CYGNUS TALES

Todor Stanev

Bartol Research Institute, University of Delaware,
Newark, DE 19716, U.S.A.

We consider the injection of intensive beams of high energy particles in close binary systems and follow some of the consequences for the behaviour of the produced high energy signals and the evolution of the system. Present experimental data are not sufficient to provide the basis for detaiiled models, but it appears quite likely that such systems are highly variable and unstable. Some additional assumptions have to made to stabilize the system over a lifetime of $\gtrsim$ 100 years.

1. INTRODUCTION

Kiel air shower array was the first to observe an excess of showers comming from the direction and in phase with Cygnus X-3[1]. The confirmation by the Haverah Park detector[2] was quick and the significance of the observation easy to appreciate. A well known binary system does not only have very large power in thermal radiation, but also manages to accelerate protons and nuclei to energies many orders of magnitude higher than the only natural accelerator studied before - the Sun. This is the only explanation of the signals, because γ-rays with enough energy to initiate the observed showers ($\gtrsim 10^6\, GeV$) cannot be produced through the usual astrophysical sychrotron radiation by relativistic electrons. And the γ-rays are the natural candidate for a stable neutral particle which can travel without washing out the 4.8 periodicity of Cyg X-3 for more than 10 *kpc* and have the cross-section to interact in the atmosphere.

The years since gave us equally large number of experimental and theoretical papers. The shower signal was seen by many detectors, always with 4.8 hrs period, but the maximum signal wobbling around the two preferred TeV γ-ray phases $\phi \sim 0.25$ and ~ 0.65. The signal is not always there, and even when seen its intensity varies by a factor of ten. It is only natural for such a prominent happening to provoke at least as many high spirited critics, as it has supporters. All characteristic features of the Cyg X-3 high energy signals are indeed easy targets for criticism. The experimental results are not reproduceable, there are no simultaneus observations with independent detectors, the statistical significance is low[3].

We shall make an attempt to analyze some of the properties of binary systems, where intensive proton beams are accelerated up to $10^8\, GeV$ and interact in the surrounding astrophysical enviroment. The inelastic collisions of the beam particles and their secondaries may change the energy ballance and the structure of such systems. Sources like Cygnus X-3 may be intrinsically variable, both in power output and in emission phase. We shall try to emphersize the reasons for which Cygnus X-3 is *not* expected to be a regular, constant intensity source of high energy signals.

2. SOME RELEVANT KNOWLEDGE ABOUT CYGNUS X-3

Although Cygnus X-3 is not visible in opticle light, the distance to the object is relatively well determined to be $\gtrsim 11.6\ kpc$ from the absorption features in 21 cm radio observations[4]. This is a strong radio source with violent outbursts during which the flux density increases by four orders of magnitude from the quiescent level of $\sim 20\ mJy$ at 20 cm and reaches luminosity of $10^{35}\, ergs\ s^{-1}$. The changes in the IR emisson are much more moderate with a peak luminosity[5] at 2.2 μm is $\sim 10^{36}\, ergs\ s^{-1}$. The X-ray luminosity of the system is $\sim 10^{37}\, ergs\ s^{-1}$ and has been observed to change within a factor of 2. The observation of Cygnus X-3 in GeV γ-rays is not confirmed, but the source is quite active in the TeV region[6] with the luminosity in this first observation estimated to $2\times10^{37}\, ergs\ s^{-1}$. It appears that the source luminosity is approximately constant with the signal energy.

With the exception of the radio signals all other wavelengths obey strictly a periodicity of $\sim$ 4.8 hrs. At thermal energies the emission maximum is very broad and there is not a total eclipse. At TeV and higher energies the signal is concentrated in less than 0.1 of the phase. It is a common belief that the 4.8 hrs period is the orbital period of a binary system. The short orbital period is an indication of a low mass system, most likely including a neutron star and its stellar companion. The system is quite closely packed, so that the companion is probably filling its Roche lobe. If this were the case for a standard neutron star mass of 1.4 $M_\odot$ and a main sequence hydrogen star the mass of the companion would be 0.55 $M_\odot$ and the distance between the stars $a = 1.8\, R_\odot$. More exotic suggestions that the companion star is an evolved helium star[7] lead to the estimates $M_c = 3.85\, M_\odot$ and $a = 2.49\, R_\odot$.

The particle accelerator uses either the kinetic energy of the neutron star (possibly utilizing the $v \times B$ field) or the potential energy of the matter accreting onto the neutron star. In very simple terms

$$emf = Blv = Bl^2/\tau \sim 10^{16}\text{–}10^{19}\, eV$$

for a typical neutron star with radius $\sim 10^6\, cm$, magnetic field of $10^{12}\, G$ and period of $10^{-3} - 1\, s$. In both cases the acceleration mechanism has to be fast and extremely efficient, because the luminosity required by the UHE γ-ray signals is very high.

Hillas[8] estimates the particle luminosity from the flux of $\gtrsim 10^{15}\, eV$ showers detected by Haverah Park as

$$L_p = \frac{\Omega}{4\pi} \frac{1}{\epsilon} \frac{1}{\tau} F_s\, 4\pi D^2,$$

where D is the distance to Cygnus X-3, Ω is the solid angle for particle acceleration and ϵ and τ are the efficiency and duty cycle for the generation of the signal. L_p in $\sim 10^7 - 10^8\, GeV$ protons comes to

$$few \times 10^{39} \frac{\Omega}{4\pi}\, ergs\ s^{-1},$$

which is a value bigger than the Eddington limit for spherical accretion on a radiating object.

3. PARTICLE PRODUCTION TARGETS

Although the problems with the acceleration mechanisms are far from solved, the neutron star obviously has the ability to accelerate proton beams up to $10^8\, GeV$. The other component necessary for production of signals is target material. The classical suggestion of Vestrand and Eichler[9] gives a good example for all related problems. Assume (Fig. 1a) that the particle accelerator is orbiting the stellar companion. When it is positioned between the companion and the observer, there is no signal in the direction of the observer, because there is no target material. When the accelerator is eclipsed by the companion signals are *produced and absorbed* in the body of the companion. Only when the proton beam grazes the atmosphere of the companion the amount of matter is sufficient for the production and tenuous enough not to absorb the signal.

This model will have very hard time to explain the observed signals mainly because it requires very low a/R_c ratio and predicts symmetric γ-ray light curve. Hillas[10] considered the energy deposited by the proton beam in the outer layers of the stellar companion which might eject a fountain of gas. The gas will be redistributed by the gravitational forces of the two stars to the configuration of Fig. 1b, which roughly corresponds to the experimentally observed emission at $\phi \sim .25$ and $\phi \sim 0.65$. The target can also be the accretion wake which the neutron star swipes on its way through the stellar wind, shown on Fig. 1c. In general such configurations are quasi stable in a phase locked close binary system.

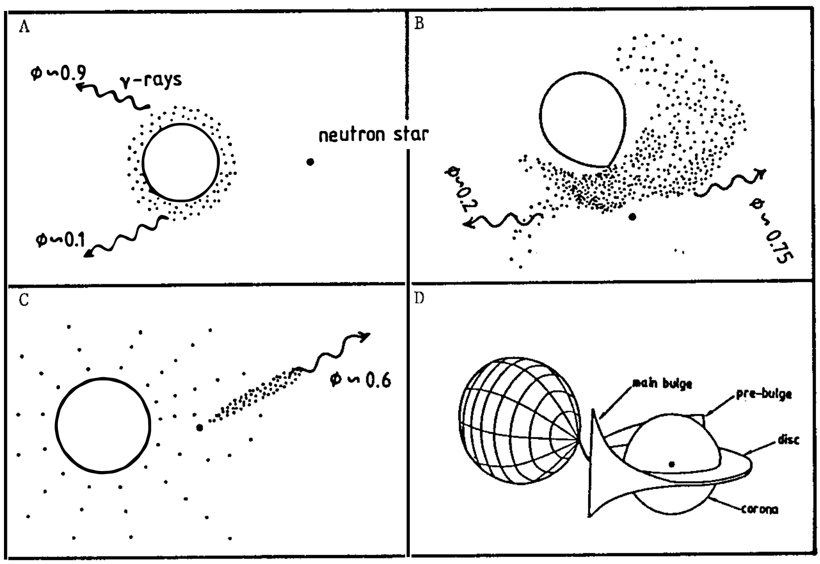

Figure 1.

Much more detailed picture was created by White and Holt[11] to explain the variation of the optical, X-ray and IR emission of the binary X1822-371, which produces light curves similar to these of Cygnus X-3, but is also visible in optical light (see Fig. 1d). The matter accreting from the stellar companion onto the neutron star forms an accretion disk with two bulges at the rim. Both the X-rays and the IR radiation (produced in the accretion disk corona) are modulated by obscuration by the bulges and possibly by the companion. The model fits perfectly the thermal emission from X1822-371 and in addition provides sufficient targets for production of high energy γ-rays. Bulges are 50-100 g/cm^2 thick and so is the accretion disk. γ-rays could be produced in these targets and the ones that are alligned with the direction of the observer (the model gives an inclination of 66° for Cygnus X-3) will be detected at Earth[12]. Unfortunately the positions of the bulges given by the model do not yield proper positions for the high energy γ-ray phases. But are we to assume that the protons in the binary system always move in straight lines?

An observation of TeV γ-ray emission from Her X-1[13] during the eclipse of the accelerator suggests exactly the opposite. Learned and Gorham[14] proposed that the proton trajectories are bent in the magnetic field of the companion. Protheroe and the author[12] explored this question further, incorporating magnetic steering in the model of Ref. 11. We calculated the trajectories of protons with a certain ratios of stellar magnetic moment to rigidity. Fig. 2 illustrates the change of the directions of the produced γ-rays (dash lines) for a ratio of magnetic moment to rigidity ratio of 0.20 $G \times R_{O}^{3} / TV$. The value used for the magnetic field of the stellar companion not excessively large. Surface magnetic fields seem to increase with the effective temperature of the star and as we shall see the stellar companionin the Cynus X-3 system should be be hot. A typical field for a class of hot stars (Ap stars) is well over a kilogauss.

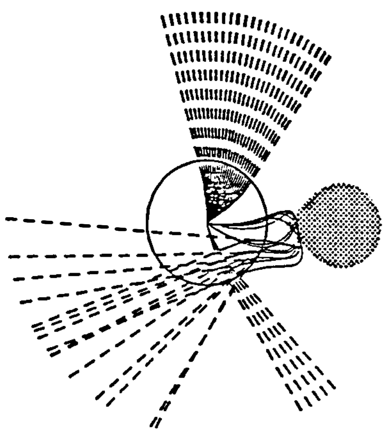

Figure 2.

The configuration of the magnetic field at the Cygnus X-3 system, probably complicated by the magnetic field of the neutron star and by the accretion disk, is not known at all. Our excersize, however, demonstrates a lot of possibilities. If the magnetic steering is effective at the system, than one does not expect signals of different energy to be produced at the same phase unless the beam is strictly monoenergetic. Furthermore, one expects a time variability on relatively short timescales (5 - 20 years), similar to the observed at our Sun. This could lead, for example, to a change from emission occuring predominantly at $\phi \sim 0.25$ to emission occuring mainly at $\phi \sim 0.63$ as appears to have happened between 1983 and 1984 with the observations of Haverah Park[15].

Not only the position of the target is difficult to estimate from the existing data, but the ideal target thickness is difficult to define. First of all it is energy dependent. Thick targets cause cascades to develop, which effectively filter out the highest energy particles and enhance lower energy components. Thin targets allow the protons to interact only once, and the production spectrum follows the x

distribution of the interaction. In addition to that the proton cross-section is not energy independent and for a $\log^2 s$ law the mean free path in hydrogen at $10^8\,GeV$ is only 16.2 g/cm^2.

In Fig. 3 the γ-ray yields from $10^8\,GeV$ protons are shown for targets with different thickness. Even the accretion disk corona, a result of the evaporation of the accretion disk ($\sim$ 2 g/cm^2) is quite effective for production of $10^{15}\,eV$ γ-rays.

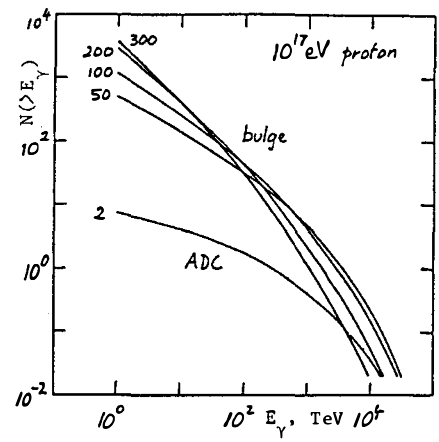

Figure 3.

If the observed spectrum is a result of electromagnetic cascading than the optimum target thickness is a function also of the magnetic field[10]. Hillas has shown that the optimum thickness for production of $10^{15}\,eV$ γ- rays decreases at least by a factor of four (from 16 r.l. to 2-4 r.l.) if electromagnetic cascades develope in a medium with embedded magnetic field of $\gtrsim$ 10 G in the case of monoenergetic proton beam of $10^8\,GeV$.

4. THE ROLE OF THE THERMAL RADIATION.

Actually there are models in which concentration of material as target for proton interactions is not needed at all. The suggestion has been made[16] that high energy γ-rays are produced in photoproduction interactions of the accelerated protons on the X-ray radiation at source. For X-ray temperature of 2 KeV the threshold for photoproduction is $\sim$ 10 TeV and the intense radiation fields at Cygnus X-3 provide $\sim$ 3 interaction lengths for protons of that energy. The spatial distribution of the target is, however, crucial because CMS energy depends on the relative directions of the proton and the photon. Copious photoproduction interactions are only possible if the acceleration site for protons is different from the X-ray production site. This process, however, can account for the observed short duration TeV γ-ray bursts[17] if they are produced on similar duration thermal radiation bursts, as seen at IR frequences[18].

An important consequence of the coexistence of intense radiation fields and high energy γ-rays at the source is the possibility for $\gamma\gamma \rightarrow e^+ e^-$ interactions. At energies $E_\gamma \epsilon > 1.3\,10^{11}(1-\cos\theta)^{-1}\,eV^2$ the thermal radiation is not any more transparent for the high energy γ-rays. TeV γ-rays will interact of 0.26 eV photons (starlight) and higher energy γ-rays on far IR radiation. This may cause additional modulation (after production) of the γ-ray emission.

Fig. 4 shows the absorption length X_γ of γ-rays as a function of the energy in the radiation field of the accretion disk corona, required for production of the modulated fraction (4 mJy) of the IR flux from Cygnus X-3[19]. The maximum absorption for this model falls between 1 and 10 TeV and X_γ is only a fraction of R_O. In certain geometrical configurations such fields could suppress γ-rays signals over a large fraction of the phase. The account for interactions on thermal photons at source can elliminate the requirement that an exact amount of target material is correctly positioned to produce the observed signals. It is possible that γ-rays are generated over a wide range of solid angles and we only see the ones that are not absorbed.

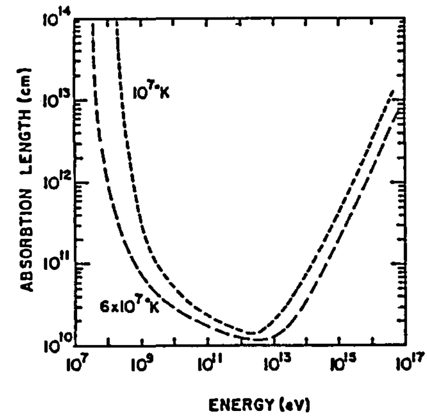

Figure 4.

5. TERMINAL THREATS

The interactions on the thermal radiation at source can be employed to explain some of the observed features of the shower signals from Cygnus X-3, but they will hardly change the evolution of the system. There is, however, another consequence of the high energy interactions, which may be life threatening for the source. The copious production of γ-rays indicates similar neutrino production by decays of charged secondaries. Neutrino signals from Cygnus X-3 are not likely to be observed at Earth (calculations agree on ν-induced muon signals of 1 event per year per 1000 m^2 detector[20]) but they may seriously affect the companion star. If all pions and muons decay, which is probably true in the tenuous gases at an astrophysical object, neutrinos eventually carry 1/2 of the beam energy. A fraction of this energy, depending mostly on the solid angle Ω under which the ν beam sees the companion star, is deposited in the interior of the star[21]. A typical value is $\sim$ 0.1 - 1 per cent of L_p, i.e. $10^{36} - 10^{37}$ $ergs\ s^{-1}$, $\sim$ 1000 times more than the intrinsic luminosity of the star. We[22] calculated the evolution for several types of stars in the presence of this strong external energy source and the main result is an increase of the mass transfer rate $\dot{M}$. If the proton luminosity is simply proportional to $\dot{M}$ the companion undergoes a runaway mass transfer on the scale of less than 100 years and as low as 10 years for come configurations, compared with the stellar evolution time scale of 10^7 years. The situation is grave also because the induced stellar winds do not shield the star like in the case with X-ray heating.

In order to stabilize the system one has to find a mechanism to decrease L_p at very high M values. Such an anticorrelation mechanism might lead to high and low states of Cygnus X-3 in high energy radiation on the time scale of years. If such a mechanism is not found we might witness the end of the swann quite soon, although it will be much more spectacular than the quiet descend suggested recently [23].

6. CONCLUSIONS

We have reviewed some of the reasons for which Cygnus X-3 could be an inherently variable system. At this stage, partially because of the scarcity of data and the consequent freedom to use them, we do not see serious contradictions between the expected and the observed behaviour of the system. A lot of theoretical work has been inspired by the existing experimental results, but *the future of* Cygnus X-3 *in the UHE energy range is still and experimental question.* New detectors (Maryland-LANL, GREX, Themis, Chicago-Michigan-Utah, South Pole), dedicated to point sources of high energy radiation have started operation or are under construction and we look forward to new experimental data.

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