ON GAMMA AND NEUTRINO RADIATION FROM CYG. X-3

V.S.Berezinsky
Institute for Nuclear Research, Academy of Sciencies of the USSR, 60th Anniversary of October Revolution Prospect 7a, II73I2, Moscow, USSR

ABSTRACT

The production of high energy gamma and neutrino radiation is studied for Cyg X-3. A heating model is proposed to explain the presence of only one gamma-pulse during 4.8h period of the source. The acceleration mechanisms are discussed. High energy neutrino flux from Cyg X-3 is calculated.

I. Introduction. Cyg X-3 is a powerful variable source detected in radio, infrared, X-ray and γ -radiation. The observed 4.8h periodicity is interpreted as orbital motion in a binary system. Recently the same periodicity was discovered in γ -radiation with $E_\gamma \gtrsim 10^{15}$ eV (Samorski and Stamm 1983, Morello et al 1983, Lloyd-Evans et al 1983). For the interpretation of the data, mostly on X-ray and γ -radiation, a binary model is invoked. A compact source in the binary can be a white dwarf or a neutron star. The separation of the two components of the binary found from 4.8h period is $A = 1.10^{11}[(M_1+M_2)/M_\odot]^{1/3}$ cm. The system must be coated by relatively dense gas. It follows from the observed cut off of X-ray spectrum which implies the total column density between 3.10^{22} and 2.10^{23} H/cm^2. The absence of the flat eclipse X-ray curve also demands for its interpretation the presence of the gas around the system in which X-ray scattering takes place. As far as high energy γ -ray production is concerned, this density is very low. To leave the system transparent for X-rays the column density must be less than 0.3-1g/cm^2 while for effective γ -ray production $x \sim 40$-70g/cm^2 is needed. The effectivity is increasing in the binary models where γ -rays are produced in atmosphere of the normal component (Berezinsky 1979), as illustrated in Fig.I

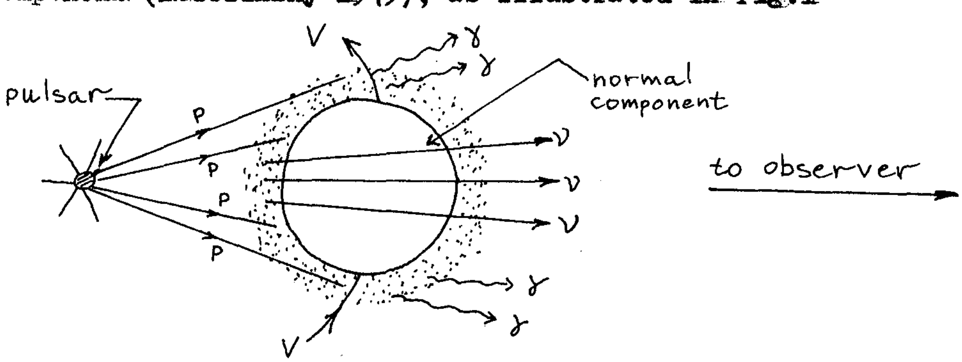

Fig.I The scheme of "ν - and γ-pulsar" (reproduced from Berezinsky 1979)

These models were put forward as possible ones for high energy neutrino radiation accompanied by relatively small flux of γ -radiation (hidden sources). They were successfully used by Vestand and Eichler (1982) for Cyg X-3. In contrast to Berezinsky (1979) Vestrand and Eichler (1982) considered also production of γ -rays by the electrons which can be important for γ -radiation with $E_\gamma \gtrsim 10^{12}$ eV.

2. Difficulties. The atmospheric model production meats difficulties of two kinds. The atmosphere of the normal component intersects the the line of sight twice during the cycle, producing thus two γ -pulses symmetric relatively to the phase of X-ray eclipse. In reality at $E_\gamma > 10^{15}$ eV only one γ-pulse was observed. The second difficulty is connected with the duration of γ-pulse expected in the aforementioned model. Gamma-rays are produced in the channel where column density of gas is $X \sim X_{rad}$. If $X \ll X_{rad}$ the π^0-mesons are not produced, if $X \gg X_{rad}$ gammas are absorbed. Suppose the effective γ-channel is limited by $x_{min} = x_{rad}$ and $x_{max} = 2x_{rad}$ and consider a star of radius R surrounded by an exponential atmosphere $\rho(h) = \rho_0 \exp(-h/H)$ where $H \approx kTR^2/(m_H \varkappa M)$ is characteristic height of atmosphere. It is easy to calculate the linear width of the channel in which the column density ranges between x_{rad} and $2x_{rad}$. It is equal to $h_1 - h_2 = H\ln 2$ and therefore $(h_1 - h_2)/R \sim H/R \ll 1$. By other words the duration of γ -pulse $\tau_\gamma \sim (h_1 - h_2)v$ is very small and hence the cosmic ray luminosity of the pulsar must be very high to explain the observed γ-ray flux.

3. Heating model. Both difficulties can be eliminated in the following model. The pulsar produces the beam of accelerated particles in the direction of the observer. When the normal component of the binary crosses the line of sight, and thus the beam, it is heated to the high temperature. The evaporated gas forms a cloud behind the star in which γ-radiation is produced. In this case there is only one γ-pulse per period and its duration is large. As a normal component we shall take the main sequence star with mass $M = 2.3 M_\odot$, with radius $R = 1.3 \cdot 10^{11}$ cm and temperature $T_0 = 7000$ K. Let us show that during orbital period the star is heated to a high temperature and then is cooled to its normal temperature. First we shall estimate the characteristic heating time τ_h. The equilibrium temperature can be calculated as

$$T_m = (L_p / 4\pi R^2 \sigma)^{1/4} = 3 \cdot 10^4 (L_p / 10^{38} erg/s)^{1/4} \quad (1)$$

where L_p is luminosity of proton beam and $\sigma = 5.6 \cdot 10$ erg.$s^{-1} cm^{-2} K^{-4}$. High energy protons undergoing nuclear collisions at the surface of the star produce a nuclear-electromagnetic cascade. The thickness of the heated crust of the star can be taken as the depth at which the cascade reaches its maximum. In our estimates we shall take for it $x \sim 10^3 g/cm^2$. The heating time is

$$\tau_h \sim \frac{3}{2} k T_m N / L_p \sim 10 s \quad (2)$$

where $N \sim 1.10^{50}$ is the number of electrons in the depth $x \sim 10$ g/cm^2 of the star. Therefore the heating time τ_h is considerably shorter than the time during which the star crosses the proton beam, $\tau_{cr} \sim \sim TR/\pi A \sim 5.10^3$ s. Now let us estimate the characteristic cooling time down to normal temperature of the star T =7000 K. Taking into account only outer surface cooling, one gets

$$\tau_c \approx kN/8\pi R^2 \sigma T_0^3 \approx 1.7\cdot10^3 s \quad (3)$$

which is considerably less than orbital period T=4.8h $\approx$ I.7.IO^{4}s.

4. High energy gamma and neutrino fluxes. Consider first the generation of γ-ray flux. It is produced in "γ-channel" as illustrated in Fig.I or in a gas cloud for a heating model through production and decay of π^0-mesons. For column density x, of target being less than nuclear one, x_N, γ-ray flux avaraged over period T can be written down as

$$F_\gamma(E)=(\tau_\gamma/T)(x/x_N)\varphi_\gamma \dot{N}_p(E)/\Omega \quad (4)$$

where τ_γ is a duration of γ-pulse, $\dot{N}_p(E)$ is the number of protons with the energy E produced by the pulsar per Is, Ω is a solid angle the proton beam is confined by (Ω=4π for isotropic case) and φ_γ is dimensionless ray yield calculated by Berezinsky and Volynsky (I979) for power-law spectra under assumption of scaling and tabulated in Table I for different values of integral spectrum exponents γ. If the normal companion of the binary is transparent for neutrinos, neutrino flux is expected to be much higher than γ-flux. As illustrated by Fig.I neutrinos are produced mainly in the atmosphere behind the star (relative to the observer) and thus a duration of ν-pulse is $\tau_\nu \sim 2R/v$, while that of γ-pulse is $\tau_\gamma \sim (h_1-h_2)/v$,i.e. $\tau_\nu/\tau_\gamma \sim 2R/H >> I$. For a heating model this ratio becomes less. Taking into account that neutrinos are produced in the thick target, one finds for period avaraged $\nu_\mu+\bar{\nu}_\mu$-flux, using neutrino yields (Berezinsky and Volynsky I979):

$$F_{\nu_\mu+\bar{\nu}_\mu}(E)=\frac{\tau_\nu}{T}\,\frac{\varphi_{\nu_\mu}+\varphi_{\bar{\nu}_\mu}}{\gamma(1-\alpha)}\,\frac{\dot{N}_p(E)}{\Omega} \quad (5)$$

where $\alpha \approx$ I/2 is a fraction of energy retained by proton in one nuclear collision. The values of $\varphi_{\nu_\mu}+\varphi_{\bar{\nu}_\mu}$ are tabulated in Table I.

Table I

γ	I.I	I.2	I.3	I.4	I.5	I.6	I.7
$\varphi_{\nu_\mu}+\varphi_{\bar{\nu}_\mu}$	0.I3	0.095	0.070	0.052	0.040	0.030	0.023
φ_γ	0.I2	0.09I	0.07I	0.056	0.045	0.036	0.029

5. Luminosity. The spectrum of protons in Eqs (4),(5) can be taken in power-law form $\dot{N}_p(E)=(\gamma-I)(E/E_0)^{-(\gamma+1)}L_p/E_0^2$, where L_p is luminosity of the source in the form of accelerated particles, $E_0 \approx$ IGeV and γ is an exponent of integral spectrum, which according to γ-observation will be taken as γ =I.I . Then from (4) using $j_\gamma(E)=F_\gamma(E)/r^2$ with r=IOkpc and $j_\gamma(>3000TeV)=I.5.IO^{-14}$ cm^{-2} s^{-1} one obtains:

$$L_p=1.4\cdot10^{40}\,\frac{\Omega}{4\pi}\,\frac{T/\tau_\gamma}{40}\ erg/s \quad (6)$$

where, according to experimental data (Lloyd-Evans et al I983) $T/\tau_\gamma >$ 40. For proton beam with $\Omega \sim$ IO^{-2} sr the luminosity decreases by factor of IOOO.

6. Detection of neutrino flux. The neutrino flux deep underground is accompanied by equilibrium muon flux. For flat spectra, when $j_{\nu_\mu} = j_{\bar\nu_\mu}$ and for $E_\mu \geq$ ITeV, when muon energy losses can be taken as $E_\mu^{-1} dE_\mu/dx = b$, the equilibrium muon flux can be expressed through muon moments $Y_\mu(E)$ and $Y_{\mu^+}(E)$ calculated by Berezinsky and Gazizov (I979):

$$j_\mu(>E_\mu) = \frac{\sigma_0 N_A}{b(E_\mu)} \left(Y_{\mu^-}(E_\mu) + Y_{\mu^+}(E_\mu) \right) j_{\nu_\mu}(>E_\mu) \qquad (7)$$

where σ_0 =I.I.IO^{-34} cm is a normalizing cross-section, N_A =6.IO^{23} is Avogado number and for E_μ =ITeV and γ =I.I Y_{μ^-} =0.25, Y_{μ^+}=0.I6 and b=4.IO^{-6} cm^2/g for a rock. The lowest neutrino flux compatible with the observed γ-ray flux can be found from (4) and (5) if to take $\tau_\nu = \tau_\gamma$ and to assume that target is thin. Since at γ =I.I $\varphi_\gamma \approx \varphi_{\nu_\mu} + \varphi_{\bar\nu_\mu}$ one gets for flux densities $j_{\nu_\mu}(E) + j_{\bar\nu_\mu}(E) \approx j_\gamma(E)$. At E$\approx$ITeV according to observations $j_\gamma \approx 3.$IO^{-11} cm^{-2}s^{-1} and hence from (7) j_μ(>ITeV)$\approx$ $\approx$I.IO^{-16} cm^{-2} s^{-1}. This lower limit flux can be detected only by very large detectors with S$\sim$IO^{5}m^2, such as DUMAND or BAIKAL, at level of counting rate $\nu \sim j_\mu \cdot S \sim 3\mu$/yr. The muons of smaller energies don't contribute significantly to the number of detected muons.

If the normal component of the binary is transparent for high energy neutrinos, neutrino flux is given by (5) with $\tau_\nu/T = R/\pi A$, where A is separation. In this case it is easy to find for R$\approx$A j_μ(>ITeV) = =7.6.IO^{-13}(L_p/IO^{40}erg$\cdot$s^{-1})(0.I/Ω)cm^{-2}s^{-1}. It corresponds to 24(L_p/IO^{40})(0.I/Ω) muons with $E_\mu \geq$ ITeV traversing the underground detector with S=I00 m^2 per Iyr. Such a possibility corresponds to very small τ_γ, as it folllows from (6).

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