.001. The arrows indicate the nominal values of the abscissa.

position of the phase peak shifts with zenith angle. With 90% confidence, the phase peak for events with zenith angles greater than 66° is located between 0 and 0.5 rather than between 0.5 and 1.0, as is the case for vertical events. Larger zenith angles presumably correspond to higher-energy primaries.

We remark briefly on several other points. Within statistics, the signal in Fig. 1 appears constant over the entire data-collection period. We also observe four multimuon events within 3° of our origin direction. Three of these events lie within the 0.65 to 0.90 phase peak; the phase of the fourth event is 0.62. The three events in the phase peak occurred within 2.5 d and within 1° of each other on 20–22 April 1983.

We have only limited information about the primary particle type, energy, and flux. These parameters are related. The relationship between the primary flux and the secondary flux depends on the mean number of muons per primary at the Soudan 1 depth, which in turn depends on primary energy and particle type. We can summarize the possibilities as follows.

(a) Neutrons: Neutrons require an energy of 10^{18} eV to reach Earth from the distance of Cygnus X-3 in one lifetime. The flux of all known cosmic rays above such an energy would produce of order one event per year in the Soudan 1 detector.

(b) Neutrinos: Neutrinos are excluded by the zenith-angle distribution.

(c) Photons: For consistency with previous measurements of surface fluxes,[1,3] the muons which we observe must come from primary photons with energy of ~ 1 TeV. A vertical muon requires about 600 GeV to reach the Soudan 1 detector. Such a muon is extremely unlikely to result from a 1-TeV photon primary. On the other hand, if the primary energy is several orders of magnitude higher, then our observed flux has an inconsistency of several orders of magnitude with the fluxes measured on the surface.

(d) New neutral particle: A fourth possibility is a new neutral primary with a large cross section for direct and indirect muon production. A new interaction or particle would require an unknown adjustment in the energy calibration of the air-shower experiments.

In summary, we confirm the effect reported in Ref. 8 but with muons of substantially higher energy and at a flux 3 orders of magnitude larger. Our observations indicate that the dilemma posed in Ref. 7 must be faced without recourse to particle misidentification as an explanation for the observed muons.

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Note added.—Since preparing this Letter, we have studied in detail the significance of our observation, specifically asking the following: (1) How is the statistical significance affected by our choice of an optimized declination 2.7° away from Cygnus X-3? (2) What significance is indicated by statistical quantities sensitive to the phase and flux structure of Cygnus X-3 as contrasted to the general χ^2 test? We conclude that the probability of a random fluctuation simulating Cygnus X-3 in our data is between 10^{-4} and 10^{-3}.

[a]Present address: Stanford Linear Accelerator Center, P.O. Box 4349, Stanford, Cal. 94305.

[b]Present address: Department of Physics, University of Maryland, College Park, Md. 20742.

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