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ABSTRACT

Assuming that the UHE air showers from Cyg X-3 are produced by photons, we calculate the expected neutrino emission from a model which produces the γ-rays in the atmosphere of the Cyg X-3 companion. We discuss the possibility of detecting such neutrinos in underground detectors and the constraints that such a signal places on the use of this model in other particle production scenarios.

INTRODUCTION

The Cyg X-3 system has been observed at energies ranging from 10^{-4} eV to 10^{16} eV, with all but the radio emission showing a 4.8 hour period.[1] If we interpret the > TeV energy particles from Cyg X-3 to be photons,[2] then the differential flux from the system is given as[3]

$$\frac{dN_{\gamma}}{dE_{TeV}} = 3\times10^{-10}\ E_{TeV}^{-2.1}\ cm^{-2}\ sec^{-1}\ TeV^{-1}\ . \qquad (1)$$

The 4.8 hour periodicity appears to be associated with the orbital period of a binary system consisting of a pulsar and $\sim 4M_{\odot}$ companion.[4]

Vestrand and Eichler[5] have used such a system to construct a model which generates > TeV γ-ray (see fig. 1). The pulsar is considered a source of high energy protons, accelerated by large potential differences set up by the rapidly rotating magnetic field of a young neutron star.[6] These protons collide with nucleons in the atmosphere of the companion star, producing π's and K's which then decay into photons and neutrinos. If the π-production region is optically thin to TeV γ-rays, the photons escape and are observed as pulses with widths determined by the size of the optically thin region and having phase dictated by the orientation at which the observer "sees" the pulsar through the companion's atmosphere. In this way, the model gives > TeV γ-ray bursts at phase .25 and .75 with $\Delta\psi \sim 5\%$, in general agreement with the data.

THE HIGH ENERGY NEUTRINO SPECTRUM

If the > TeV events from Cyg X-3 are caused by photons, then the observed γ-ray spectrum is related to a π-spectrum which in turn can be related to a neutrino flux at the earth. Consider the observed γ-ray spectrum to originate from a source spectrum of the form

$$\frac{dS_\gamma}{dE_\gamma} = AE^{-n} . \tag{2}$$

In the model of Vestrand and Eichler, each π° decay produces 2γ's and so

$$\frac{dS_{\pi^\circ}}{dE_\pi} = A2^{n-1}E^{-n} . \tag{3}$$

Each nucleon-proton interaction produces as many $\pi^\pm$ as π° and so

$$\frac{ds_{\pi^\pm}}{dE} = 2\frac{ds_{\pi^\circ}}{dE} = 2^n\frac{dS_\gamma}{dE_\gamma} . \tag{4}$$

We get a ν_μ from each charged π decay, having an energy $E_\nu = 1/2[1-(m_\mu/m_\pi)^2]E_\pi$. Therefore the relationship between the neutrino source spectrum and the γ-ray source spectrum is[7]

$$\frac{dS_\nu}{dE_\nu} = [1-(\frac{m_\mu}{m_\pi})^2] \frac{dS_\gamma}{dE_\gamma} . \tag{5}$$

The neutrino source spectrum is degraded by $\nu N \to \mu x$ interactions as it is propagated through the companion star. The neutrino-nucleon cross section is[8]

$$\sigma = \begin{cases} 7\times10^{-36}\ E_{TeV}\ cm^2 & (E \lesssim 100\ TeV) \\ 1.2\times10^{-34}\ \ln E_{TeV}\ cm^2 & (E \gtrsim 100\ TeV) , \end{cases} \tag{6}$$

and the degredation at a given phase is dependent upon the amount of material a neutrino traverses at that phase (see fig. 1). We have used a ZAMS model of a 2.8 $M_\odot$ star[9] to approximate the density profile of the companion. The effect of neutrino absorption as a function of phase is shown in fig. 2 and the resulting neutrino "light-curves" are shown in fig. 3.

The derivation of the neutrino source spectrum assumed that the π's and K's decay before interacting. The condition that this assumption be valid is just that the decay lengths be shorter than a few interaction lengths:

$$\lambda_{dec} = (\gamma c\tau)_{\pi,K} \lesssim 3 \cdot \lambda_{Int} = (\frac{3}{n\sigma_{Int}})_{\pi,K} . \tag{7}$$

Taking $\sigma_{Int} = 3\times10^{-26} cm^2$ at TeV energies and scaling n to stellar envelope densities ($10^{-6} g\ cm^{-3}$) we have

$$\left.\begin{array}{ll} \pi: & 5\times10^6\ E_{TeV}\ cm \\ K: & 8\times10^5\ E_{TeV}\ cm \end{array}\right\} \lesssim 6\times10^7/\rho_{-6}\ cm , \tag{8}$$

where $\rho_{-6} \equiv \rho/10^{-6}$g cm^{-3}. The inequality of equation (8) does not hold for $E > E_c = 100/\rho_{-6}$ TeV. In this energy range, only neutrinos produced by charmed (or heavier flavor) meson decay will be emitted, with a flux of $\sigma_{charm}/\sigma_{\pi,K}$ relative to that produced by π and K decay. Heavy flavor production is down by a factor of $10^2 - 10^3$ relative to π-K production and thus the neutrino spectrum above 100 TeV should be down by a factor of $10^2 - 10^3$ relative to the flux expected from the decay pipe scenario. π's and K's produced with $E > E_c$ will have their energy reduced until $E \sim E_c$, at which point they produce a neutrino with $E_\nu \sim E_c$ resulting in a bump in the neutrino spectrum at E_c.

Finally, we can calculate the relationship between the observed differential energy spectra of neutrinos and γ-rays. Taking into account the fact that we only see photons from π^0 decay under favorable orientations we write

$$\frac{dN_\nu}{dE} = \left[1-\left(\frac{m_\mu}{m_\pi}\right)^2\right]^{2.1} \frac{\Delta\psi_\nu}{\Delta\psi_\gamma} \cdot \frac{dN_\gamma}{dE}, \quad (9)$$

where $\Delta\psi_\nu$ (~ 40%) and $\Delta\psi_\gamma$ (~ 5%) are the duty cycles of neutrino and γ-ray production. Thus

$$\frac{dN_\nu}{dE} = 4\times10^{-10}\, E_{TeV}^{-2.1}\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{TeV} \quad (E<E_c) \quad (10)$$

and about $10^{-2} - 10^{-3}$ of this value for $E > E_c$.

THE NEUTRINO SIGNAL IN UNDERGROUND DETECTORS

Here we discuss the possibility of observing the nuetrino flux from Cyg X-3 in an underground water Cerenkov-type detector (e.g. the IMB proton decay detector[10] having dimensions 17m × 18m × 23m, located at a depth of 1500 m.w.e.). In figure 4, we give a generic sketch of such a detector. Muon neutrinos from Cyg X-3 can cause two types of events in these detectors. They can: (1) Interact within the detector, producing a muon which is observed by its Cerenkov radiation; or (2) Interact with the earth, producing a muon which passes through the detector. Events (1) will be called contained events and events (2) will be called external events.

The probability of observing a contained event is just the ratio of the average detector trajectory to the interaction length:

$$\ell_c(E_\nu) = \frac{\langle\ell\rangle_{det}}{\lambda_{Int}} = \langle\ell\rangle n\sigma = \begin{cases} 4\times10^{-9}\, \ell_{10}\, E_{TeV} & (E\lesssim100\text{TeV}) \\ 7\times10^{-8}\, \ell_{10} \ln E_{TeV} & (E\gtrsim100\text{TeV}) \end{cases}, \quad (11)$$

where $\ell_{10} \cdot 10$ m = $\langle\ell\rangle_{det}$ (m.w.e.), $n = 6\times10^{23}$ cm^{-3}, and σ is taken from equation (6).

In order to calculate the probability of observing an external event, we need to know the range of a muon in rock. Taking into account energy losses due to ionization, bremsstrallung, pair production, and inelastic collisions, we can write[12]

$$-\frac{dE}{dx} = 1.9\times10^{-6}\ \mathrm{TeV\ cm^{-1}} + 4\times10^{-6}\ E_{TeV}\ \mathrm{cm^{-1}}\ , \qquad (12)$$

which gives a muon range of

$$R(E_{TeV}^{\mu} = 3\times10^{5}\ln\ (1 + 2E_{TeV}^{\mu})\ \mathrm{cm}. \qquad (13)$$

The fact that muons made within R(E) of the detector extends the size of the detector towards Cyg X-3 and results in a probability for an external event of

$$P_e(E_\nu) \simeq \frac{R[(1-y)E_\nu]}{\lambda_{Int}} \simeq 1\times10^{-6}E_{TeV}^{\nu}\ln[1+2(1-y)E_{TeV}^{\nu}]\ (E_{TeV}<100) \qquad (14)$$

where (1-y) is the fraction of energy carried off by the muon in a $\nu N \rightarrow \mu x$ interaction. For simplicity, we take $y \simeq 1/2$.[12] Note that P_e/P_c increases with energy, making contained events rare in a signal dominated by > TeV neutrinos.

The rate of external events due to a neutrino spectrum of the form $dN_\nu/dE = aE^{-n}$ incident upon a detector of cross sectional area A is

$$\Gamma_e = A \int P_e(E)\ \frac{dN_\nu}{dE}\ dE$$

$$= Aa\ 1\times10^{-6} \int E_{TeV}^{-n+1}\ \ln(1+E_{TeV})dE \qquad (E_{TeV}<100)\ . \qquad (15)$$

For a spectral index n < 3, the integral of equation (15) is dominated by 10 - 100 TeV events, cut off by the logarithmic range dependence. In this energy regime we expect external events to be 1000 times more likely than contained events.

Using the neutrino spectrum derived from the observed photon spectrum in the previous section ($a = 4\times10^{-10}\mathrm{cm^{-2}sec^{-1}}$ and $n = 2.1$) and scaling A to the IMB detector ($A_{IMB} \simeq 400\ \mathrm{m}^2$), the predicted event rate for Cyg X-3 is

$$\Gamma^{Cyg\ X-3} \simeq 2\times10^{-8}\ \mathrm{sec^{-1}}/400\ \mathrm{m}^2\ , \qquad (16)$$

or slightly less (.6) than 1 event/year.

This signal must be picked out from the muon background due to cosmic ray interactions in the atmosphere. Since muons have a finite range in earth (see equation (13)), there is a zenith angle dependent energy threshold for a background muon to reach the detector,

$$E_{TeV}^{TH}(\Upsilon) = \frac{1}{2}\left[\exp\frac{x(\Upsilon)}{3\times10^{5}} - 1\right]\ , \qquad (17)$$

where Υ is the zenith angle and from figure 4,

$$x(\gamma) = R\{(\frac{d}{R} - 1)\cos\gamma + [(\frac{d}{R} - 1)^2 \cos^2\gamma - \frac{d}{R}(\frac{d}{R} - 2)]^{1/2}\} . \quad (18)$$

Using the fact that the integrated muon background goes as E^{-2},[13] the background rate in IMB is

$$\frac{d\Gamma^{BCKGRND}}{d\Omega} = 5\times10^{-4}[\exp(\frac{.5}{\cos\gamma}) - 1]^{-2}\ sec^{-1}\ deg^{-2} , \quad (19)$$

which must be multiplied by the solid angle corresponding to the detector's acceptance cone.[14] The muon background as a function of zenith angle is shown in figure 5.

In the case of Cyg X-3, one cannot use the zenith angle dependence of the muon background to full advantage because of Cyg X-3's location for northern hemisphere observers. With a declination of 40.8°, the zenith angle of Cyg X-3 is restricted to the range $\theta - 40.8° \leq \gamma \leq 139.2° - \theta$ for an observer at latitude θ. This confinement reduces northern latitude exposure times to a few hours/day (e.g. IMB has $\gamma > 86°$ for ~ 5 hours/day).

NEUTRINO PRODUCED MUONS AND CONSTRAINTS ON CYG X-3

Observations of the muon-content and zenith angle dependence of the air showers from the direction of Cyg X-3 appear to indicate that the showers cannot be caused by photons or neutrinos.[15] The phase correlation and directionality of the signal and the distance to Cyg X-3 constrain the air shower particle to be neutral, less than a few GeV in mass, and metastable ($\tau \gtrsim$ months).[15] Several authors[16] have tried to construct scenarios in which these "cygnets" are produced. We would like to point out that even if the air showers are not due to photons, the neutrino flux accompanying the creation of cygnets and the fact that cygnets have not been seen in accelerator searches places severe constraints on using a Verstrand and Eichler-type mechanism for cygent production.

This model would use pN → Cygnet, (π,K) interactions in the companion's atmosphere to produce the cygnet flux. The ratio of cygnets to muon neutrinos is just

$$\frac{N_{\nu\mu}}{N_c} \simeq \frac{N_\pi}{N_c} = \frac{\sigma_\pi}{\sigma_c} . \quad (20)$$

If we want cygnets to have the same flux as indicated by air showers, then the rate of external events in IMB scales as

$$\Gamma^{Cyg\ X-3} \simeq \frac{\sigma_\pi}{\sigma_c} \cdot yr^{-1} . \quad (21)$$

The fact that we don't see neutrinos from Cyg X-3 implies that $\sigma_c \gtrsim 10^{-2}\ \sigma_\pi$ (i.e. $\Gamma^{Cyg\ X-3} \lesssim 10^2\ yr^{-1}$). A GeV particle with this large a production cross section would be difficult to hide in accelerator searches. Therefore the model for producing anything but neutrinos and γ-rays with a proton beam hitting the companion star seems to be inconsistent with our calculation of the neutrino signal and we conclude that such new particles must come directly from the compact object.

SUMMARY

Using a model which produces > TeV γ-rays, we have calculated the expected neutrino flux from Cyg X-3, normalized to the photon flux (see equation (10)). The source of spectrum of neutrinos is modified by passage through the companion star, resulting in the neutrino "light curves" of figure 3. The event rate in an underground detector is about 1/yr/400 m^2. Although the rate is not measurable with current detectors, this calculation can be used to put limits on the production of other types of particles in the Cyg X-3 system.

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Note added: After our work of ref. 9 was completed we learned of similar work by: T. Gaisser and T. Stanev, Phys. Rev. Lett., in press (1985); V. S. Berezinsky, C. Castagnoli, and P. Galeotti, preprint (1985); G. Cocconi, CERN preprint (1985). These groups reached similar conclusions to ours.

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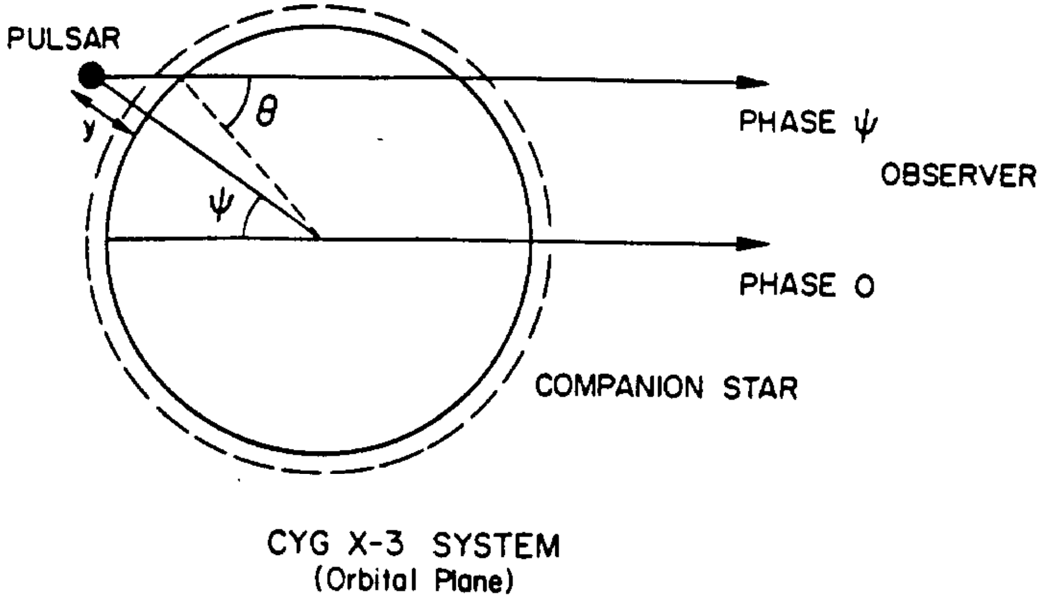


FIGURE 1

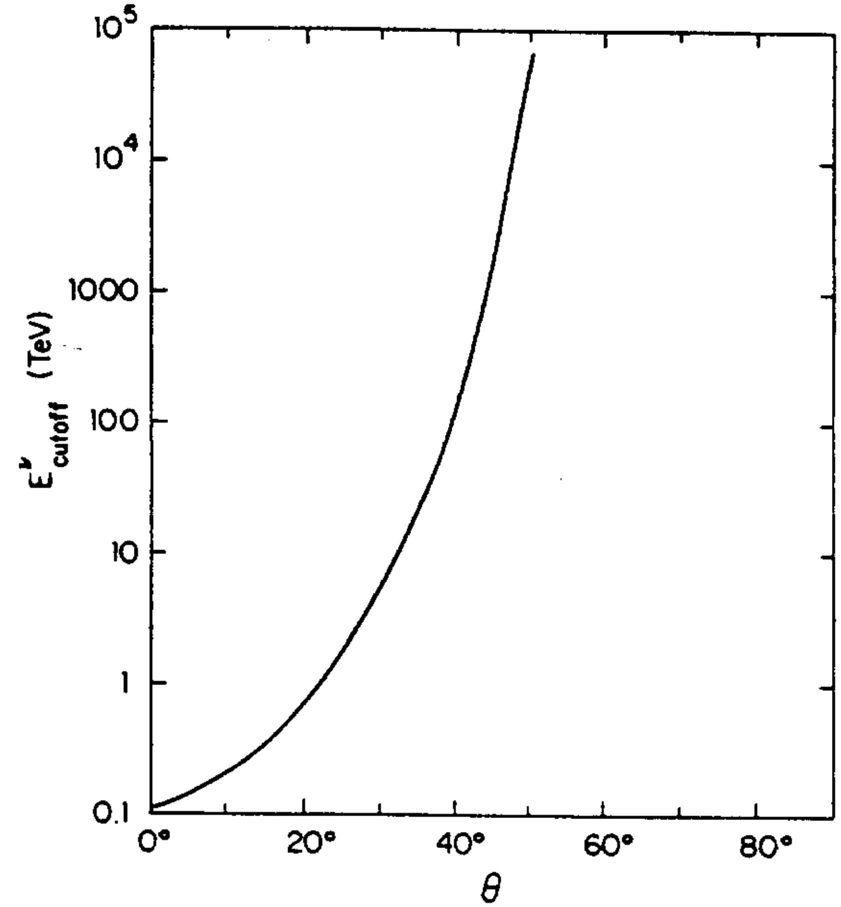


FIGURE 2

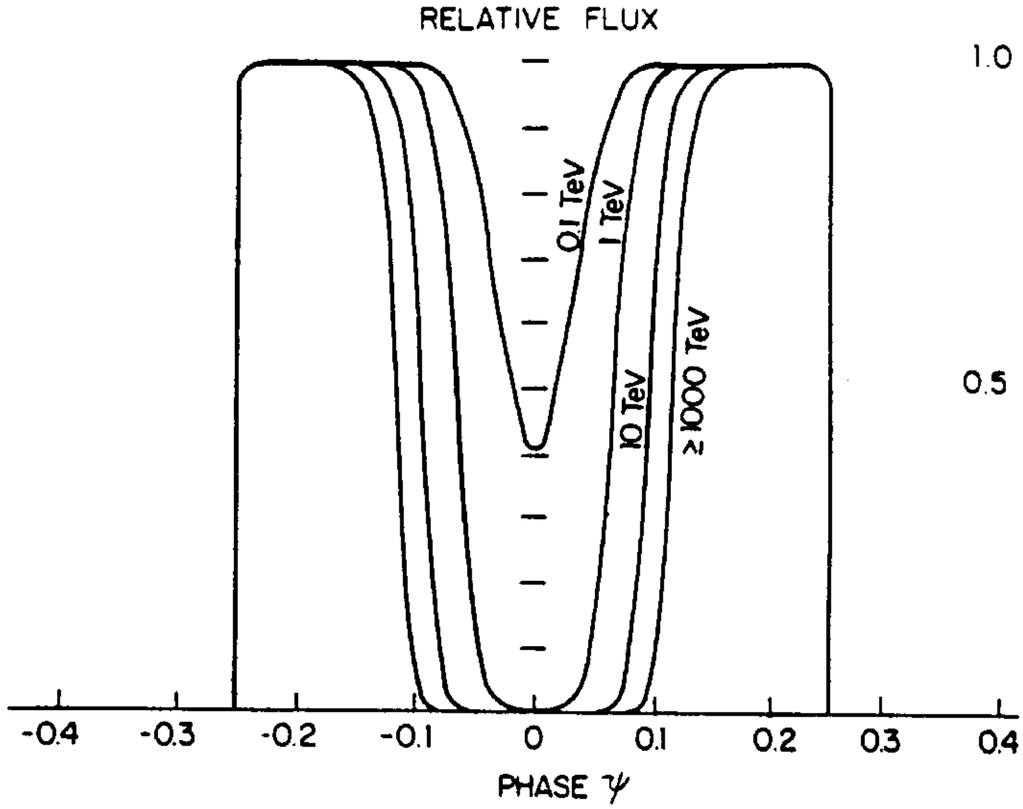


FIGURE 3

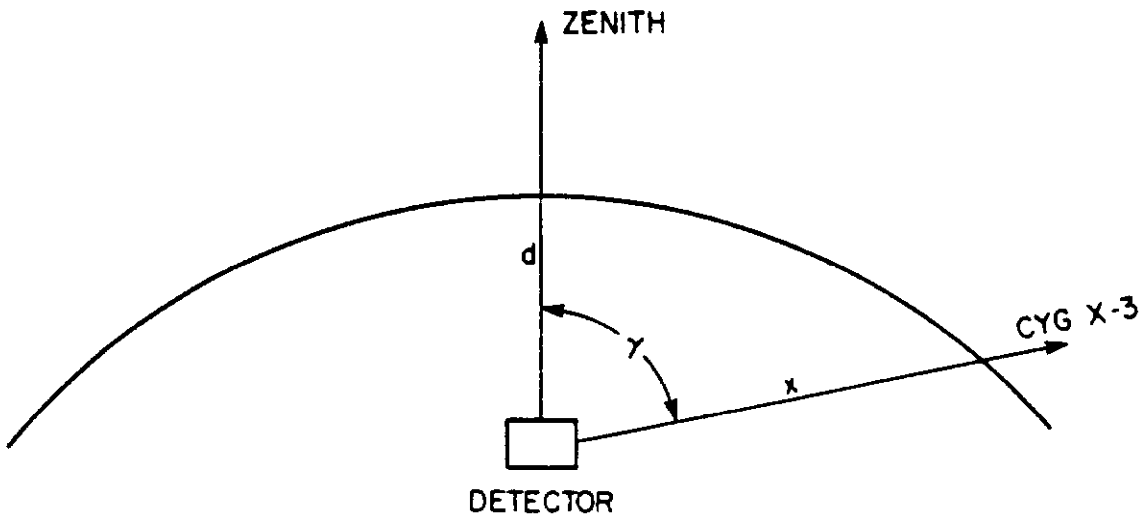
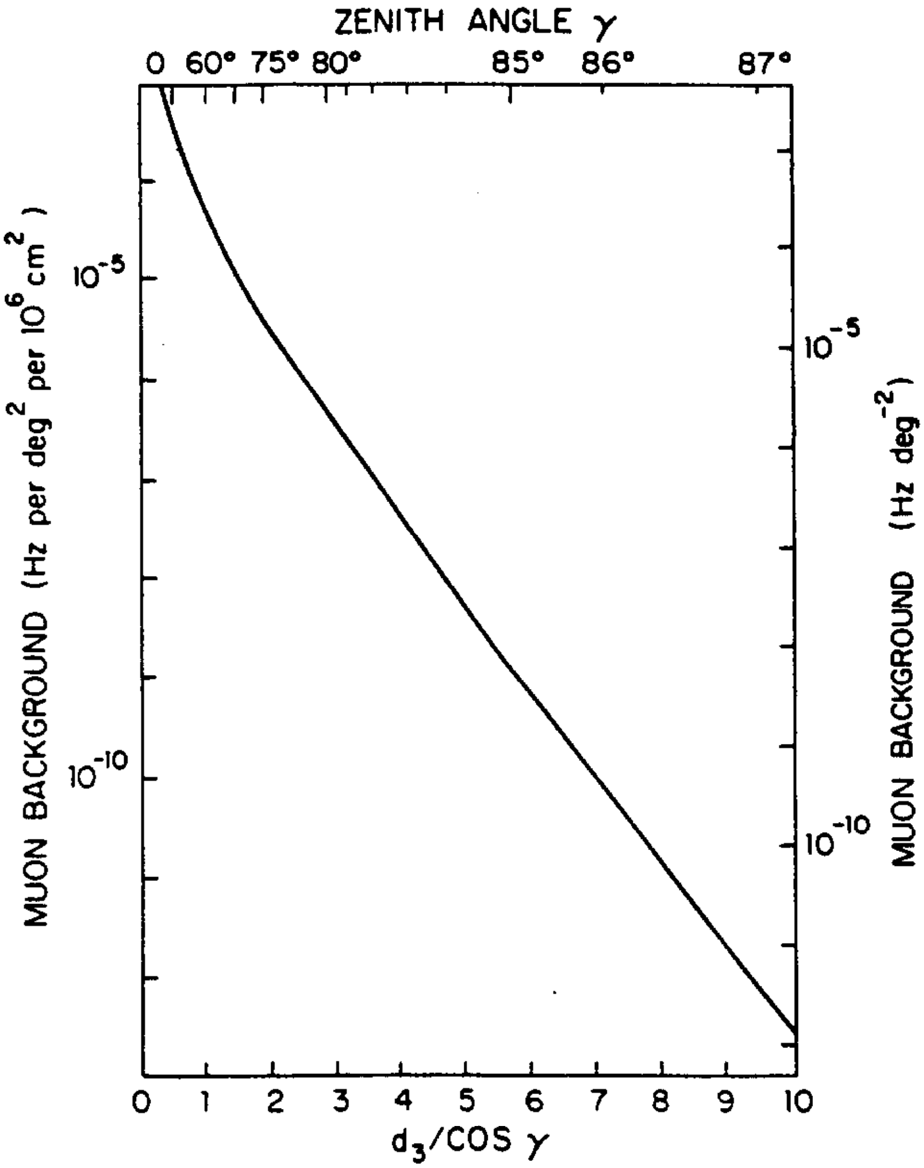


FIGURE 4


ZENITH ANGLE γ
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MUON BACKGROUND (Hz per deg² per 10⁶ cm²)
10⁻⁵
10⁻¹⁰
MUON BACKGROUND (Hz deg⁻²)
10⁻⁵
10⁻¹⁰
0 1 2 3 4 5 6 7 8 9 10
d₃/COS γ

FIGURE 5