Gamma-rays from the close massive binary Cyg X-3

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Abstract

Some observations indicate the existence of an energetic pulsar in the massive binary Cyg X-3. We assume that such a pulsar injects relativistic $e^{\pm}$ pairs which propagate radially in the pulsar wind zone. These $e^{\pm}$ pairs initiate inverse Compton $e^{\pm}$ pair cascade in a very strong anisotropic radiation field of the Wolf-Rayet star. We calculate the expected phase dependent gamma-ray spectra produced in such a cascade.

1. Introduction

The Cyg X-3 binary system contains a massive Wolf-Rayet (WR) star, with the surface temperature $> (7-9)\times 10^4$ K and the radius $R_{\rm WR} = (1.6-8.6)\mathrm{R}_{\odot}$, and a compact object on nearly circular orbit with the period of 4.8 hrs and separation of the components estimated on $(3.2-5.6)R_{\odot}$, where $R_{\odot}$ is the Sun radius. The compact object is probably a neutron star (NS), the mass limit < 3.6 M$_{\odot}$ [7], with the period of ~ 12.59 ms and the surface magnetic field of 5×10^{11} G [2]. The inclination of this system is not precisely known: $i > 60^{\rm o}$ [4], $74^{\rm o}$ [8], $\sim 24^{\rm o}$ [7]. The Cyg X-3 is in the error box of the EGRET source, 2EG J2033+4112 [6].

2. Propagation of $e^{\pm}$ pairs and gamma-rays

We investigate the propagation of $e^{\pm}$ pairs which are injected by an energetic pulsar into the strong radiation field of the WR star. These $e^{\pm}$ pairs, accelerated in the inner pulsar magnetosphere or in the pulsar wind zone, have the monoenergetic or the power law spectrum (depending on the model). If the pulsar is close to the star then pairs initiate inverse Compton (IC) $e^{\pm}$ pair cascade in the anisotropic thermal radiation of the star [1]. In order to determine the conditions for such a cascade to occur, the optical depths for the $e^{\pm}$ pairs and γ-rays in the radiation field of the star are calculated (see Fig. 1), applying as an example the parameters of the massive star in the Cyg X-3 system, i.e. the separation of the WR-NS, $3.6R_{\odot}$, the massive star radius, $1.6R_{\odot}$, and its effective surface temperature, $1.4\times 10^5 K$. It is found that even in the least favorable case ($\theta = 0^{\rm o}$), the secondary γ-ray photons with energies 10^6 MeV should be absorbed.

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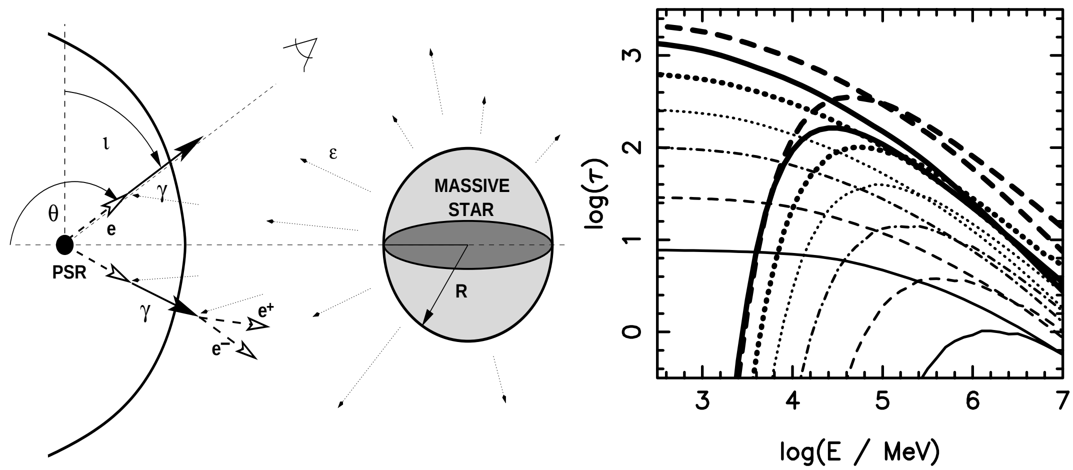

Fig. 1. (Left) The geometry of the binary system: the pulsar (PSR), the shock region (thick full curve). $e^{\pm}$ pairs, injected by the pulsar, lose energy on IC process during their propagation in the pulsar wind zone. Secondary γ-rays from ICS are absorbed in the radiation of the massive star. The observer is located at the angle θ. (Right) The optical depths for $e^{\pm}$ pairs and γ-rays injected at the angles $\theta = 0^{\rm o}$ (thin solid curve), $30^{\rm o}$ (thin dashed), $60^{\rm o}$ (thin dot-dashed), $90^{\rm o}$ (thin dotted), $120^{\rm o}$ (thick dotted), $150^{\rm o}$ (thick dashed), and $180^{\rm o}$ (thick solid). The direction tangent to the star surface is at the angle $\theta \approx 154^{\rm o}$.

In a more realistic case, the pulsar wind is confined around the pulsar due to its interaction with the massive stellar wind. Even then, the optical depths for $e^{\pm}$ pairs and γ-rays propagating in the pulsar wind zone are large, proving that the IC $e^{\pm}$ pair cascade starts to develop already inside the pulsar wind zone. The geometry of the pulsar wind shock is described by $\eta = L_d/\dot{M}Vc$, which is determined by the parameters of the NS and WR winds, $L_{\rm d}$ the spin down luminosity of the pulsar, $\dot{M}$ the mass loss rate, and V the wind velocity of the WR star in the Cyg X-3 system. The typical parameters of the WR stars are in the range: $\dot{M} = (0.8 - 8) \times 10^{-5}$ M$_\odot$ yr^{-1}, $V = (1 - 5) \times 10^3$ km s^{-1}, which gives $0.008 < \eta < 0.3$, for the NS in the Cyg X-3. The shock position (radial distance from the pulsar) is then at $\rho_0 = \frac{\sqrt{\eta}}{1+\sqrt{\eta}}D$. Figs. 2 show the optical depths for $e^{\pm}$ pairs and γ-rays inside the pulsar wind zone for the parameters mentioned above and the inclination angle of the system equal to $24^{\rm o}$, for different orbital phases of the NS around the WR star. These optical depths are large enough to support efficient development of the cascade in this binary system.

3. Gamma-ray spectra from Cyg X-3

The γ-ray spectra from the IC $e^{\pm}$ pair cascade are calculated by applying the Monte Carlo method. Two different models for injection of $e^{\pm}$ pairs by the pulsar are considered: (1) monoenergetic injection of $e^{\pm}$ pairs from the inner

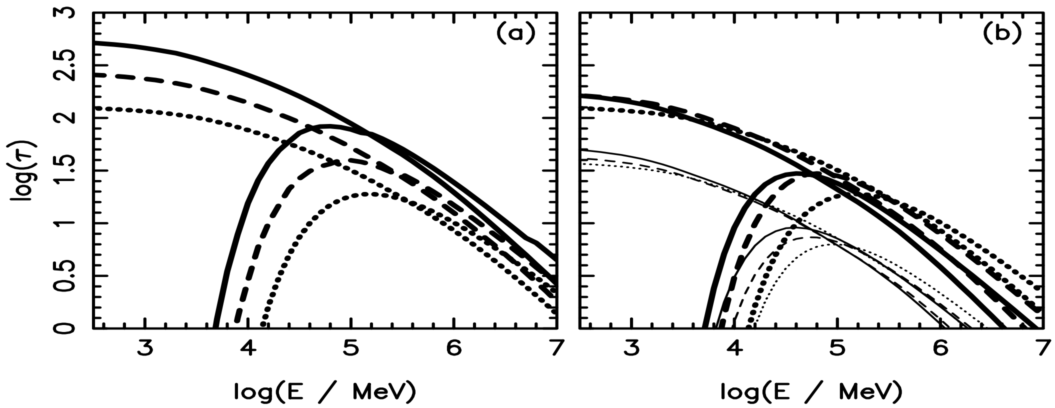

Fig. 2. (a) Optical depths for $e^{\pm}$ pairs on ICS process and for absorption of γ-ray photons in the unterminated propagation through the anisotropic radiation of the Cyg X-3 massive star as a function of the phase of the pulsar, $\varphi = 0^{o}$ (solid curve), 90^{o} (dashed), and 180^{o} (dotted). (b) as in (a) but in the case of the propagation in the pulsar wind shock limited to the shock region for two values of $\eta = 0.03$ (thin curves), and 0.3 (thick).

pulsar magnetosphere into the wind zone with energies 10^6 MeV; (2) injection from the inner pulsar magnetosphere with the power law spectrum between 100 MeV - 400 GeV and the differential spectral index -1.2 [5]. $e^{\pm}$ pairs injected from the inner pulsar magnetosphere move radially almost at rest in respect to the pulsar wind. Therefore their synchrotron losses can be neglected. The primary and secondary $e^{\pm}$ pairs from the cascade are followed up to the shock region where they are isotropised and captured by the magnetic fields. When calculating the spectra of cascade γ-rays which leave the system, we include their absorption in the radiation field above the pulsar wind shock. The secondary $e^{\pm}$ pairs, produced above the pulsar wind shock, do not contribute farther to the IC cascade since they lose energy mainly on synchrotron process in the magnetic field of the WR star.

Fig. 3 shows the spectra of γ-rays which escape from the binary system as a function of the pulsar orbital phase for two locations of the pulsar wind shock determined by $\eta = 0.3$ and 0.03. It is evident that the model postulates relatively weak variability of the γ-ray flux with the orbital period of the system in the 100 MeV - 1 GeV energy range, and a very strong variability of the γ-ray flux above ~ 10 GeV. In fact, the EGRET telescope does not report any modulation of the γ-ray signal from the Cyg X-3 direction (the source 2EG J2033+4112 [6]). If this model is valid, then very strong modulation with the 4.8 hr binary period in the energy range above 10 GeV should be observed by the MAGIC Cherenkov telescope.

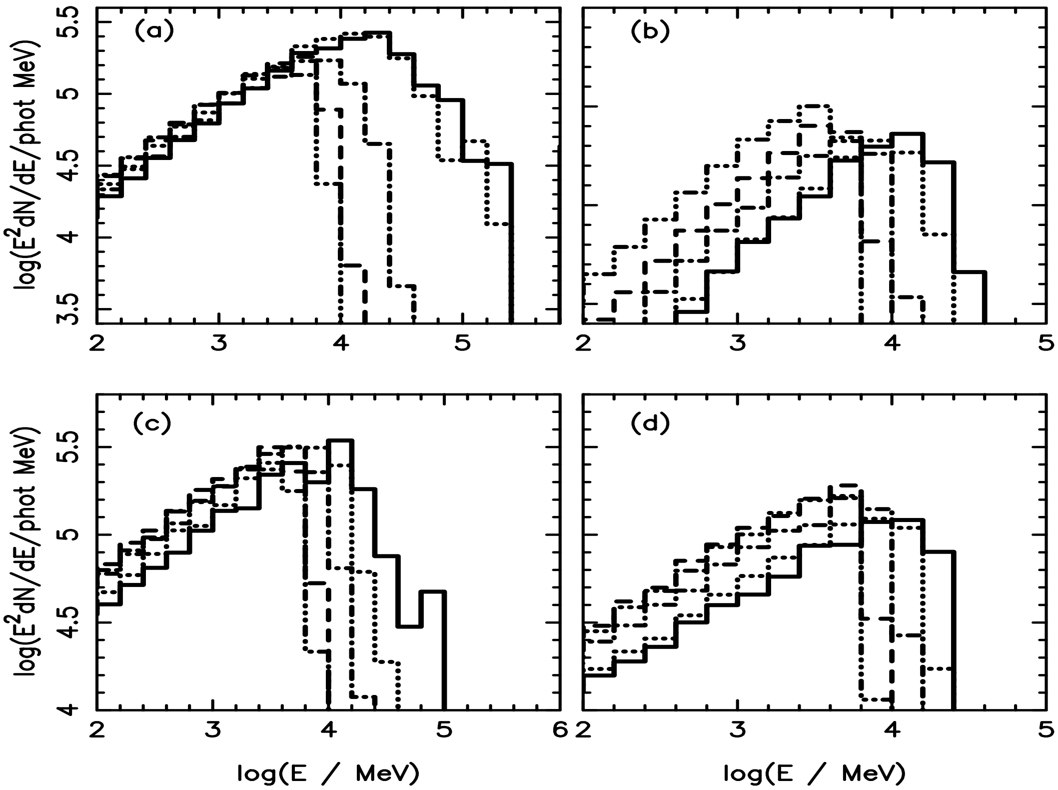

Fig. 3. The photon spectra in the case of monoenergetic injection of primary $e^{\pm}$ pairs with the Lorentz factor $\gamma = 10^6$ (a and b) and in the case of power law injection of primary $e^{\pm}$ pairs (c and d), for the values of $\eta = 0.3$ (a and c) and 0.03 (b and d). Specific histograms show the spectra for different phases of the NS $\varphi = 0^o$ (dot-dot-dot-dashed), 45^o (dashed), 90^o (dot-dashed), 135^o (dotted), and 180^o (solid).

4. References

1. Bednarek, W. 1997, A&A 322, 523; 2000, A&A 362, 646
2. Brazier A., et al. 1990, ApJ 350, 745
3. Cherepashchuk A., Moffat A. 1994, ApJ 424, 53
4. Hanson M., Still M., Fender R. 2000, ApJ 541, 308
5. Hibschman J.A., Arons J. 2001, ApJ 560, 871
6. Mori M. et al. 1997, ApJ 476, 842
7. Stark M., Saia M. 2003, astro-ph/0301554
8. van Kerkwijk M. et al. 1996, A&A 314, 521