CYGNUS X-3 AND OTHER ULTRA-HIGH-ENERGY γ-RAY SOURCES

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ABSTRACT. Recently, several binary X-ray sources have been found to be sources of ultra high energy γ-ray emission. Air shower observations indicate photon energies $\gtrsim 10^{15}$ eV. We review the current status of observations from the source Cygnus X-3, and compare this data with that from the sources Hercules X-1, Vela X-1, and LMC X-4. Current theoretical models for the production of γ-rays and the acceleration of high energy particles are discussed and the consequences for the evolution of such systems are examined.

I. INTRODUCTION

When a pencil is dropped onto a tabletop from a height of about one centimeter the energy liberated in the form of sound waves and heat is about 10^{16} eV. Individual photons from the binary X-Ray source Cygnus X-3 have been observed (e.g. Samorski and Stamm, 1983; Lloyd Evans et al 1983) to be carrying such macroscopic quantities of energy at a rate such that an area the size of a football field (at the distance of the earth) is bombarded by such photons about 10 times each year. This enormous energy per photon as well as the large implied particle luminosity at the source places constraints on mechanisms for accelerating the particles required to produce such photons. Further, the presence of a high energy particle accelerator in a binary star system has implications on the evolution of the star system itself. The purpose of this review is to examine some of the proposed methods for accelerating particles to ultra-high-energies (UHE; photon energy $E \gtrsim 10^{15}$ eV) and to look at some of the effects that such particles have on binary star systems, such as Cyg X-3.

We begin in section II, with a short synopsis of the observations of Cygnus X-3 from radio through UHE γ-rays, and a look at the other systems where UHE γ-rays have been reported. In section III, we examine the stellar-beam-dump model of γ-ray production (e.g. Vestrand and Eichler, 1979, 1982, Berezinsky, 1980) wherein protons that have been accelerated by a compact star to energies of about 10^{17} eV bombard a normal stellar companion. Neutral pions are produced which

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decay into γ-rays observable when the line of sight to the compact star grazes the limb of the companion star. In section IV we examine three proposed methods of accelerating particles: a pulsar (Eichler and Vestrand, 1984), the accretion disk dynamo (Chanmugam and Brecher 1985) and shock acceleration (e.g. Eichler and Vestrand 1985, Kazanas and Ellison 1986). In section V consequences of having a particle accelerator in the stellar system are considered (e.g. Berezinsky 1980, Stecker et al 1985, Gaisser et al 1986) focusing on the formation of a stellar wind, and the internal heating of the star from neutrino absorption.

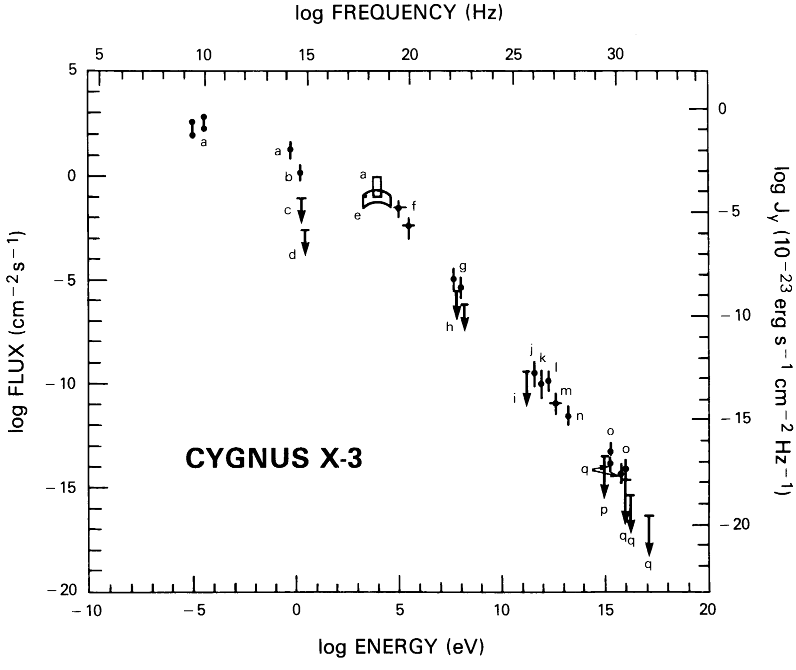

Figure 1. Spectrum of Cygnus X-3. References: a)Mason et al 1976 b) Weekes et al 1982 c)Weekes et al 1981 d)Westphal et al 1972 e) Serlemitsos et al 1975 f) Meegan et al 1979 g) Lamb et al 1977 h) Hermsen 1983 i) Weekes et al 1977 j) Lamb et al 1981 k)Dowthwaite et al 1983 l) Neshpor et al 1979 m)Stepanian et al 1982 n) Morello et al 1983 o)Samorski et al 1983 p) Hayashida et al 1981 q) Lloyd-Evans et al 1983.

II. OBSERVATIONS

Cygnus X-3 has been observed from the radio to the UHE γ-ray regime. Figure 1 is a composite spectrum of some of the data obtained during the 16 years of observations in the various wavelength bands.

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If we assume that all the reported detections are real, then from X-rays (at ~ 10^4 eV) to UHE γ-rays (at ~ 10^{16} eV) the spectrum is a power law. The energy exponent in the differential energy flux (and also the integral number flux) is -1.1 (i.e. EdN/dE ~ $E^{-1.1}$, where dN/dE is the photon number flux per unit energy interval at photon energy E). Note that some of the upper limits contradict the detected fluxes. At ~ 10^8 eV the SAS-II detections (Lamb et al 1977) (at 4.5σ) contradict the COS-B upper limits (Hermsen 1983). And observations at ~ 10^{11} eV by Weekes et al (1977) seem to contradict the other positive detections in this energy range (e.g. Vladimirsky et al 1975, Neshpor et al 1979, Danaher et al 1981, Lamb et al 1981), while Hayashidi et al (1981) report upper limits in the PeV (10^{15} eV) energy range inconsistent with the data of Samorski and Stamm (1983). Time variability of the source may be at work (indeed Bhat et al 1985 report evidence for a secular decrease in flux in the PeV range on a decade long time scale.) Variability is certainly present at lower frequencies, as in the radio (e.g. Gregory et al 1972), IR (Becklin et al 1973), and X-Ray (e.g. Elsner et al 1980). In a more skeptical interpretation, Chardin and Gerbier (1985) question the consistency of the observations and suggest that if the γ-ray signals were actually just statistical fluctuations above the background a power law spectrum would be produced with the same index as is observed.

The upper limits in the optical reflect the ~ 19 magnitudes of extinction (Weekes and Geary 1982) in the direction of Cyg X-3 due to galactic dust while the upper limits at energies greater than ~ 10^{16} eV are interpreted as evidence for a real cutoff in the spectrum (Lloyd-Evans et al 1983).

Periodicity on a 4.8 hour timescale has been observed over 16 decades in energy (from IR through UHE γ-ray). In the X-ray regime (~ 10 keV) the light curve is nearly sinusoidal (e.g. Bonnet-Bidaud and van der Klis 1981). At IR energies the depth of the modulation is less (Mason et al 1976) as it is in the high energy X-ray regime (Molnar 1985). In the Very High Energy range (VHE: E >~ 10^{11} eV) the light curve appears to have a narrow peak at a phase of ~.6 (relative to phase 0 at X-ray minimum), with a width in phase of about .02 to .05. At UHE the phase also varies with observing group and with time, but phases of about .6 and .2 have been observed with some consistency (Lambert et al 1985). In many of the γ-ray detections a stastically significant signal is not observed until it is folded onto the 4.8 hour period. The resulting signals are typically 2 to 4 standard deviations above the background (cf. Chardin and Gerbier 1985).

Periodicity or variability on other timescales have been reported at a variety of periods. Potentially one of the most significant is the report of a 12.6 ms periodicity in the VHE γ-ray data (Chadwick et al 1985b) In addition this group tentatively reported that their data is consistent with a period derivative of 4.5 x 10^{-15} ss^{-1} (Turver et al 1986). These observations have yet to be confirmed by independent groups however.

Periodicity in the radio on a 4.95 hour timescale has been reported (Molnar et al 1985). Molnar et al find that flux density variations (flaring) at wavelengths between 1 and 6 cm exhibits a

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periodicity with a period that is definitely different than the 4.8 hour X-ray period.

Other periodicities or variability time scales which have been reported are: 19 days (Chadwick et al 1985a) and 34.1 days (Molteni et al 1980). Variability at shorter timescales are indicated in the power spectrum of the X-ray data which is proportional to $\nu^{-1.8}$ (where ν is frequency) for frequencies between 10^{-4} and 10^{-3} Hz (Willingale et al 1985). Quasi-periodic-oscilations have been observed (also in the X-Ray regime) with periods in the 50 to 1500 s range (van der Klis and Jansen 1985).

In addition to the electromagnetic signal from Cygnus X-3, two underground experiments (SOUDAN and NUSEX) which detect TeV muons have reported possible time modulated excess muon fluxes from the direction of Cygnus X-3 (Marshak et al 1985, Battistoni et al 1985). Other underground experiments have also searched for muon fluxes and have failed to detect them (cf. Oyama et al 1986, Chudakov 1986). The experiments vary in depth of rock (from about 10^6 to 5×10^6 g/cm^2) and corresponding muon threshold energies (from ~.2 TeV to ~3 TeV). The upper limits of some of the negative experiments contradict the positive results. In addition, in both the SOUDAN and NUSEX experiment the angular windows that were used in the direction of Cygnus X-3 were much larger than the angular resolution of the experiment. This was done in order to maximize the detected signal, but the theoretical justification is not apparent (although cf. Ramana Murthy 1986 and references therein).

The question of what primary particle produces the muons adds more uncertainty to the whole problem. As pointed out by Marshak et al (1985) if the primaries were neutrons they would need energies greater than 10^{18} eV to make it to earth without decaying. If they were produced by photons they would need energies >> TeV energies in order to produce a ~0.6 TeV muon. In both cases surface detectors would have detected neutron or photon fluxes several orders of magnitude larger than what is observed. Finally if they were neutrinos, they would not have observed an intensity dependence on the grammage of overlying rock (as was observed) as the earth itself would be optically thin to the neutrinos. In light of these large uncertainties in the muon detections we focus our subsequent discussion strictly on the implications of the UHE and lower energy photons.

In addition to Cygnus X-3, 3 other binary X-ray systems have reported detections of UHE γ-rays: Vela X-1 (Protheroe et al 1984), LMC X-4 (Protheroe and Clay 1985) and Her X-1 (Balstruaitis et al 1985). Table 1 (from Gaisser et al 1986) summarizes some of the properties of these sources. It is apparent that except for the property of being an X-ray binary, they are not a particularly homogeneous set of objects. If the VHE γ-ray observations of Cyg X-3 indicate the underlying rotation period of the neutron star, the rotation periods vary over 4 decades, the orbital periods and companion masses vary over nearly 2 decades and the inferred UHE cosmic ray luminosity varies over nearly 4 decades. The inferred cosmic ray luminosity is given by:

$$L_{CR} = 4\pi d^2 F_\gamma (\Delta\Omega/4\pi) (.02/D_\gamma) (.1/\varepsilon) \quad (1)$$

Here d is the distance to the binary system, F_γ is the time averaged UHE γ-ray flux, ΔΩ is the solid angle subtended by the cosmic ray proton accelerator (assumed equal to 4π), D_γ is the orbital phase interval over which UHE γ-rays are observed, and ε is the assumed efficiency for converting cosmic ray particle energy into γ-ray energy. Equation (1) is based on the "stellar-beam-dump" model, to be discussed in the next section.

Table 1: Parameters of Binary X-Ray/UHE γ-Ray Systems[1]

System	Rotation Period (s)	Binary Period (days)	Companion Mass ($M/M_\odot$)	a/R†	Distance (kpc)	L_{CR} (erg/s)
Cygnus X-3	.0126(?)	0.19	<4	>1	>8	~ 10^{39}
Vela X-1	283.	8.965	~23	12	1.4	~ 10^{37}
LMC X-4	13.5	1.408	~19	3.5	55	~ 10^{41}
Her X-1	1.24	1.7	2.4	6	4	~ 10^{38}

[1]From Gaisser et al 1986; †a = orbital semi-major axis; R = companion star radius

III. THE STELLAR BEAM DUMP MODEL

The most developed model to account for the UHE γ-rays from Cyg X-3 is the "stellar beam dump model" (cf. Vestrand and Eichler 1979, 1982; Berezinsky 1980). In this model protons (or in some theories neutrons) accelerated in the vicinity of a black hole or a neutron star strike the companion star producing neutral and charged pions. Neutral pions decay into γ-rays which if directed into the star will be absorbed; if produced near the limb of the star and the grammage traversed is sufficiently low they may escape from the system. Thus γ-rays will be observed as the star goes into and out of eclipse. The width of the γ-ray pulse is determined by the density distribution of the atmosphere and wind of the companion, which may be severely altered by the cosmic-ray bombardment (cf. section V). Hillas (1984) calculates the spectrum of a monoenergetic (10^{17} eV) proton beam bombarding an atmosphere (with a magnetic field of ~ 10^3 G) and finds a γ-ray spectrum which is consistent with the observed spectrum.

This model requires that the Cygnus X-3 system be an eclipsing X-ray binary. The X-ray light curve however does not show a sharp eclipse but rather is nearly sinusoidal in character. This has led some authors to conclude that matter in the system, in the form of a stellar wind (Pringle 1974, Davidsen and Ostriker 1974) or a shell around the system (i.e. the "cocoon" of Milgrom, 1976), scatters the X-rays and thus smooths the sharp eclipse. See Hertz et al (1978) and Ghosh et al (1981) for a detailed comparison of the two models.

However, in an alternative explanation an accretion disk corona is the source of X-rays which are eclipsed by bulges in the accretion disk associated with the accretion stream (White and Holt, 1982). Molnar (1985) suggests that the frequency dependence of the depth of modulation of the light curves argues for the accretion disk corona model and against the wind or cocoon models. In such a model the bulges associated with the eclipses may provide the grammage for γ-ray production although the details of such a model have not been explored.

In the stellar beam dump model γ-rays are produced in the interaction of UHE particles with target matter. One attractive feature of such models is that the acceleration region which may involve relatively high magnetic fields is distinct from the γ-ray production region which is required to have low magnetic fields ($\lesssim 10^3$ G for $E \sim 10^{15}$ eV) in order to avoid magnetic pair creation (cf. Stephens and Verma, 1984).

One problem with the model is that a γ-ray phase of 0.6 is not consistent with the beam dump model which predicts an eclipse from phase 0.75 to 0.25 if $a/R = 1$ and a narrower range about phase 0 for larger, expected values of a/R. Attempts (e.g. Hillas 1985) to account for this phase assuming a wake through a stellar wind from the companion have been proposed which try to preserve the basic feature of the model.

IV. ACCELERATION MODELS

Models for producing UHE particles in the vicinity of a compact star can be divided into three types: pulsar acceleration (Eichler and Vestrand, 1984), shock acceleration (see e.g. Eichler and Vestrand 1985, Kazanas and Ellison 1986) and the accretion disk dynamo (Chanmugam and Brecher 1985).

A pulsar has long been suspected of being a member of the Cyg X-3 system (e.g. Pringle 1974). As the photon energy has gone up, the idea of having a fast young pulsar as the accelerator has become more appealing (e.g. Lamb et al 1977, Eichler and Vestrand, 1984). Goldreich and Julian (1969) pointed out that the maximum potential drop $\Delta\phi$ available along the open field lines above a pulsar yields a maximum energy of:

$$e\Delta\phi \sim eB\left(\frac{R\Omega}{c}\right)^2 R \sim 10^{17}\left(\frac{B}{10^{12}G}\right)\left(\frac{10\text{ms}}{P}\right)^2 \text{ eV} \qquad (2)$$

Here B is the surface neutron star field, $P \equiv 2\pi/\Omega$ is the pulsar rotation period and $R \simeq 10^6$ cm is the neutron star radius. However, much of pulsar theory indicates that pair creation may limit the potential drops to a small fraction of this potential (e.g. Ruderman and Sutherland 1975, Arons and Scharlemann, 1979).

The maximum luminosity L is that given by spindown of a magnetized rotating dipole (Gunn and Ostriker 1969) and is approximately given by: $L \sim 10^{39}\ (B/10^{12})^2\ (10\text{ms}/P)^4$ erg s^{-1}. The lifetime t for this loss mechanism is: $t \sim P/\dot{P} \simeq 1000\ (P/10\text{ms})^2 (10^{12}\text{G}/B)^2$ years. Thus, a pulsar with rotation period of about 10ms, and surface magnetic field strength of about 10^{12} G has a total luminosity, maximum electrostatic potential, and lifetime consistent with what is needed for Cygnus X-3. If observations by Chadwick et al (1985) of P = 12ms and the report by Turver et al (1986) of $\dot{P} \sim 4.5 \times 10^{-14} s^{-1}$ (corresponding to an approximate surface field of 8×10^{11} G) are confirmed, the weight of evidence for the pulsar model will be compelling. Indeed, the fact that the Crab pulsar is a TeV source (Grindlay et al 1976) (although not a strong PeV source, cf. Boone et al 1984) provides evidence for particle energies up to TeV energies for isolated neutron stars. On the other hand, in the 3 other UHE sources the maximum potential drops across the polar cap are not large enough to account for the PeV emission.

In the pulsar model particles are accelerated electrostatically, and the energy source is the stored rotational energy of the neutron star. In the accretion disk dynamo model (Lovelace, 1978, applied to Cygnus X-3 by Chanmugam and Brecher, 1985) particles are again accelerated electrostatically but with energy derived from accretion of matter down to the Alfven radius (where the magnetic and kinetic energy densities are equal).

The basic idea is that the matter that is moving azimuthally in the accretion disk around the neutron star encounters a vertical component to the magnetic field. In the frame comoving with the plasma the conductivity is high so that the comoving electric field is approximately zero. In the pulsar frame this requires that $\underline{E} = -(\underline{v} \times \underline{B})/c$ yielding a radial electric field in the accretion disk. Thus the maximum energy available is roughly eEr_A:

$$e\Delta\phi \sim \frac{e}{c}\left(\frac{GM}{r_A}\right)^{\frac{1}{2}} r_A B_A \sim 10^{16}\left(\frac{M}{M_\odot}\right)^{\frac{1}{2}}\left(\frac{B_A}{10^8 G}\right)\left(\frac{r_A}{10^6 cm}\right)^{\frac{1}{2}} eV \quad (3)$$

Here $B_A \equiv$ the magnetic field at r_A, $r_A \equiv$ the Alfven radius $\simeq 10^6$ cm $(B/10^8 G)^{4/7} (R/10^6 \text{ cm})^{10/7} (L/10^{38} \text{erg s}^{-1})^{-2/7}$ (see e.g. Shapiro and Teukolsky 1983 and references therein), M is the neutron star mass. In this picture the inner edge of the accretion disk has a magnetic field strength determined by the dipolar magnetic field of the neutron star. The maximum luminosity in cosmic ray particles is the accretion luminosity $L \sim GM\dot{M}/r_A$ which must be $\lesssim$ the Eddington luminosity $\simeq 1.3 \times 10^{38} (M/M_\odot)$ erg s^{-1}. The basic picture then is that particles will be accelerated along field lines which do not penetrate the disk (i.e. the open field lines), creating a "spray" of high energy particles.

The lifetime for accretion to occur is long: t $\simeq$ $\simeq 10^8 (R/r_A) (10^{38} \text{ erg s}^{-1}/L)(M_c/M_\odot)$ years, where M_c is the companion mass and $\dot{M}$ is the mass loss rate from the companion star (assumed equal to the mass accretion rate onto the neutron star). Note that in this model the highest potential drop occurs when r_A is small (i.e. ~ R). Here the Keplerian velocity is largest resulting in a large electric field. But a small r_A requires a weak magnetic field, some 4 orders of magnitude weaker than in the pulsar case.

The main advantage of appealing to this model is that Vela X-1, LMC X-4, and Her X-1 are slow rotators yet apparently generate UHE particles, and so accretion power is a common link. Disadvantages of the model include the fact that the luminosity is limited to ~ 10^{38} erg s^{-1} for a neutron star, apparently in conflict with Cyg X-3 and LMC X-4. Thus, it requires an efficiency better than unity in those cases and close to unity for the other two. Further, the plasma distribution will respond to electric fields generated in and above the disk, perhaps reducing the potential and changing the plasma configuration. A more self-consistent treatment is needed to confirm this idea.

Also utilizing accretion power for the energy source is the shock acceleration model (e.g. Vestrand and Eichler 1982, Eichler and Vestrand, 1985, Kazanas and Ellison, 1986). In this model, a shock is expected to form at the Alfven radius. Particles are caught in a squeeze between magnetic irregularities in the fast moving inflowing upstream matter and the slowly moving irregularities in the post-shocked material. In this Fermi acceleration mechanism (e.g. Bell 1978, Blandford and Ostriker 1978), the average number of scatterings before a particle increases its energy by of order its own energy is ~ $1/\beta^2$, where β is the difference between the pre- and post- shocked fluid velocity (in units of c). β is assumed to be of order $(GM/r_A c^2)^{\frac{1}{2}}$. The maximum energy achievable is found by balancing the characteristic acceleration time with the energy loss time, which can be from radiative losses, or as in this example, escape from the region with characteristic dimension r_A:

$$\left(\frac{r_A}{\lambda}\right)^2\left(\frac{\lambda}{c}\right) = \frac{1}{\beta^2}\left(\frac{\lambda}{c}\right)$$

$$\rightarrow\ E_{max} \sim 10^{16}\left(\frac{r}{R}\right)^{-\frac{1}{4}}\left(\frac{M}{M_\odot}\right)^{\frac{1}{4}}\left(\frac{L}{10^{38}\ \mathrm{erg/s}}\right)^{\frac{1}{2}}\ \mathrm{eV} \qquad (4)$$

Here λ is the mean free path between scatterings off magnetic irregularities assumed to be equal to the particle gyro-radius. The energy is again maximized when the shock radius occurs near the stellar surface (although equation (4) indicates the dependence on radius is relatively weak). As in the accretion disk dynamo this requires the magnetic moment to be small (B_s ~ 10^8 G) for this to occur. And since this scenario is also accretion powered, the lifetime is the same (t ~ 10^8 years).

The virtues and problems of this model are similar to those of the accretion disk dynamo in the sense that slow rotators are not a problem, but that Eddington limited accretion onto a neutron star provides a maximum L ~ 10^{38} erg/s assuming 100% efficiency, whereas the actual efficiency is not known. Another advantage of shock acceleration is that it has been observed in solar system contexts, whereas accretion disk dynamos are still purely theoretical constructs.

IV. CONSEQUENCES OF PARTICLE ACCELERATORS IN BINARY STAR SYSTEMS

In addition to being a passive target for the production of γ-rays, the companion star itself will be altered by the impingent particle energy implied by equation (1). Formation of an expanded atmosphere or stellar wind (cf. Basko and Sunyaev 1973, Berezinsky 1980, Stecker et al 1985, Gaisser et al 1986) can occur due to the atmospheric heating by the bombarding cosmic rays. Heating of the stellar interior from neutrinos produced in the atmosphere (cf. Stecker et al 1985, Gaisser et al 1986, Harding et al 1987) can alter the stellar structure, possibly even disrupting the system.

A 10^{17} eV photon is thermalized after traversing a grammage X ~300 g cm^{-2}. This corresponds to a linear depth of several tens of thousands of kilometers beneath the surface of a solar mass main sequence star. If the radiation pressure gradient produced by the thermalized particle energy exceeds gravity (i.e. locally super-Eddington heating) a wind will be formed with terminal velocity approximately given by:

$$v \sim \left(\frac{L_B \kappa}{2\pi f R c}\right)^{\frac{1}{2}} \sim 10^8 \left(\frac{L_B}{10^{39}\ \mathrm{erg/s}}\right)^{\frac{1}{2}} \left(\frac{R_\odot}{R}\right)^{\frac{1}{2}} f^{-\frac{1}{2}}\ \mathrm{cm/s} \qquad (5)$$

Here L_B is the cosmic ray power incident upon the star, κ is the radiative opacity ($\cong .4$ cm^2/g for electron scattering) and f is the fraction of the surface area of the star illuminated by cosmic rays. Since the optical depth $\tau \sim \kappa X >> 1$ the radiation does not escape and the beam energy will largely be converted into kinetic energy of mass motion:

$$\dot{M} \sim \frac{2L_B}{v^2} \simeq \frac{4\pi f R c}{\kappa} \simeq 10^{-3}\ f\ \left(\frac{R}{R_\odot}\right)\ M_\odot \mathrm{yr}^{-1}. \qquad (6)$$

Note that this is independent of the power being dissipated into the star, as long as the stellar heating rate is super-Eddington (Stecker et al 1985). The orbital period of Cygnus X-3 is increasing (e.g. Bonnet-Bidaud and van der Klis 1981) with the derivative satisfying $\dot{P}/P \simeq 10^{-6}$ yr^{-1}. If the orbital angular momentum of the wind of the companion star is lost then $\dot{P}/P \simeq \frac{1}{2}(\dot{M}/M_T)$ (Davidsen and Ostriker 1974), where M_T is the total mass of the system. In order that $\dot{M}$ of equation (6) not produce a $\dot{P}$ larger than is observed, either a small fraction of the star is illuminated by cosmic rays ($f \sim 10^{-3}$) or the incident cosmic ray flux is sub-Eddington.

When a high energy proton collides with a target nucleus, in addition to the neutral pions that are produced (which decay into γ-rays) charged pions are also produced. The charged pions will do one of two things: If the decay time is less than a mean free collision time they will decay into a neutrino and a muon, the latter further decaying into two neutrinos and an electron or positron. If the decay time is greater than a mean free collision time the charged pions will interact and cascade suppressing the production of the high energy neutrinos that are produced when the pions decay. This results in a neutrino spectrum in which only neutrinos with energy less than $E_{\nu c} \simeq 1.3\ (10^{-6}\ \mathrm{g\ cm^{-3}}/\rho)$ TeV will be produced. Here ρ is the density in the atmosphere where the high energy neutrinos are produced (at X >~ 30 g cm^{-2}). The density at X = 30 g cm^{-2} is ~ $10^{-6}\ (M_c/M_\odot)^{-0.9}$ g cm^{-3} (Gaisser et al 1986). Thus $E_{\nu c} \sim .7\ (M_c/M_\odot)^{0.9}$ TeV which is a much smaller energy than the 10^5 TeV assumed for the incident cosmic ray particles. For neutrino energies $E_\nu <\sim 10$ TeV the neutrino cross section σ_ν is linear with E_ν: $\sigma_\nu \simeq 5 \times 10^{-36}$ (E_ν/1 TeV) cm^2. The optical depth through the star $\tau(E_{\nu c}) \sim \sigma_\nu nR \sim .4(M_c/M_\odot)^{0.3}$, implying a relatively large fraction of the neutrinos will be absorbed nearly uniformly throughout the stellar interior. For a wind atmosphere, in which the density falls off as r^{-2} (where r is the radial distance) the density at X = 30 g cm^{-2} is roughly (h/R) times the density in an undistrubed star, where h/R ($\sim 10^{-3}$) is the ratio of undisturbed scale height to stellar radius. Thus, for a wind atmosphere the high energy neutrino production is not as efficiently suppressed and the optical depth to these higher energy neutrinos is even greater. Gaisser et al find that for main sequence stars ~5 to 20% of the incident cosmic ray energy flux can be carried into the stellar interior by neutrinos and be absorbed. This can provide more energy to the stellar interior than is produced by the star's self generated nuclear burning. The timescale for the star to absorb a gravitational binding energy t_B is given by:

$$t_B \sim \frac{GM_c^2}{\varepsilon RL_B} \sim 6 \times 10^3 \left(\frac{M_c}{M_\odot}\right)^2 \left(\frac{.2}{\varepsilon}\right) \left(\frac{R_\odot}{R}\right) \left(\frac{10^{38}\text{erg/s}}{L_B}\right) \text{ yrs.} \qquad (7)$$

Here ε is the fraction of L_B that is converted into neutrinos and absorbed in the star. For Cygnus X-3 this timescale ($\sim 10^4$ years) is much shorter than the observed mass loss time scale (10^6 years) and the timescales associated with acceleration mechanisms that use accretion as an energy source ($\sim 10^8$ years) but is comparable with the proposed pulsar lifetime ($\sim 10^3$ years). Since the radiative diffusion time is longer ($\sim 10^6$ years) the star will expand and can even be disrupted on this short timescale.

V. CONCLUSION

It is difficult to draw a firm conclusion from the story that we have just presented. The various UHE data, after years of observations, still do not present a unique picture of the luminosity and phase of emission. The most often cited phase does not fit neatly into γ-ray production in a stellar companion. The proposed acceleration schemes, although encouraging, are still plausibility arguments rather than full fledged dynamic models. And the inferred mass loss rate and lifetime against neutrino absorption places limits on the sustained cosmic ray luminosity that can exist in a binary system. Clearly, the story of Cygnus X-3 and its bretheren is still unfolding.

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DISCUSSION

Colgate: If the beam is locally super-Eddington at the companion star, then mass loss would be large. This was discussed at Moriond. Have you come to a conclusion about this mass loss?

Barnard: Equation (6) indicates that if a large fraction of the star is illuminated by a super-Eddington cosmic ray beam the mass loss rate ($\sim 10^{-3}$ M$\odot$ yr^{-1}) would indeed contradict the observed $\dot{P}/P \sim 10^{-6}$ yr^{-1}. However, even if $L_{CR} \sim 10^{39}$ erg/s a .5M$\odot$ main sequence star will subtend a solid angle of $\sim .02 \times 4\pi$, implying an absorbed luminosity of only 2×10^{37} erg/s, which is sub-Eddington. Thus, we may expect the mass loss rate to be substantially less than is given by equation (6) because the assumption of super-Eddington heating may not occur at the companion star even if the implied cosmic ray luminosity is super-Eddington at the compact star.