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

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ABSTRACT

The Soudan 1 experiment has obtained additional evidence for underground muons associated with the x-ray pulsar Cygnus X-3. We report the preliminary analysis of data recorded during the October 1985 radio outburst of Cygnus X-3, which show a significant excess of muons for a narrow range of Cygnus X-3 phases.

Several observers have reported cosmic-ray air showers originated by 1 to 1000 TeV primaries associated with the x-ray pulsar Cygnus X-3.¹ Both the direction (declination 40.8° , right ascension 307.6°) and flux modulation characteristics (4.8 hour period) of Cygnus X-3 are used to associate the showers with this source. The primaries must be stable (Cygnus X-3 is at least 37,000 light years away), electrically neutral (to avoid deflection by the galactic magnetic field), light (to preserve the phase signature), and must initiate showers in the atmosphere (to be detected). The photon is the only known particle which satisfies the criteria.

During 1981-3, the 30-ton Soudan 1 proton-decay detector acquired a large data sample of cosmic-ray muons which had penetrated its 2000 ft rock overburden (surface energy > 650 GeV). Analysis of these data by methods similar to those used by air-shower experiments have shown evidence for a substantial flux of underground muons associated with Cygnus X-3.² This flux is several hundred times that expected from the photon primaries associated with the source, leading to a serious dilemma which seems to require the existence of a new phenomenon. Either multi-TeV photons have an unexpected new interaction which produces high-energy muons, or the primary is a new, neutral, light, stable particle. While the NUSEX experiment has also reported underground muons associated with Cygnus X-3,³ other experiments have reported flux limits lower than Soudan 1 and NUSEX.⁴

The Soudan 1 detector recorded 340,000 cosmic-ray muon events between February 1985 and February 1986. This 0.4 year live-time data sample is about 40% of the 1981-3 sample. We report here the preliminary results from the analysis of the new data. The previous evidence for underground muons associated with Cygnus X-3 relied on coherence with the precisely known 4.8-hour periodicity of the source.² Events pointing to within 3° of the source direction were binned according to the phase determined from the arrival time and the known ephemeris of Cygnus X-3.⁵ The

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resulting phase plot showed an excess of events with phases between 0.65 and 0.90, consistent with the phases of air-shower observations. The new data show no evidence for an excess of events in any phase interval. Similarly, no signal is seen in the phase plot for muons which arrived during high-rate periods (within 30 minutes of another muon).²

From 3-13 October 1985, Cygnus X-3 produced the most intense radio outburst ever recorded for this source.⁶ The phase plot for the 102 muon events recorded between 24 September and 7 October is shown in Fig. 1. The signal has been enhanced by choosing this two-week period about a week earlier than the peak in radio emissions, by increasing the angular acceptance from a 3° to a 5° half-angle cone, and by choosing phase bins of 0.025 instead of 0.05. The background shown in the figure was obtained from 23 5° cones centered at the same declination as Cygnus X-3, but at other right ascensions spaced at 15° intervals. Figure 2 shows the rate of muons per week in the 0.725-0.750 phase interval selected from Fig. 1. The 16 events recorded from 24 September to 21 October is much larger than the 6.3 events expected from the analysis of the 23 background directions during the same four weeks; the Poisson probability for such an occurrence is 0.05%. The probability of such a fluctuation occurring in one of the 10 phase bins of our 1981-3 peak is ten times this, or 0.5%.

In order to better assess the statistical significance of this result, we have performed a search for other bursts of muons in

Fig. 1. Cygnus X-3 phase plots for events between 24 September and 7 October 1985, within 5° of the source direction. The solid histogram is for the Cygnus X-3 direction, and the dashed histogram is for 23 the off-source directions.

narrow bins of Cygnus X-3 phase and time. The number of events in each of 4600 bins of phase (0.005 bin width) and time (2 week bin width) was calculated for the 1985-6 data sample. Figure 3 is a histogram of the occupation frequency of these two-dimensional phase-time bins, for both the Cygnus X-3 direction and the 23 background directions. The average number of events per bin is 0.3; the numbers of events expected from the Poisson distribution with this average are shown in the figure. The phase-time bin with 6 muons has the phase range of 0.740 to 0.745 and the time range of 24 September to 7 October. The probability of such an occurrence is consistent with the 0.5% derived from Fig. 2. Data from the 23 background directions had no bursts with more than five muons in any phase-time bin.

Observation of underground muons with Soudan 1 will continue until the much larger Soudan 2 experiment begins operation. With several other large underground experiments also operating, the question of whether Cygnus X-3 emissions include primaries which produce underground muons should be resolved within the next few years.

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Fig. 2. Events recorded per week within the phase interval 0.725 to 0.750. The solid histogram is for events within 5° of the Cygnus X-3 direction, and the dashed histogram is obtained from the 23 off-source directions. Weeks with zero background events indicate times when the detector was off.

Fig. 3. Frequency of occurrence of different bin populations in two-dimensional phase-time plots, for on-source (solid) and off-source (dashed) data during 1985-6. The average bin population is 0.3, and the points show the expected Poisson distribution for this average. The one bin with six events occurred during the Cygnus X-3 radio outburst.

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