Calculation of Neutrino Flux from Cygnus X-3

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(Received 12 March 1985)

We estimate the flux of neutrinos produced by protons accelerated by the compact partner in Cygnus X-3. Such neutrinos are produced in collisions with the atmosphere of the companion, and there can be substantial modulation due to absorption in the companion. The resulting flux of upward muons induced by neutrinos in rock below an underground detector is at the level of 1 per 1000 m^2 per year.

PACS numbers: 96.40.Qr, 14.60.Gh, 95.85.Qx, 97.80.Jp

If the high-energy photons from Cygnus X-3 are from decay of π^0 mesons produced by collisions of protons (or heavier ions) accelerated in the system, then there will be a related flux of neutrinos from decay of charged pions.[1] The recent discovery[2,3] of 10^{15}–10^{16}-eV photons from Cygnus X-3 has led to more specific models of this binary system,[4,5] including possible acceleration mechanisms in the compact partner and details of the production of photons by accelerated protons in the atmosphere of the companion star. At the same time, experimental efforts to detect neutrinos from extraterrestrial sources have intensified.[6–8] In the high-energy region of interest here, the technique is to look for upward muons induced by interactions of ν_μ in the material surrounding a deep detector.

We have estimated the neutrino spectrum for two different assumptions about the spectrum of accelerated protons: (1) Hillas's model,[5] in which a beam of 10^{17}-eV protons produces the observed E_γ^{-2} photon spectrum by $p \rightarrow \pi^0 \rightarrow \gamma \rightarrow$ (electromagnetic cascade); and (2) a generic picture in which the photon spectrum is due to protons with the same spectral index. The resulting neutrino spectra at Earth (under the assumption of a distance of 10 kpc and a power of 10^{39} ergs/sec) are shown in Fig. 1.

We next fold these neutrino spectra with the probability for producing upward muons, taking account of W-propagator effects in the charged-current cross section of the neutrinos and antineutrinos and using the appropriate range-energy relations for the produced muons.[9] For Hillas's model, which requires $\sim 10^{39}$ ergs/sec of accelerated protons at 10^{17} eV,[5] we find an upward muon flux of 2×10^{-15} cm^{-2} s^{-1} from a single angular bin. This is to be compared with a total upward flux of muons above 2 GeV from atmospherically produced neutrinos of 1.6×10^{-12} cm^{-2} s^{-1}, spread over the entire 2π-sr solid angle below the horizon.[10] For the same power in a proton spectrum $\propto E^{-2}$ for 1 TeV $\leq E \leq 10^5$ TeV the expected upward muon flux from a point source at 10 kpc is about 2.6×10^{-15} cm^{-2} s^{-1}.

Such a source would therefore give a signal of 0.5–1 upward muon per year per 1000 m^2 for a fully efficient detector. In fact, however, for the portion of the time that Cygnus X-3 is above the horizon (which is large for detectors around 40–50° north latitude) the signal is likely to be overwhelmed by atmospheric muons and the efficiency correspondingly reduced. Nevertheless, given the uncertainty in the power of the source, the large number of existing and proposed underground detectors, the fact that the above estimate is tantalizingly close to detectability, and the likely existence of similar sources in more favorable locations,[11] we believe that it is worth exploring this calculation in somewhat more detail.

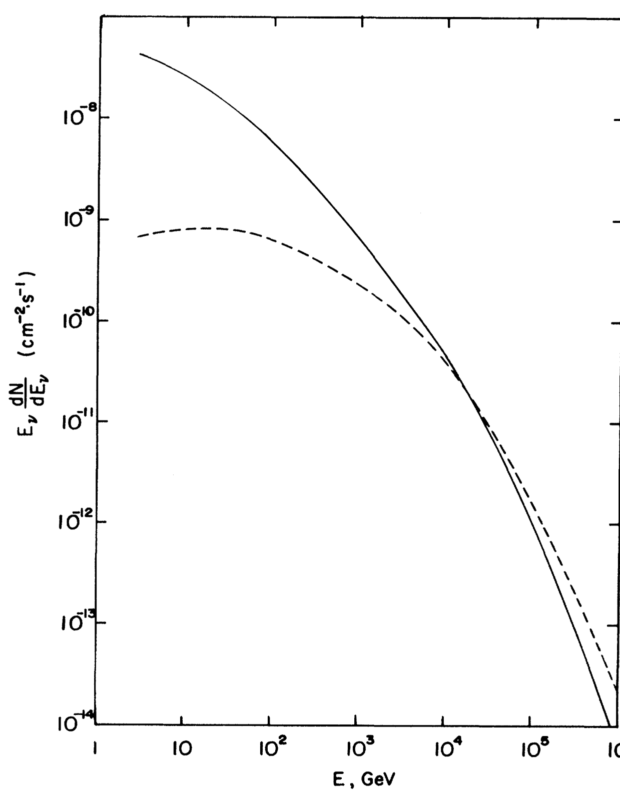

FIG. 1. Neutrino spectra at Earth from a 10^8-GeV monoenergetic beam (dashed line) and power-law spectrum with slope 2 (full line) for the density profile of Table I averaged over one period.

We have previously calculated the flux of neutrinos produced by cosmic rays cascading in the atmosphere of Earth,[12] including details of production and decay of pions, kaons, and muons and energy loss of charged particles in the atmosphere. The calculation is essentially the same here but with a stellar atmosphere instead (scale height ~ 8000 km, $\rho \lesssim 10^{-7}$ g/cm^3 in the region of particle production, and a composition of hydrogen and helium). In fact, the distribution of matter in Cygnus X-3 is very uncertain and undoubtedly much distorted by the energy output of the compact object. On the basis of the shape of the x-ray phase diagram, it is estimated that the orbital radius of the compact object is only ~ 1.05 times the radius of the companion star, the mass of which is $< 4M_\odot$.

Nevertheless, for illustration, we take the density profile of the companion star to be that of a main-sequence star with $M/M_\odot = 2.8$, $R/R_\odot = 2$, and a surface temperature of 10 000 K. The inner density distribution[13] and the outer atmosphere[14] of such a star are well known. To interpolate between these two regions (which is the crucial regime of densities and ranges for pion production and decay) we assume[15] $\rho \propto T^{3.25}$. This leads to the density profile of Table I. Although such a symmetric, quiescent picture is unrealistic, it will be a useful illustration because it contains a range of densities and distances that will characterize a more realistic model. Moreover, we find that the neutrino-induced muon flux is rather independent of details of the matter distribution in the production region.

In Fig. 2 we superimpose the expected flux of neutrino-induced upward muons on the x-ray phase diagram[16] of Cygnus X-3. The neutrinos are essentially 180° out of phase with the x rays because intervening matter is required to produce neutrinos, whereas it tends to absorb x rays or prevent their production.[17] In addition, there is a dip in the neutrino-induced flux at maximum eclipse due to absorption of pions and neutrinos. At maximum eclipse the highest-energy pions penetrate more than an interaction length of matter before decaying, so that some potential neutrino parents cascade, ultimately dissipating their energy in photons (through π^0 decay) as well as in lower-energy neutrinos. Moreover, the highest-energy neutrinos themselves are absorbed for trajectories near the center of the companion star. If, however, the system is viewed rather far from the plane of the orbit there may be no prominent dip. These absorption effects are greater for the monoenergetic proton beam than for the power-law case because of the harder spectrum of secondaries from a monoenergetic beam (see Fig. 1). [The charged-current cross sections[9] relevant to absorption of neutrinos by the companion can be approximated by

$$\sigma_\nu = \frac{(0.7\times 10^{-38}\ \mathrm{cm^2\ GeV^{-1}})E_\nu}{1+E_\nu/\epsilon_w \ln[E_\nu/(50\ \mathrm{GeV})]},$$

and

$$\sigma_{\bar\nu} = \frac{(0.3\times 10^{-38}\ \mathrm{cm^2\ GeV^{-1}})E_\nu}{1+E_\nu/\{2.33\epsilon_w \ln[E_\nu/(50\ \mathrm{GeV})]\}},$$

where $\epsilon_w \equiv M_w^2/2m_p \cong 3500$ GeV.]

Of somewhat more practical interest is the fact that—for a given power in the primary proton beam—the neutrino-induced muon flux at Earth is remarkably independent of the details of the matter distribution in the production region. In Fig. 3 we show the spectra of neutrinos produced in slabs of matter of various thicknesses and densities for the monoenergetic proton beam. Table II gives the expected upward muon flux corresponding to various fixed densities, on the assumption of a thickness of 1000 g/cm^2, a dis-

TABLE I. Assumed density profile of the companion star used to illustrate neutrino production in Cygnus X-3. (Radius at optical depth unity is 1.4×10^{11} cm, radius at top of atmosphere is 1.442×10^{11} cm and radius to compact partner is 1.474×10^{11} cm.) X_t and h_t are the total column density and length of a chord at impact parameter r, and ωt is the corresponding phase angle of the compact partner.

r (10^6 km)	ρ (g/cm^3)	h_t (cm)	X_t (g/cm^2)	ωt (degrees)
0	38	2.884×10^{11}	2.10×10^{12}	0°
0.721	0.31	2.498×10^{11}	2.16×10^{10}	29.3
1.249	1.3×10^{-4}	1.442×10^{11}	9.8×10^{6}	57.9
1.355	1.0×10^{-5}	9.86×10^{10}	4.8×10^{5}	66.8
1.399	1.1×10^{-6}	7.46×10^{10}	3.34×10^{4}	71.7°
1.420	1.3×10^{-7}	5.01×10^{10}	2760	74.5°
1.428	3.1×10^{-8}	3.52×10^{10}	534	75.6°
1.434	5×10^{-9}	2.51×10^{10}	64	76.6°
1.442	0	0	0	78°

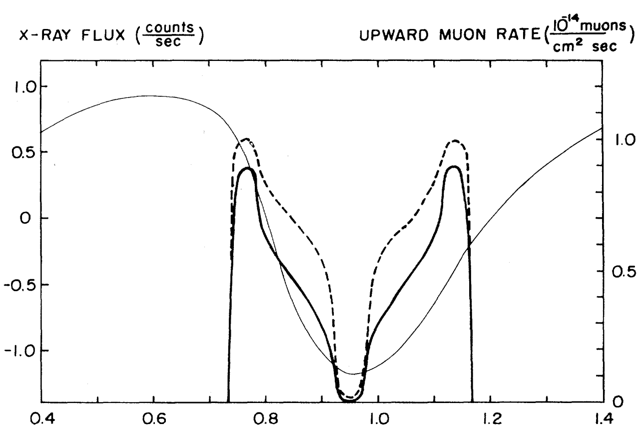

FIG. 2. Phase dependence of upward muons from Cygnus X-3 neutrinos: 10^8-GeV beam, solid curve; power-law spectrum, dashed curve. The thin line shows the light curve in x rays.

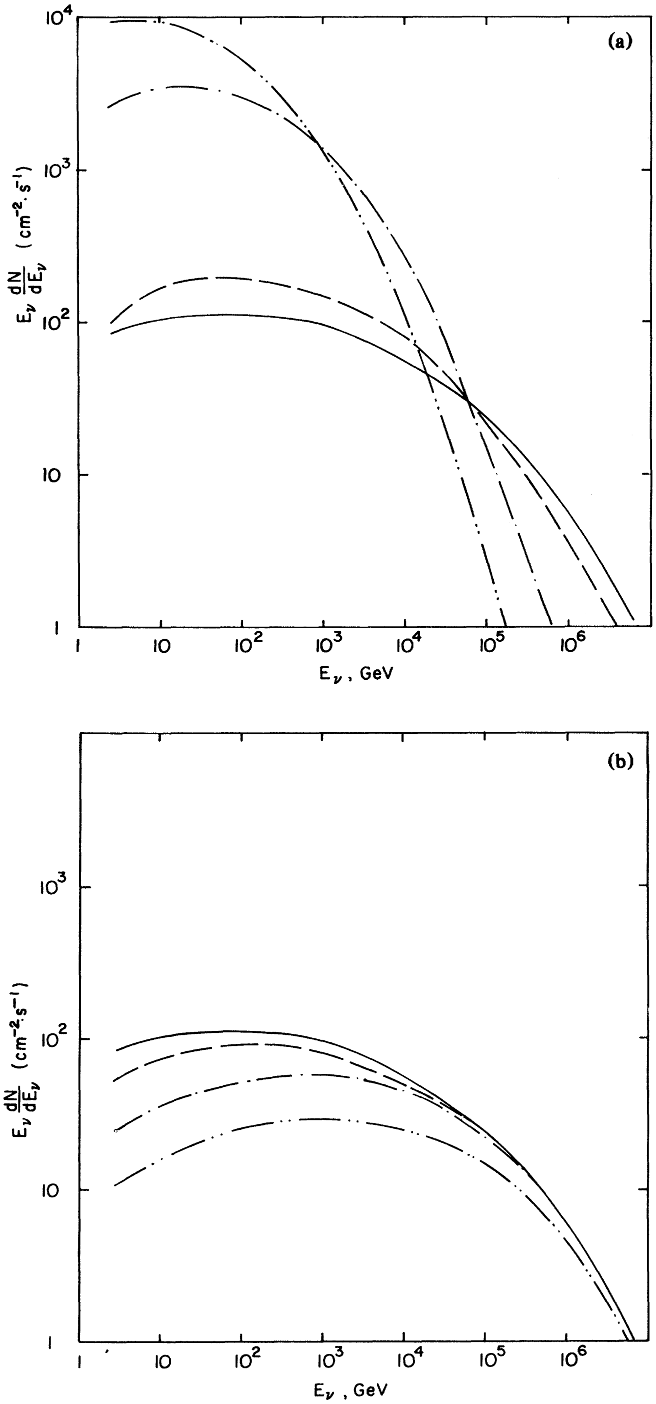

FIG. 3. Neutrino spectra produced by a 10^8-GeV proton in an atmosphere of uniform density. (a) Column density 1000 g/cm^2. Density 10^{-12} g/cm^3, solid curve; 10^{-9} g/cm^3, dashed curve; 10^{-7} g/cm^3, dot-dashed curve; and 10^{-6} g/cm^3, double-dotted dashed curve. (b) Density 10^{-12} g/cm^3. Column density 1000 g/cm^2, solid curve; 300 g/cm^2, dashed curve; 100 g/cm^2, dot-dashed curve; and 30 g/cm^2, double-dotted dashed curve.

TABLE II. Upward muon fluxes induced by neutrino fluxes produced in uniform-density atmospheres.

	Flux (cm^{-2} s^{-1})	
Density (g/cm^3)	10^8-GeV proton beam	Power-spectrum proton beam ($\gamma = 2$)
10^{-12}	2.3×10^{-15}	4.1×10^{-15}
10^{-9}	2.3×10^{-15}	4.1×10^{-15}
10^{-7}	3.3×10^{-15}	3.5×10^{-15}
10^{-6}	1.3×10^{-15}	2.5×10^{-15}

tance of 10 kpc, and a power in primary protons at the source of 10^{39} ergs/sec. Here, we assumed that neutrino production occurred during 40% of the orbital period. The upward muon flux is reduced by no more than a factor of 2 if the thickness is reduced to 30 g/cm^2. We note that these artificial examples give results within a factor of 2 of the detailed calculation for a companion with the density distribution of Table I.

We conclude, therefore, that the estimate of the flux of neutrino-induced muons is relatively insensitive to details of the matter distribution in the source and depends primarily on the power output in cosmic rays.

After completing this calculation we learned of an independent calculation by R. Kolb, M. Turner, and T. Walker that reaches a similar conclusion about the magnitude of the expected ν-induced muon signal from Cygnus X-3.

We are grateful to G. Auriemma, Dermott Mullan, and Harry Shipman for helpful conversations. This work was supported in part by the National Science Foundation through Grant No. PHY-8410989 and the U. S. Department of Energy through Grant No. DE-AC02-78ER05007.

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[11]Vela X-1 is below the horizon much of the time for a detector at 40–50° N latitude, and it produces a high-energy photon flux at Earth comparable to that of Cygnus X-3, though it is about an order of magnitude closer than Cygnus X-3 and therefore presumably has an intrinsic luminosity two orders of magnitude lower. See R. J. Protheroe, R. W. Clay, and P. R. Gerhardy, Astrophys. J. **280**, L47 (1984) for a discussion of Vela X-1.

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