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**HIGH ENERGY NEUTRINO ABSORPTION AND
ITS EFFECT ON STARS IN CLOSE X-RAY BINARIES**

T.K. GAISSER

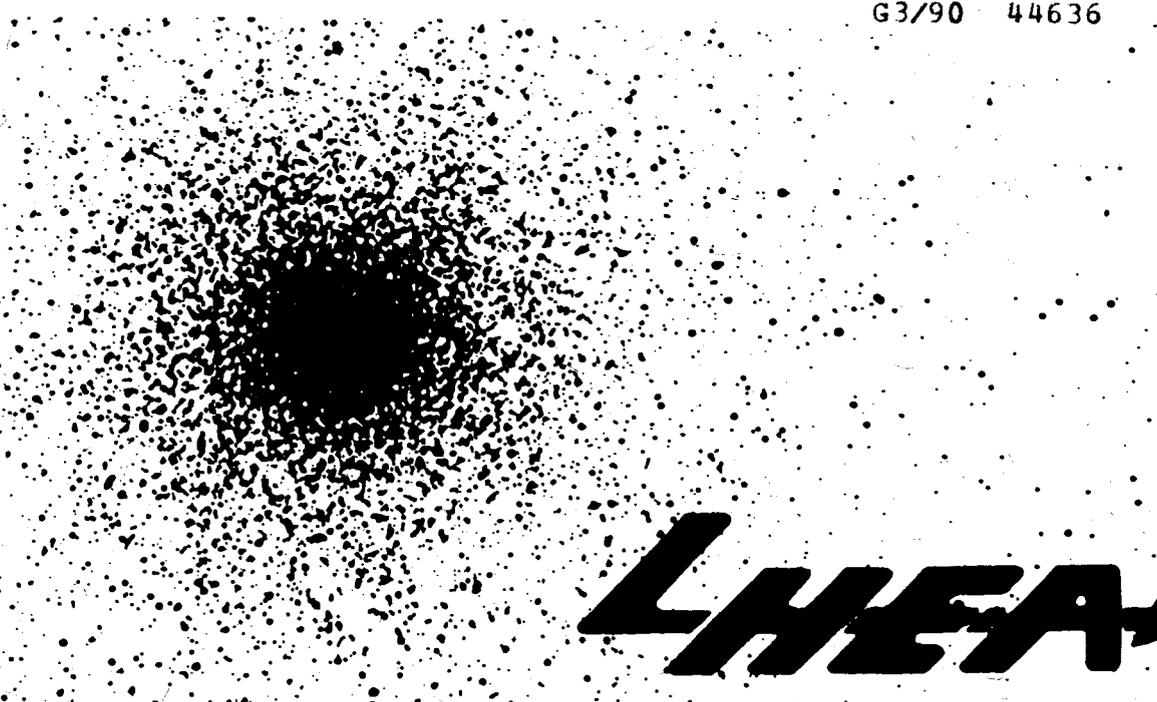
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This paper discusses and elaborates on work done in collaboration with Drs. T. Stanev of the Bartol Research Foundation and A. K. Harding and J. J. Barnard of Goddard Space Flight Center regarding the physics and astrophysics of high energy neutrino production and interactions in close X-ray binary systems. These studies were stimulated by recent observations of ultrahigh energy γ -rays and possibly other ultrahigh energy particles coming from the directions of Cygnus X-3 and other binary systems and possessing the periodicity characteristics of these systems. These experimental reports have potentially profound implications for particle physics, cosmic-ray physics and astrophysics. The implications are that such systems are copious sources of high-energy cosmic rays, the first such sources discovered. In addition, only a few of these systems could account for a significant fraction of the ultrahigh energy cosmic rays in the galaxy. Thus, theoretical and observational studies of such systems will enable us to understand at

least some of the mechanics involved in generating cosmic rays. In addition, reports of underground muons produced by neutral particles coming from the direction of Cygnus X-3 have raised the possibility of new particle physics.

The γ -ray observations alone imply the production of high energy cosmic rays in such copious quantities as to have possibly profound effects on the evolution and stability of the binary systems themselves, at least in some cases. This raises an interesting new astrophysics problem. On the other hand, a detailed understanding of the physics and astrophysical effects of high-energy particles, or beams of such particles, enables us to determine upper limits for the generation of cosmic-ray particles in such binary systems¹. This, in turn, has important implications for interpreting the underground muon results, which we will discuss.

We have considered such systems in which a compact object, such as a neutron star, is a strong source of high energy particles which, in turn, produce photons, neutrinos and other secondary particles by interactions in the atmosphere of the companion star. The highest energy neutrinos are absorbed deep in the companion and the associated energy deposition may be large enough to affect its structure or lead to its ultimate disruption. We have evaluated this neutrino heating, starting with a detailed numerical calculation of the hadronic cascade induced in the atmosphere of the companion star. For some theoretical models, the resulting energy deposition from neutrino absorption may be so great as to disrupt the companion star over an astronomically small timescale of the order of 10,000 years. Even if the energy deposition is smaller, it may still be high enough to alter the system substantially, perhaps leading to quenching of high-energy signals from the source. Given the cosmic-ray luminosities required to produce the observed γ -rays from Cygnus X-3 and LMC X-4, such a situation may occur in these sources.

Variability may occur on a much smaller timescale, owing to a strong stellar wind generated in the atmosphere of the companion star by cosmic-ray energy deposition. Such variability may also be produced by the effects of Roche lobe overflow generated by the stellar wind and by changes in the internal structure and stability of the companion star owing to the absorption of high energy neutrinos.

It should be clear from all of these considerations, that theoretical studies such as the ones discussed here are important for planning muon and neutrino astronomy observations with detectors such as DUMAND and those detectors at Gran Sasso and Lake Baikal as well as for interpreting the results of these observations.

Reports of air showers with $E > 10^{15}$ eV from Cygnus X-3², LMC X-4³, Vela X-1⁴, and Hercules X-1⁵, have been interpreted as requiring production of neutral secondaries by cosmic rays accelerated by the compact partner of these systems. If neutral pions are the source of photons that produce the observed air showers, then charged pions must also be produced, and they will give rise to neutrinos⁶. There is a question as to whether the muon content of these showers is high, indicative of hadronically induced showers⁷, or low, indicative of electromagnetically (photon) induced showers (Kifune, *et al.*, Ref. 2). It has been proposed⁸ that the atmosphere of the companion star provides the grammage required to stop the accelerated particles and produce high energy γ -rays. (The X-ray light curve indicates a much smaller grammage in circumstellar gas.) Reports of underground muons from secondary ultrahigh energy particles produced by Cygnus X-3⁹ although in question¹⁰ have led to speculations of exotic particles and production mechanisms¹¹ (see, however Ref. 12) which would also be accompanied by charged pion-neutrino production, so that neutrino beams would also arise in these scenarios.

What happens when the companion star acts as a beam dump for its compact partner which is a powerful primary cosmic-ray accelerator? What is the resulting neutrino flux and how much energy is absorbed? How does the system respond to rates of energy deposition which may be much greater than the stellar luminosity of the companion? These questions can arise even independently of the γ -ray production model, since it is hard to imagine a situation within a close binary system where cosmic rays generated at the compact object will avoid hitting the companion star. They have been the subjects of our studies.¹ We reconsider them here.

It is obvious that the "particle beam" produces a hadronic cascade in the outer layers of the companion. This cascade ultimately gives rise to neutrinos and photons. Using previously developed techniques¹³, we can calculate the rate of energy deposition in the companion by the cascade,

with emphasis on the neutrinos which penetrate deeply into the star. We finally conclude with a discussion of the consequences of this energy deposition for the stability of the system.

Hillas⁹ has calculated the electromagnetic cascade produced by collisions of the accelerated protons in a distribution of gas around the companion. He estimated that the observed air shower signal from Cygnus X-3 requires a cosmic-ray luminosity for the source of

$$L_{cr} = 3 \times 10^{39} \left(\frac{0.02}{D_\gamma} \right) \frac{\Delta\Omega}{4\pi} (d/12 \text{ kpc})^2 \text{ ergs s}^{-1} \quad (1)$$

where D_γ is the duty cycle for production of the photon signal, $\Delta\Omega$ is the solid angle into which the high energy particles are beamed and d is the distance from the observer to the source. The power for other sources may be similarly estimated from their observed signals, and these results

TABLE 1

Aspect Ratio (a/R) and Estimated Cosmic Ray Luminosity for Several Binary Systems

System	(d) binary period (days)	(d) companion mass (M_\odot)	(a) a/R	(d) distance (kpc)	(b) L_{cr} (erg/s)
Cygnus X-3	0.19	≤ 4 (c)	~ 1.4	≥ 12	10^{39}
Vela X-1	8.965	23	12	1.4	$\sim 10^{37}$
LMC X-4	1.408	~ 19	3.5	50	$\sim 10^{41}$
Her X-1	1.7	2.4	6	4	$\sim 10^{38}$

(a) Ratio of separation to companion star radius, estimated from Kepler's third law assuming the compact object to have mass $1.4 M_\odot$. Here R is the radius of a zero-age main sequence star of the given mass.

(b) L_{cr} is estimated as in Eq. (1).

(c) Assuming the compact object to be a neutron star from recent evidence that it is a pulsar¹⁴, and the companion star radius to be less than the orbital radius. For stability, the companion star must not exceed its Roche lobe by much, giving a limit of $\sim 0.5 M_\odot$ for a main sequence star.

(d) From Ref. 15 and references therein, except for Cygnus X-3.

are summarized in Table 1. An important point is that a photon spectrum with $dn_\gamma/dE \propto E^{-2}$, as observed, can be produced by a parent spectrum that is harder than E^{-2} , including a δ -function spectrum. The E^{-2} photon spectrum is then achieved by electromagnetic cascading, either in strong ambient magnetic fields or in the gas.

In order to understand qualitative aspects of the results it is helpful to see where in the companion star various processes occur. The hadronic cascade starts when $X < m_H/\sigma \sim 30\text{-}40 \text{ g/cm}^2$ in hydrogen for nucleon energies around 10^7 GeV ¹⁶. By ten interaction lengths it has saturated. This range of depths occurs in the outer part of the star at a density of about $2 \times 10^{-7} \text{ g/cm}^3$. In contrast, the interaction length of multi-TeV neutrinos is of order 10^{11} g/cm^2 , which occurs deep in the star at densities of order $1\text{-}10 \text{ g/cm}^3$. Thus, neutrino production and absorption are quite separate. Qualitative estimates as well as detailed calculations suggest the following scenario: The hadronic cascade in the outer layers of the companion heats and expands the surface and drives a stellar wind. These effects are discussed and estimated by Gaisser, et al. (Ref. 1). Neutrinos penetrate into or through the star, depending on their direction and energy. For close binaries (a/R small) energy deposition can be significant.

We have carried out detailed calculations of neutrino energy deposition for two specific companion masses as a function of a/R (Gaisser, et al., Ref. 1), with the results summarized in Table 2. Each case has been computed for two extreme spectra, viz., $b = 0$ and $b = R$ where b is the impact parameter of the trajectory from the compact object through the companion (See Fig. 1). In the $b = R$ case, cascading takes place at low densities along the edge of the star so that all of the pions and kaons which are produced will decay. This gives the hardest neutrino spectrum. The $b = 0$ case, on the other hand, gives the softest neutrino spectrum, because the pions cascade to produce lower energy pions which

decay. These two extremes should bracket the true result, which is uncertain because of the extremely violent conditions near the stellar surface.

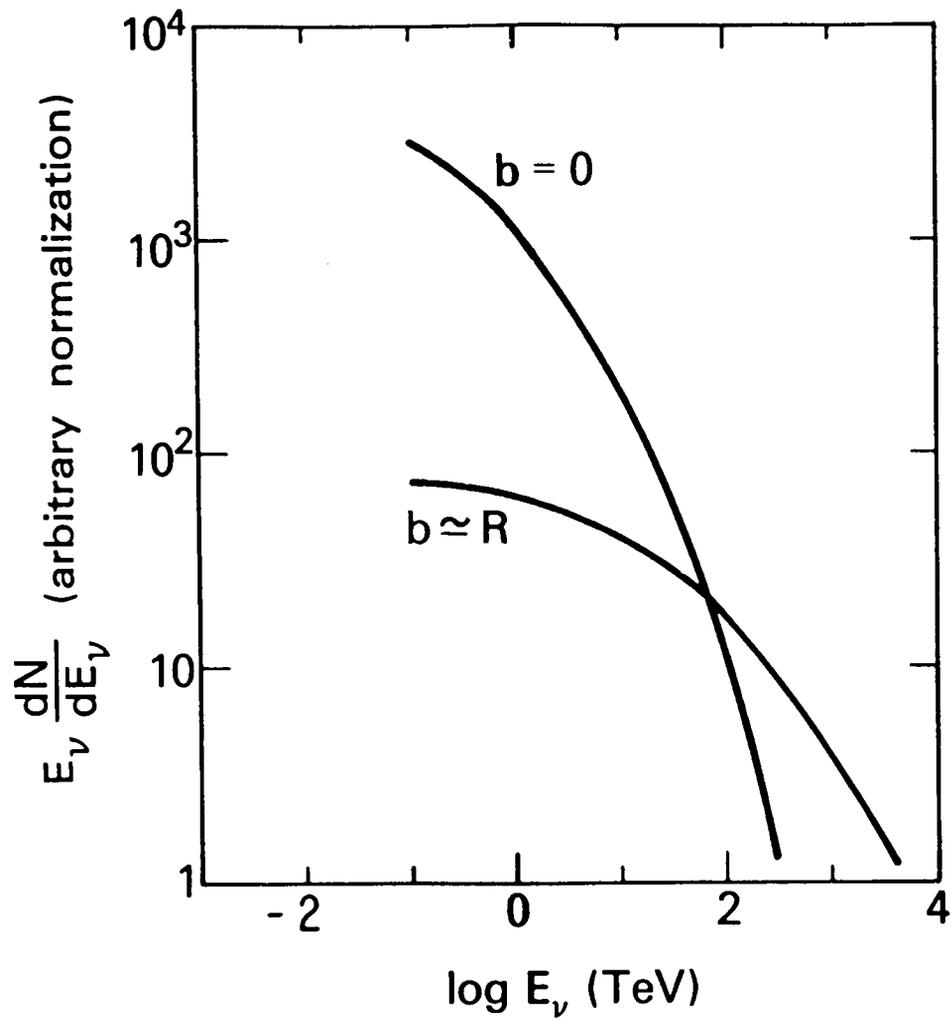


Figure 1. Neutrino spectrum at production, given a monoenergetic primary cosmic-ray spectrum of 10^{17} eV energy.

The dominant process for interaction of the ν_{μ} 's produced when charged pions decay is the charged current mode



The cross section for this process rises linearly with neutrino energy until the 10-100 TeV range, after which it increases logarithmically¹⁷. The mean thickness of a $2.8 M_{\odot}$ companion star is $\sim 2 \times 10^{11} \text{ g/cm}^2$ which is equal to the neutrino interaction length for neutrino energy $\sim 2 \text{ TeV}$. Most neutrinos above this energy will be absorbed. Since the critical energy below which neutrinos will be produced by pion decay in the outer part of the star is $\gg 2 \text{ TeV}$, we expect absorption of neutrino energy deep in the star to be important. Because of the high density of the region in which most neutrinos interact, their energy deposition will be fairly localized relative to the point of absorption, even for that part of the energy that goes into muons. Charged pions will interact and dissipate energy by cascading rather than decaying. High energy neutral pions will decay to high energy photons, which will produce electromagnetic cascades. Thus, virtually all of the energy of the neutrinos which interact will be in the form of low energy photons heating the interior of the star.

Using the standard stellar atmosphere profiles and taking account of pion cascading, we have numerically calculated the neutrino energy deposition, $\eta_{\nu} = fL_{\nu}$, as a function of a/R for two examples, the $2.8 M_{\odot}$ example referred to above and a main sequence star of $15 M_{\odot}$. Table 2 displays the results as a fraction of the cosmic-ray power that is deposited in the companion by high energy neutrinos for the two extreme production spectra calculated at $b = 0$ (soft) and at $b = R$ (hard). Here L_{ν} is the total produced neutrino luminosity and f is the fraction of the neutrino power that is absorbed in the companion. Thus, the quantity tabulated is η_{ν}/L_{CR} .

Figures 2 and 3 are contour maps of the localized energy deposition for our two examples for particular values of a/R . In Fig. 2 ($2.8 M_{\odot}$) we show results for the $b = 0$ neutrino production spectrum and in Fig. 3

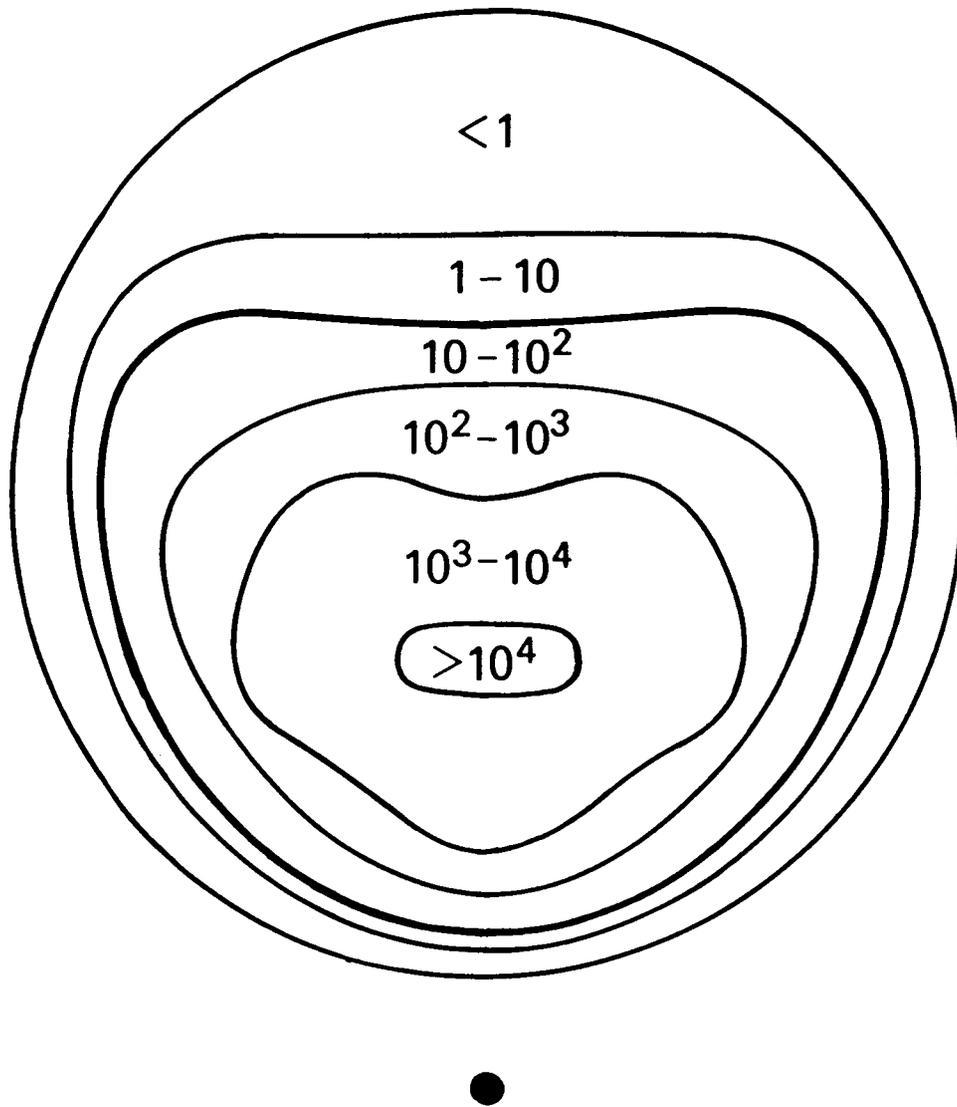


Figure 2. Contour map of energy deposition per unit volume ($\text{erg/cm}^3/\text{sec}$) for $M = 2.8 M_{\odot}$, $a/R = 1.2$, and the $b = 0$ neutrino spectrum.

($15 M_{\odot}$) we show the $b = R$ production spectrum. The primary cosmic-ray spectrum was assumed to be a δ -function with $E = 10^8$ GeV.

TABLE 2
Neutrino Energy Deposition in the Companion Star as a Fraction
of Total Cosmic Ray Luminosity

a/R	2.8 M_{\odot}		15 M_{\odot}	
	b=0	b=R	b=0	b=R
1.1	.0078	.040	.011	.058
1.2	.0064	.033	.0088	.046
1.6	.0035	.017	.0047	.024
2.0	.0022	.011	.0035	.015
3.0	.00098	.0047	.0013	.0063

Let us consider the dynamical effects of the resulting neutrino heating. There are at least two relevant quantities to which the neutrino heating rate η_{ν} should be compared, *viz.*, the Eddington luminosity, L_E , and the stellar luminosity, L , due to nucleosynthesis. If the neutrino energy deposition rate exceeds L_E the whole system may be disrupted. If η_{ν} is less than L_E but greater than L the system may be modified substantially in a time shorter than the lifetime of the system as estimated from the observed orbital period derivative. Stecker, *et al.*¹, have suggested that the companion may expand in response to the neutrino heating and quench the accelerator. We now discuss these possibilities in greater detail, in light of the more accurate estimates of neutrino energy deposition given in the preceding section.

If the companion star can absorb a significant fraction of its binding energy, it will alter its structure. The time to absorb a binding energy, $E_B = GM^2/R$, at a rate equal to the heating by neutrinos is

$$t_B = E_B / \eta_\nu = 10^3 \text{yr} \left(\frac{M}{M_\odot} \right) \left(\frac{R_\odot}{R} \right) \left(\frac{L_E}{\eta_\nu} \right) \quad (3)$$

at which point the star will be completely disrupted. For heating rates near the Eddington limit, this time is relatively short.

If the neutrino heating rate in the interior of the star exceeds the intrinsic stellar luminosity, the central temperature will initially increase. The star will adjust to restore hydrostatic equilibrium, reducing the central temperature on a dynamic timescale $t_D = 1/\sqrt{G\rho} \sim 1$ hr, which is short compared to t_B . In a dynamic timescale, the central temperature will increase by only a small fraction of the initial temperature. Even though the nuclear reaction rates in the core are a sensitive function of temperature, their resulting increase will not be large enough to cause a thermal runaway. Instead, the star will expand on the much longer timescale t_B , maintaining quasi-hydrostatic equilibrium. As the star expands the central temperature drops. At the same time, the radiative cooling at the surface increases (as a result of the larger surface area) and the entire star actually cools as a result of the extra heating. From the virial theorem and energy conservation, one can show that the initial behavior of the radius of the star as a function of time during which continuous heating $\eta_\nu > L$ occurs is

$$R(t) = R_0 / [1 - t/t_0] \quad t < t_0 \quad (4)$$

where the constant $t_0 = (GM^2/R_0)/\delta L$, $\delta L = \eta_\nu - L$, and R_0 is the initial radius of the star. This equation assumes that all of the absorbed energy goes into work against gravity in expanding the star, which is a good approximation until the photon diffusion time becomes comparable to t_0 . At this point, the star begins to lose some energy through radiative cooling from the surface, and the expansion will slow down (unless $\eta_\nu > L_E$). As the companion star expands it will become somewhat more transparent to neutrinos than the initial "undisturbed" star for which the absorption calculations were done. Thus, the characteristic time would be somewhat longer than the estimates given here, but not significantly so for close binaries. Even for heating rates

substantially below L_E , significant Roche lobe overflow effects will result in instabilities. Eventually the companion star radius in a close binary could increase enough to exceed the orbital radius and

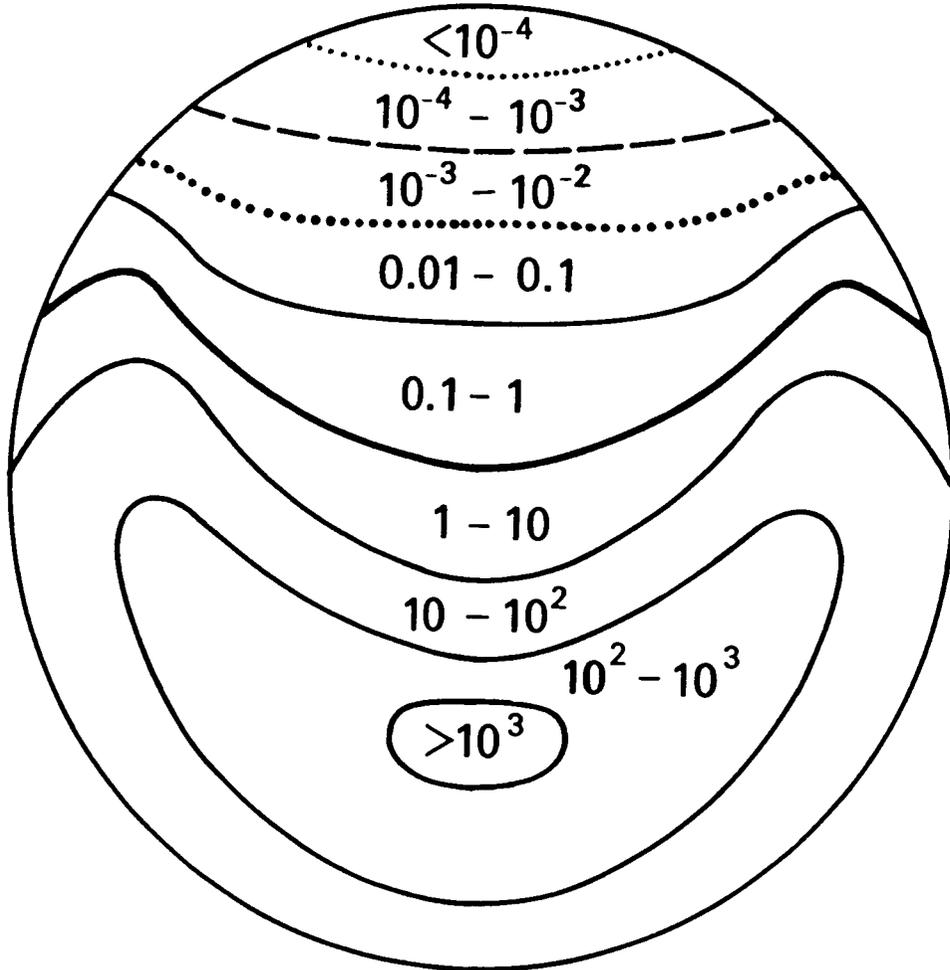


Figure 3. Same as 5b for $M = 15 M_{\odot}$, $a/R = 2$ and a $b \approx R$ spectrum.

engulf the compact object. We speculate that such effects could lead to a mechanism for periodically turning the accelerator on and off and which might lead to various observable effects in addition to modulation of the high energy signal, such as pulsations, radio outbursts, X-ray outbursts, etc.

TABLE 3
Neutrino Heating vs. Stellar Luminosities

	η_ν	L	L_E	$t_0(\text{yr})$
Cyg X-3(a)	10^{37}	10^{35}	3×10^{38}	4×10^4
Her X-1(a)	$\sim 10^{35}$	10^{35}	3×10^{38}	---
LMC X-4(b)	3×10^{38}	10^{38}	10^{39}	6×10^3
Vela X-1(b)	$< 10^{34}$	10^{38}	10^{39}	---

(a) 2.8 solar mass model
(b) 15 solar mass model

For Hercules X-1 and possibly Cygnus X-3, the 2.8 M_\odot example is the relevant one, whereas for LMC X-4 and Vela X-1 the companion mass is somewhat above 15 M_\odot . In the first case $L_E \sim 3 \times 10^{38}$ erg/s and $L \sim 10^{35}$ erg/s and in the second the corresponding numbers are 10^{39} erg/s and 10^{38} erg/s. We now use information from Tables 1 and 2 to make the comparison with the neutrino energy deposition. For Vela X-1 the separation is so great and the companion so massive that $\eta_\nu \ll L$. For Hercules X-1, $\eta_\nu \sim L$. The other two cases are the most interesting because in both cases the neutrino energy deposition is substantially greater than the stellar luminosity. For the 2.8 M_\odot case, we estimate $\eta_\nu \approx 10^{37}$ erg/s for the neutrino heating rate and the expansion timescale $t_0 \sim t_B = 3.8 \times 10^4$ yr. From equation (4), it follows that the time for the star to expand to the radius of the orbit when $a/R_0 = 1.2$ is $t = 6.3 \times 10^3$ yr. In the 15 M_\odot (LMC X-4) case, we estimate a heating rate of $\eta_\nu \approx 3 \times 10^{38}$ erg/s,

giving $t_0 = 6.2 \times 10^3$ yr and $t = 4.4 \times 10^3$ yr for $a/R_0 = 3.5$. Table 3 shows a summary of luminosities and neutrino energy deposition rate for the systems which we have considered. For the Cygnus X-3 and LMC X-4 systems in particular, our calculated neutrino heating rate exceeds the intrinsic stellar luminosity, changing the internal structure of the companion star. We estimate that these systems will evolve or change their structure on the characteristic timescale t_0 .

Several possible scenarios may follow the neutrino-heating induced expansion of the companion star. If the acceleration mechanism is quenched when the compact object is engulfed in the atmosphere of the companion, then neutrino production and heating will cease, and the star will begin to contract. Once the companion has contracted within the radius of the orbit, the acceleration might resume, and some kind of periodic behavior may characteristics on timescales of $10^3 - 10^4$ yr. result. The period would be no longer than t_0 , the timescale on which stellar radius changes occur, which is probably too long to be observable in the Cygnus X-3 and LMC X-4 systems. (The lower limit on the period is $\sim t_0$). But if this periodic turning on and off of the acceleration adjusts itself so that the time-averaged heating of the star is approximately equal to L , then the fraction of time during which acceleration is on will be $f_{\text{on}} = L/n_\nu - 10^{-2}$ for the Cygnus X-3 case. The interval of time during which the source is turned on in a period t_0 is then $f_{\text{on}} t_0 \leq 100$ yr. If the oscillation period is between t_0 and several years the γ -ray observations would indicate an average luminosity of the star to be a few percent of $\sim 10^{39}$ ergs s^{-1} . This is larger than what is expected for an intermediate mass main sequence star.

If the accelerator does not turn off inside the envelope of the companion star, then the heating and expansion of the star will continue. On a timescale t_0 , the stellar material surrounding the compact object will become optically thick, first to the X-rays (depth of $\sim 1 \text{ g/cm}^2$) and then to the γ -rays (depth of $\sim 50 \text{ g/cm}^2$). This timescale may be shortened by the orbital decay due to frictional dissipation in the stellar atmosphere¹⁸.

Should the compact object then fall to the center of the companion star and somehow continue to accelerate high-energy particles, it is amusing

to speculate that a "hidden neutrino source" (e.g. Berezhinsky⁸) might result, but here again the stellar atmosphere would continue to expand and be blown off. Needless to say, in this "swallowed star" configuration, no significant γ -ray flux or time-variable neutrino flux would be expected, so that this case does not refer to any of the real observed systems which are the main concern of this paper.

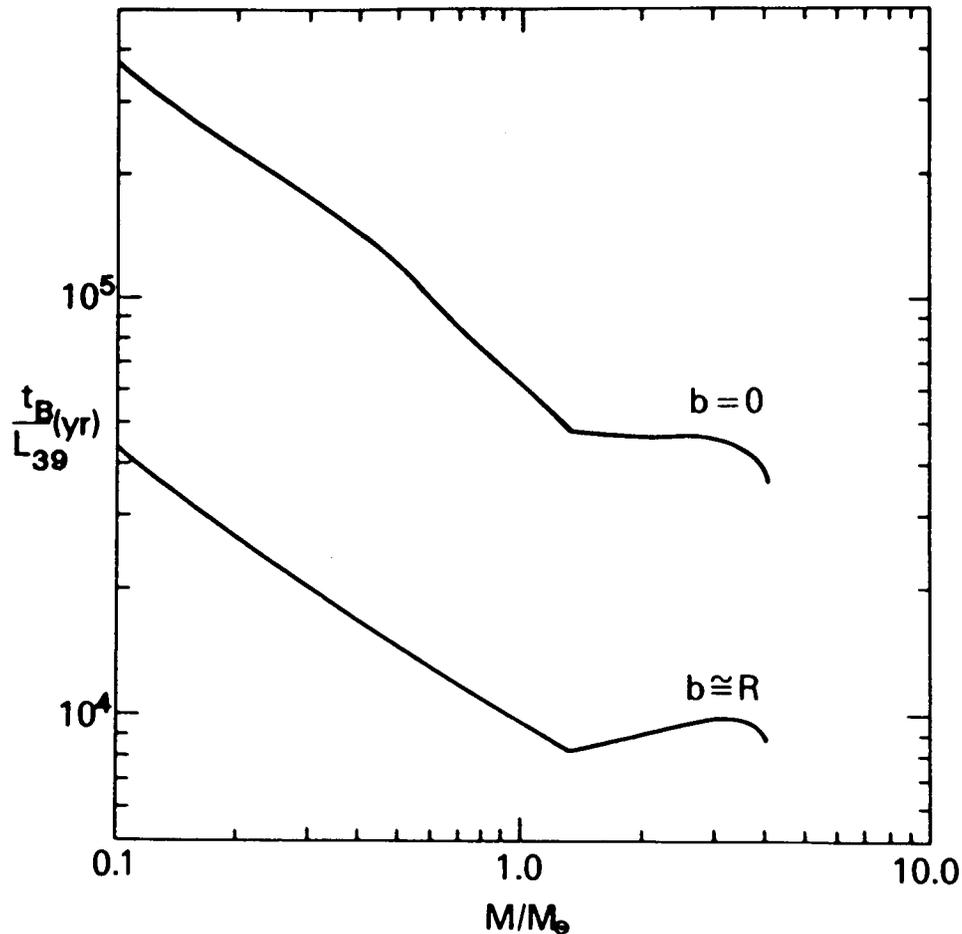


Figure 4. Lifetime of a main-sequence companion star against disruption by neutrino heating in the Cygnus X-3 system, scaled by the incident proton luminosity $L_{39} = L_{cr}/10^{39} \text{ erg s}^{-1}$, as a function of its mass from Eq (16). The upper and lower curves were determined for the two extreme neutrino spectra produced at impact parameters $b = 0$ and $b = R$. Values of .20 and .05 were used for the neutrino production efficiency ϵ in the $b = R$ and $b = 0$ cases respectively. The mass-radius relation for main sequence stars is that given in Ref. 21.

Since it lies beyond a very dusty region of the Galaxy, no optical emission has been seen from the companion in the Cygnus X-3 system. Thus, its mass is very uncertain, in contrast to the other UHE binaries whose companions have been detected optically. Requiring the companion to be a main sequence star with a radius less than the orbital radius gives a mass upper limit of $4 M_{\odot}$ (Vestrand and Eichler⁶). Requiring the star to fit inside its own Roche lobe gives an upper limit of $0.5 M_{\odot}$ for a main sequence star¹⁹ and $4 M_{\odot}$ for a He star²⁰. Although the detailed results presented above for Cygnus X-3 were obtained for a $2.8 M_{\odot}$ companion, the time scales will not be qualitatively different for a companion mass as low as $0.5 M_{\odot}$. The characteristic expansion timescale is plotted as a function of stellar mass in Figure 4 for the two extreme neutrino production spectra.¹ The break around $1.3 M_{\odot}$ results from a corresponding break in the particular mass-radius relation which we have used²¹. The lifetime of a $0.5 M_{\odot}$ star is between $\sim 10^4$ yr and $\sim 10^5$ yr, with the lower value applicable to a star with a dense wind and the higher value being an upper limit. This lifetime is a very small fraction of the main sequence lifetime of a $0.5 M_{\odot}$ star and is not significantly different from that derived for the $2.8 M_{\odot}$ star.

Several factors may influence the above constraints imposed by neutrino heating of the companion star. We have assumed that the accelerated particles are emitted isotropically. If the cosmic rays from the source are sufficiently anisotropic, then neutrinos would not heat the entire volume of the companion star. While there are no direct constraints on the solid angle of the particle beam in any of the UHE γ -ray sources, in the case of Cygnus X-3, constraints on the mass loss from the companion star may indicate that the beam heats a small fraction of the stellar surface area (Stecker, et al., Ref 1). However, as long as the total energy incident on the star remains the same, we do not expect, given the near uniform energy deposition over the star (cf. Figs. 2 and 3), that the neutrino absorption will change significantly. There is also evidence that Cygnus X-3 is a highly variable source at high energies on a time scale of $\ll 100$ yr.²², which would ease the energy constraints on the system, since our limits refer to time averaged energy constraints over time scale of 100 years or more.

Finally, we note that in the case of Cygnus X-3, n_ν could be as much as 1.5 orders of magnitude larger without completely disrupting the system. For LMC X-4 it could be a factor of three or so larger. Thus, the neutrino-induced signal could be as large as 10-30/1000 m^2/year , rather than the more conservative estimate of \sim one per year in 1000 m^2 . This would require D_γ in Eq. (1) to be much smaller than 1/50. However, this duty factor for production of photons is very model dependent because of the narrow range of thicknesses for which high energy photons can be produced without being reabsorbed. A flux as large as this limiting value would still not be large enough to explain the reported underground signals from the direction of Cygnus X-3 observed with exposures of $\sim 10 \text{ m}^2 \text{ yr}^{10}$, however it could be detectable in the large area detectors proposed for Gran Sasso²³ and certainly in a detector with an area as large as 10^5 m^2 as proposed for DUMAND²⁴

The implications of our calculations for the underground muon results and their explanation in terms of new particles (cygnets) are potentially quite interesting. Cygnets (e.g. quark nuggets, photinos, etc.) are most likely generated by the primary particle beam with an efficiency $\epsilon_{\text{Cyg}} \ll \epsilon_\gamma$. Defining $\epsilon_{\text{Cyg}}/\epsilon_\gamma \equiv \xi$, we note that in order to explain the underground muon results, we require a cosmic-ray beam power which is a factor ξ^{-1} higher than those used in the calculations above. In the case of Cygnus X-3, however, the underground muon data, when taken at face value, indicate that the TeV photon and μ fluxes are comparable. We may therefore be faced with a contradiction if the muon data are taken at face value.

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