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UNDERGROUND MUONS FROM CYGNUS X-3

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ABSTRACT

Underground detectors, intended for searches for nucleon decay and other rare processes, have recently begun searching for evidence of astrophysical sources, particularly Cygnus X-3, in the cosmic ray muons they record. Some evidence for signals from Cygnus X-3 has been reported. The underground observations are reported here in the context of previous (surface) observations of the source at high energies.

INTRODUCTION

Since its discovery in x-ray emissions in 1966[1], Cygnus X-3 has been observed across the electromagnetic spectrum from radio up to 10^{16} eV. The higher energy ranges (> 0.1 TeV) are observed in air showers where so far there is no direct identification of the primary particle. That these signals are a continuation of the electromagnetic radiation observed at lower energies is inferred from their spatial and temporal coherence, which, given the distance to Cyg X-3 (> 12 kpc) and the intervening magnetic fields, could only be provided by the photon among the known particles.

Some doubt was cast on the identification of the primaries from Cyg X-3 as photons by the Kiel experiment[2], which observed a muon content in extensive air showers from Cyg X-3 almost equal to that from background cosmic ray showers, assumed to be initiated by proton primaries. Photon-initiated showers would be expected to have a muon content lower by about a factor of 10.

It has recently become possible to extend the searches for muons associated with Cyg X-3 (and potentially from other point sources) to much higher energies by exploiting the underground tracking experiments which have begun operations in the last few years, designed primarily to search for nucleon decay. Initial results from these experiments show surprisingly high muon fluxes. If confirmed, these results appear to require either a new type of particle as the cosmic

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DISCLAIMER

ray primary or new interactions for photons (or possibly neutrinos) in the TeV energy range. This paper briefly reviews previous observations of Cyg X-3, then summarizes the observations of underground experiments, and finally mentions the efforts in progress to account for the underground muon fluxes.

HISTORY OF CYGNUS X-3 OBSERVATIONS

Cyg X-3 was first observed as a point source of x-rays in a rocket-borne detector[1]. The x-ray intensity was later found to be modulated with a regular period of approximately 4.8 hours[3]. TeV air showers were observed by the Cerenkov technique as early as 1972[4]. A giant radio outburst in September, 1972,[5] permitted a precise determination of the direction of the source, which led to detection in the infrared[6]. There followed in short order observations at 30 MeV[7] and 100 MeV[8]. The first observations in the PeV (10^{15} eV) range were made by the Kiel extensive air shower array group[9] and confirmation was provided by the Haverah Park EAS experiment[10].

All Cyg X-3 signals except for radio are correlated with the x-ray modulation of ca. 4.8 hours, which is generally interpreted as the orbital period of a close binary system, involving a compact star such as a neutron star and a normal companion star. Several precise fits to the x-ray modulation have been made. The one in general use now is due to van der Klis and Bonnet-Bidaud[11]. Although the x-ray signals from Cyg X-3 show a fairly continuous modulation with close to a sinusoidal shape, signals with energies above 100 GeV occur in a much shorter part of the 4.8 hour period, typically during only 0.1 of the total period. Observations cluster about two regions of phase at about 0.2 - 0.3 and 0.6 - 0.7, where the phase of the 4.8 hour period is defined to run from 0 to 1 and 0 (or 1) corresponds to the x-ray minimum. Most observations show signals in only one of these two phase groups.

The energy source for Cygnus X-3 emissions is understood to be accretion of matter from the companion star onto the compact star. The x-ray emission is then due to local heating[12], while gamma rays may arise from acceleration of protons to perhaps 10^{17} eV which then interact at grazing incidence with the material of the companion star to produce neutral pions,[13,14] which in turn decay to produce the observed photons.

Radio absorption measurements indicate that Cyg X-3 is at least 12 kpc (39,000 light years) from the earth. The estimated total energy emission is 10^{39} ergs/sec. It seems possible that Cygnus X-3 and perhaps a few other sources like it can account for all the high energy cosmic rays in the galaxy.[14] Observed fluxes from Cyg X-3 are shown in Fig. 1 for energies above 100 GeV. The integral spectrum is fit fairly well by a simple E^{-1} curve.

MUONS AND UNDERGROUND EXPERIMENTS

Several sophisticated detectors are now situated in underground locations at various depths, intended for searches for nucleon decays, magnetic monopoles, and other phenomena. Some of them have been used to search for muons from Cygnus X-3 with threshold energies set by the overburden ranging from 0.65 TeV to 3 TeV.

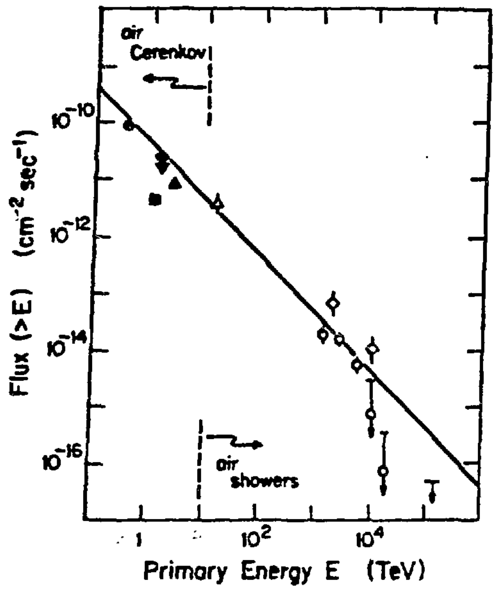

Fig. 1. Integral spectrum of air showers associated with Cygnus X-3. The solid line is a fit to an E^{-1} shape.

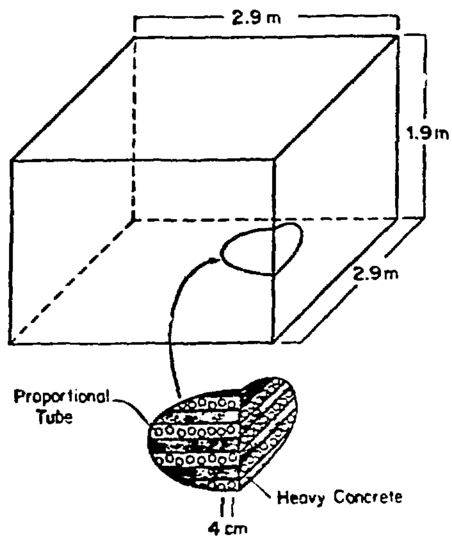

Fig. 2. The Soudan 1 detector.

As an example, the Soudan 1 detector[5] is shown in Fig. 2. It is constructed of horizontal layers of proportional tubes embedded in heavy concrete. Each layer is 2.9 m square and contains 72 tubes of diameter 2.8 cm. Alternate layers are rotated by 90°, so that two orthogonal views are generated of tracks in the detector. There are a total of 48 layers, making a total detector height of 1.9 m. The detector is placed in the Soudan iron mine in northern Minnesota at a depth of 1800 meters of water equivalent (mwe) at a location 48° N. latitude, 92° W. longitude. Data was collected between September 1981 and November 1983 for a live time of 0.96 year. Cosmic ray muons are observed in the detector as straight tracks. Typical angular resolution is estimated to be $\pm 1.4^{\circ}$ and the uncertainty in the absolute orientation of the detector is estimated to be $\pm 1.5^{\circ}$. The calculated rms multiple coulomb scattering angle for passage through the overburden is 0.8°.

Muons were selected coming from a 3^o half angle cone about the nominal direction of Cygnus X-3 ($\delta = 40.8^o$, $\alpha = 307.6^o$). Using the ephemeris of Ref. 11 to determine the Cyg X-3 phase of each event yields the histogram of Fig. 3a. Excess events above the background are seen in the phase range 0.65-0.90, amounting to 60 events. The background is determined from off-source α's and in the selected phase range has an rms uncertainty of 17 events, so that the significance of the peak is 3.5σ. Fig. 3b shows the phase plot for nearby off-source directions at the same declination. If the on-source phase peak were due to systematic effects such as a thin spot in the overburden or uneven distribution of live time, similar peaks should appear in the off-source distributions.

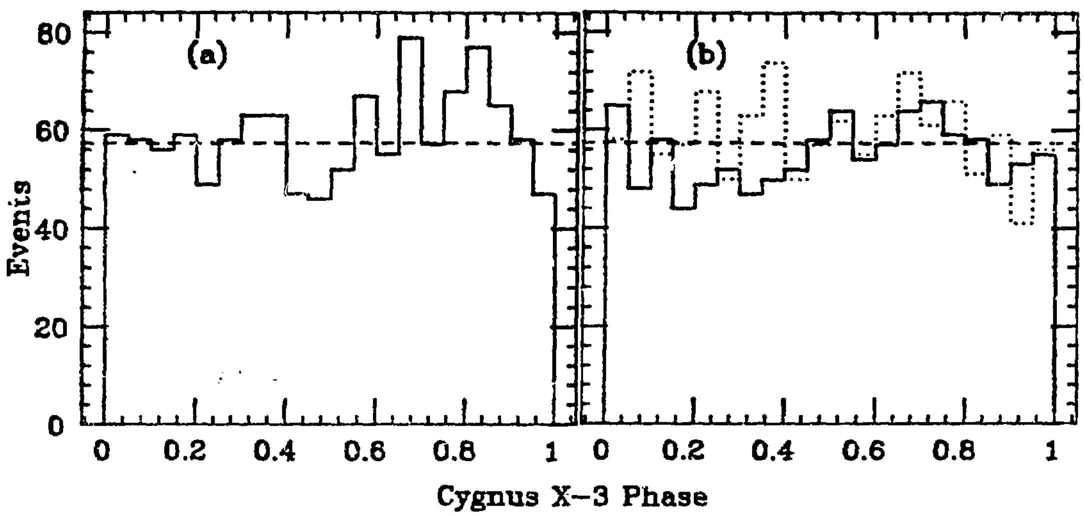

Fig. 3. Cygnus X-3 phase plots from Soudan 1 for (a) on-source muons and (b) off-source, with α less by 10^o (dotted) and greater by 10^o (solid). For both plots, the average background is shown dashed.

Since there is evidence of considerable variation in the intensity of Cyg X-3 in the air Cerenkov data [16], an attempt has been made to pick out high rate periods in the Soudan 1 data, by selecting pairs of muons within the 3^o cone about Cyg X-3 that come within 0.5 hour of each other. The result is Fig. 4, where the average phase of each pair has been plotted. Again a peak appears within the phase region 0.65 - 0.90 containing 29 events with a background uncertainty of 6 events, giving a significance of 4.5 σ.

The NUSEX experiment has also reported[17] results of a search for underground muons from Cygnus X-3. This experiment is located in a road tunnel under Mt. Blanc (45.8^o N. latitude, 6.8^o E. longitude) at a minimum depth of 4600 mwe, giving a threshold muon energy of 3 TeV. It is also a tracking detector with an area of $(3.5\ m)^2$. It has reported on data with a live time of 2.4 years, taken between June

1982 and February 1985, and has included muons within ±5° of Cyg X-3 in both δ and α. The resulting phase plot is shown in Fig. 5. It shows an excess above background in the phase bin from 0.7 - 0.8, containing 19 ± 3.6 events (5σ).

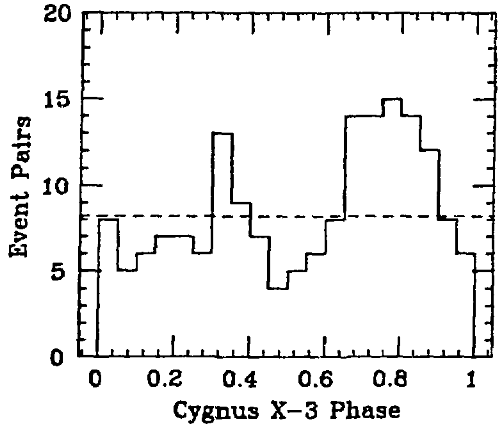

Fig. 4. Average phase of pairs of muons arriving within 0.5 hour in Soudan 1.

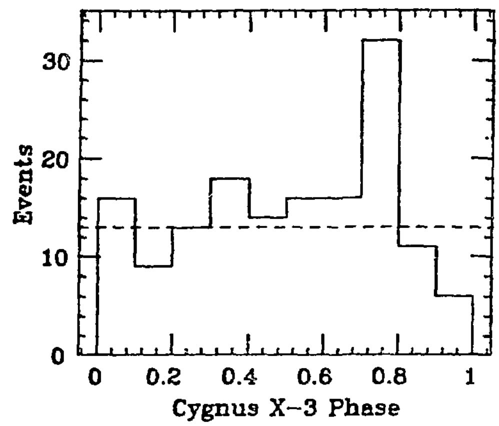

Fig. 5. Cygnus X-3 phase plot from NUSEX.

The Frejus experiment, located in the Frejus tunnel, has been taking data while completing the construction of their detector. Their minimum depth is 4400 mwe, corresponding to a threshold muon energy of 2.5 TeV, at a location 45.1° N latitude, 6.7° E. longitude. Completed, it has an area of 72 m^2. Early results from the Frejus experiment were reported this summer[18], and are shown in Fig. 6. The angular cuts used are the same as for the NUSEX experiment. Because the detector was growing while data was being taken, this data is predominantly from the first half of 1985. It shows an excess above background for the phase bin 0.6 - 0.7 amounting to 11 ± 4.3 events (2.5σ). The Frejus collaboration does not consider that at this level their data indicate clear evidence for the presence of a signal from Cyg X-3.

I summarize the fluxes implied by the three underground experiments in Fig. 7, where I have attempted to correct the data from each detector to reflect the rate that would be observed with Cygnus X-3 directly overhead. Fluxes are average over the entire period of observation. The solid line on Fig. 7 is the absolutely normalized E^{-1} line that fits the air shower experiments, indicating that the underground experiments see about the same flux of muons as the air shower experiments see of showers attributed to photons. Four other detectors (IMB, HPW, Homestake, and Kamioka) have reported upper limits consistent with these fluxes.

The magnitude of the problem raised by the underground muon rates is indicated by the calculated points on Fig. 7 of predicted muon

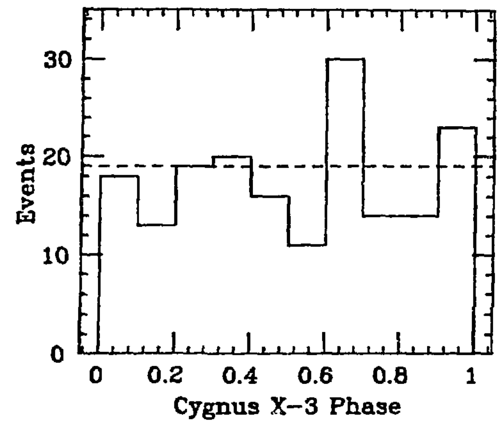

Fig. 6. Cygnus X-3 phase plot from Frejus.

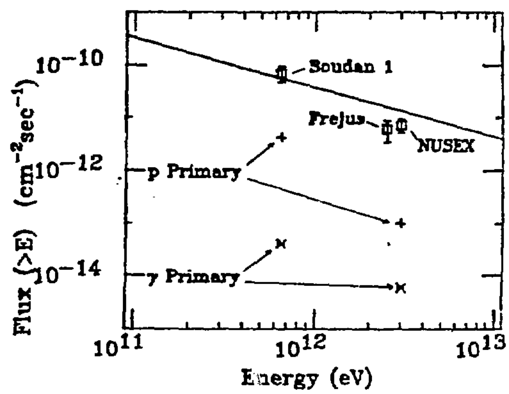

Fig. 7. Integrated flux rates for underground muons from Soudan 1, NUSEX, and Frejus. The solid line is the E^{-1} fit from Fig. 1. Predicted rates are shown if underground muons are associated with air showers on two assumptions about primaries.

rates if the air shower primaries are photons or even protons.[19] If correct, the underground muon rates are very hard to reconcile with the air shower rates. There is the possibility of a very high flux of neutrinos, although this would not be predicted from the model of the source outlined above. This possibility can be ruled out by the zenith angle subdivisions of the data made by the Soudan 1 and NUSEX groups. The neutrino hypothesis would suggest a rate independent of depth. The results from the two experiments are plotted in Fig. 8 with zenith angle translated into the equivalent depth. The result is clearly inconsistent with the neutrino hypothesis.

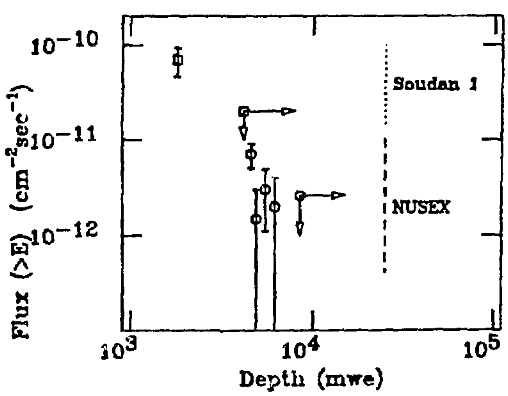

Fig. 8. Depth dependence of underground muon flux.

POSSIBLE EXPLANATIONS

Current attempts at understanding the underground data fall into two groups: either known particles have new interactions at energies above 1 TeV or the underground muons (and perhaps the air showers) from Cyg X-3 are produced by previously unknown primary species. In any case, the observed space and time coherence of the signals require that the primary particle be neutral, long lived ($> 10^6$ sec) and light ($m <$ few GeV).[20]

In the first category are suggestions from Ochs and Stodolsky[21] of a new threshold in the photo-nuclear cross section and from Mohapatra et al.[22] and Ralston[23] of enhanced neutrino cross-sections. None of these authors appear to consider the offered explanations as particularly compelling. In the second category is a suggestion from G. Baym et al.,[24] building on previous suggestions of quark matter in cosmic rays. They suggest that the compact object of Cyg X-3 may be a quark star rather than a neutron star. Chunks of the quark matter may then be knocked off the surface and accelerated to the normal star, where at grazing incidence as above some of them are made electrically neutral for the journey to Earth. A specific particle that fits into this picture is the H (doubly strange dibaryon) proposed by Jaffe.[25]

CONCLUSIONS

While the three underground experiments give rather consistent results, I believe that the overall statistical significance is still rather marginal, and the apparent observations of underground muons from Cyg X-3 should be regarded as interesting but still to be finally proven. The statistical worries are underlined by the fact that each experiment has made some arbitrary choices as to what data is chosen as signal, either in the angular range, in the phase range, or in both, thus decreasing the statistical significance of the observations. A particular point of concern is the approximately 3 times greater solid angle cut used for the two deeper detectors, which is not justified by the inherent detector resolutions or by expected multiple Coulomb scattering in the overburden. Additional data will become available in the next year or two that should clarify matters. In particular, the Frejus and Homestake detectors have large areas. The apparent rate fluctuations may allow time correlations to be made between the various experiments, with a consequent reduction of background. It is also important for the underground detectors to search for other sources known to give TeV air showers, such as Hercules X-1.

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