GAMMA-RAYS

FROM MASSIVE BINARIES

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 Sources of TeV gamma-rays
 PSR 1259+63/SS2883 - (HESS)
 LS 5039 - (HESS)
 LSI 303 +61° - (MAGIC)
 Cyg X-1 - (MAGIC)
 Westerlund 2 → WR 20a (?) - (HESS)

 The IC e[±] pair cascade model

Scenarios for gamma-ray production Propagation of gamma-rays Confrontation with observations

PSR 1259-63/SS2883

the orbit	massive star SS2883/Be
$a = 177 R_{Be}$	$R = 6R_{\odot}$
$\varepsilon = 0.87$	$M = 10 \ M_{\odot}$
$i = 36^{o}$	$\dot{M} \sim 2 \times 10^{-7} M_{\odot} \mathrm{yr}^{-1}$
$P_{orb} = 1236.72 \mathrm{days}$	$V \sim 2 \times 10^6 \mathrm{m s^{-1}}$
$d = 1.5 - 4.5 \mathrm{kpc}$	$L = 3.3 \times 10^{37} \mathrm{erg}\mathrm{s}^{-1}$
	$T_{\star} = 2.7 \times 10^4 \mathrm{K}$
pulsar PSR 1259-63	
$P = 47.7 \mathrm{ms}$	
$L = 8.3 \times 10^{35} \mathrm{ergs}^{-1}$	
$B = 3.3 \times 10^{11} \mathrm{G}$	

Table 1: Parameters of the PSR B1259-63/SS2883 binary system applied in the model.



Figure 1:



The parameters of the binary system LS 5039

- Orbital period: 4.4 days; semimajor axis: 3.4r_{*}; ellipticity: 0.35 ± 0.04; azimuth angle: ω = 225°, r_p = 2.2r_{*} and r_a = 4.5r_{*}; inclination: i = 24.9° ± 2.8°.
- Massive star: $r_{\star} = 9.3 R_{\odot}$; $T_{\star} = 3.9 \times 10^4$ K.

The parameters of the binary system LSI + 61 303

- Orbital period: 26.5 days; semimajor axis: 5.3r_{*}; ellipticity: 0.72; azimuth angle: ω = 70°, r_p = 1.5r_{*} and r_a = 9.15r_{*}; inclination: i = 25° - 60°.
- Massive star: $r_{\star} = 13.4 R_{\odot}$; $T_{\star} = 2.8 \times 10^4$ K.



Figure 3:

LS 5039







Cyg X-1

The parameters of the binary system:

- Orbital period: 5.6 days; semimajor axis: 2.15r_⋆; ellipticity: ~ 0.0; inclination: i = 30°.
- Massive star: $r_{\star} = 20R_{\odot}$; $T_{\star} = 3 \times 10^4$ K.



Figure 7:



Westerlund 2 (WR 20a)

- Extreme example, WR 20a, contains two WR stars with masses ~ $70M_{\odot}$, surface temperature $T = 10^5T_5$ K $\approx 4 \times 10^4$ K, and radii ~ $20R_{\odot}$, on an orbit with the semimajor axis $a/2 \sim 26R_{\odot}$.
- WR type stars very strong winds: $\dot{M} \sim (0.8 8) \times 10^{-5} M_{\odot}$ yr⁻¹, $v_{\mathbf{W}} \sim (1 - 5) \times 10^3$ km s⁻¹, and $B = 10^3 B_3$ G $\sim 10^4$ Gs. Such winds collide creating a double shock structure.



Scenarios for γ -ray production

Microquasar





Energetic pulsar





Propagation of gamma-rays - optical depths





Figure 10: Massive star: $R = 8.6 \times 10^{11}$ cm, $T = 3 \times 10^{4}$ K (Cen X-3), Bednarek (2000). (a) $E_{\gamma} = 1$ TeV. (b) Distance D = 1.4R.

Microquasar model - $IC e^{\pm}$ pair cascade

- Electrons are accelerated in the jet with the power law spectrum. They are isotropic in the jet frame.
- 2. Energy converted into electrons along the jet: (model I):

$$L(z) \propto z^{-2}$$

(model II):

$$L(z) = const$$

- 3. Electrons lose energy on Synchrotron and IC process in the jet. For energies above a few GeV, they cool locally in the jet.
- 4. Gamma-rays absorbed and initiate IC e^{\pm} pair cascade in the stellar radiation. Cascade develop anisotropically.
- 5. Secondary e^{\pm} pairs isotropised locally in the jet.
- 6. Count cascade γ -ray photons escaping at specific directions on the sky.
- 7. Doppler factor of the jet small. Relativistic effects can be neglected.

• The magnetic field along the jet with conical structure,

$$B(x) = B_{\rm d}\eta/(1+\alpha z) \approx B_{\rm d}/(\alpha z) \quad \text{for} \quad z \gg 1/\alpha, \tag{1}$$

 $\alpha = 0.1$ rad, $B_{\rm d}$ is the magnetic field at the bottom of the jet, z distance along the jet.

• The acceleration efficiency of electrons in the jet,

$$\dot{P}_{\rm acc}(\gamma) = \xi c E / r_{\rm L} \approx 10^{13} \xi B \quad \text{eV s}^{-1}, \tag{2}$$

 ξ is the acceleration parameter, $r_{\rm L} = E/eB$.

• The energy loss rate by the synchrotron process,

$$\dot{P}_{\rm syn}(\gamma) = \frac{4}{3}\sigma_{\rm T} c U_{\rm B} \gamma^2 \approx 7 \times 10^{-4} B^2 \gamma^2 \quad \text{eV s}^{-1}.$$
 (3)

• The energy loss rate on IC scattering in T regime,

$$\dot{P}_{\rm IC}^{\rm T}(\gamma) = \frac{4}{3} \sigma_{\rm T} c U_{\rm rad} \gamma^2 \approx 1.2 T_4^4 \gamma^2 / r^2 \quad \text{eV s}^{-1}.$$
 (4)

• The energy loss rate in the KN regime,

$$\dot{P}_{\rm IC}^{\rm KN}(\gamma) \approx \dot{P}_{\rm IC}^{\rm T}(\gamma_{\rm T/KN}) \ln \left(4k_{\rm B}T\gamma/mc^2 - 2\right).$$
(5)

• The maximum energies allowed by IC and synchrotron processes,

$$\gamma_{\rm IC}^{\rm T} \approx 1.6 \times 10^6 (\xi B)^{1/2} r / T_4^2,$$

 $\gamma_{\rm IC}^{\rm KN} \approx 1.5 \times 10^5 e^{(71\xi Br^2/T_4^2)} / T_4$
 $\gamma_{\rm syn} \approx 6 \times 10^7 (\xi/B)^{1/2}.$

• The advection time scale > the cooling time scales,

$$z < 110T_4\eta/v_{\rm j}.$$
 (6)

Maximum Lorentz factors of electrons



Figure 11: The maximum Lorentz factors of electrons as a function of the distance, z, from the base of the jet, for different acceleration efficiencies: $\xi = 0.3$ (full curves), $\xi = 0.1$ (dotted), and 0.03 (dashed), for two ratios of the magnetic field to accretion disk radiation energy densities counted at the base of the jet, equal to $\eta = 0.1$ (figures a and c), and 0.01 (b and d), for the periastron passage of the compact object (a and b) and for the apastron passage (b and d). LSI 303 +61°



Figure 12: The γ -ray light curves in the energy range 1 - 10 GeV and > 200 GeV are shown in the middle figures for the inclination angles of the binary system $i = 30^{\circ}$ (full curve) and $i = 60^{\circ}$ (dashed). The cascade γ -ray spectra escaping towards the observer for selected phases of the compact object, these two inclination angles are shown in the bottom figures: the periastron (full curve) and the apastron passages (dot-dashed), the maximum γ -ray flux at phase 0.3 (dashed), and the flux at the local small TeV γ -ray peak at phase 0.95 (dotted).



Figure 13: The multi-wavelength spectrum observed from LSI +61° 303 (Xray data from the ROSAT (R - Goldoni & Mereghetti 1995) and the OSSE (O - Tavani et al. 1996), and in γ -rays from the COMPTEL (C - van Dijk et al. 1996), the EGRET (E - Kniffen et al. 1997), and the upper limits from the Whipple (W - > 500 GeV (Hall et al. 2003) and > 350 GeV (Fegan et al. 2005)) are compared with the inverse Compton and synchrotron spectra calculated in terms of IC e[±] pair cascade model (for $\xi = 0.1$ and $\eta = 0.1$ and the electron spectrum $\propto E^{-2.4}$).



The γ -ray light curves in LS 5039



Figure 14: Spectral Energy Distributions (SED) from cascades initiated by primary electrons injected in the jet with: the efficiency of electron injection depending on the distance from the base of the jet as $N(z) \propto z^{-2}$ (independently on the phase of the binary system), and differential power law spectrum of electrons with the index equal to -2. The left figures show the γ -ray spectra, produced at the periastron passage of the compact object for the observer located at the inclination angles $i = 25^{\circ}$ and 60° , from the *jet* and *counter-jet* (the *sum* of both). The jets propagate perpendicular to the plane of the binary system. The γ -ray spectra produced at the apastron passage of the compact object are shown on the right figures. The specific spectra are calculated for the acceleration conditions in the jet described by the parameters: $\xi = 0.03$ and $\eta = 0.1$ (full curves), $\xi = 0.3$ and $\eta = 0.01$, (dashed), and $\xi = 0.3$ and $\eta = 0.1$ (dot-dashed).



Figure 15: Gamma-ray light curves in the energy range 1-10 GeV (dashed curves) and >200 GeV (full curves) produced by electrons accelerated in the jets of Cyg X-1 for the acceleration parameters $\xi = 0.1$ and $\eta = 0.1$, γ -rays from electrons accelerated in the jet (thin curves) and in the jet + counter-jet (thick curves). The phases of the compact object 0.0 (dashed curve), 0.45 (dotted), and 0.5 (full).

$$Cyg X-1$$

PSR 1259-63/SS2883





Figure 16: The optical depths. $T_{\star} = 2.7 \times 10^4$ K and its radius is $R_{\star} = 4.2 \times 10^{11}$ cm (a). The optical depths are shown as a function of energy of interacting particle, assuming their rectilinear propagation from the injection place at $r \approx 23R_{\star}$ up to the infinity. $\theta = 60^{\circ}$ (dot-dashed line), $\theta = 90^{\circ}$ (dashed), $\theta = 120^{\circ}$ (dot-dot-dot-dashed), $\theta = 150^{\circ}$ (solid), $\theta = 180^{\circ}$ (dotted). The optical depths for leptons on ICS process as a function of the distance from the surface of the massive star (b). The energies of leptons is fixed to $E_e = 4 \times 10^5$ MeV and the angles of injection are the following: $\theta = 0^{\circ}$ (dot-dot-dot-dashed line), $\theta = 30^{\circ}$ (dotted), $\theta = 60^{\circ}$ (dot-dashed), $\theta = 90^{\circ}$ (dashed), $\theta = 120^{\circ}$ (thin solid), $\theta = 150^{\circ}$ (thick solid). The shadow square on the both graphs show the value of the optical depth equal to unity for leptons with energy $E_e = 4 \times 10^5$ MeV, injection angle $\theta \sim 150^{\circ}$, and at the distance $r \sim 23R_{\star}$.



Figure 17: The comparison of the γ -ray light curves obtained in terms of the model II ($\omega_d = 158^{\circ}, \Delta \omega = 20^{\circ}, \theta_d = 20^{\circ}, i_d = 30^{\circ}$) and model I ($\omega_d = 142^{\circ}, \Delta \omega = 5^{\circ}, \theta_d = 20^{\circ}, i_d = 40^{\circ}$) with the observations of PSR B1259-63/SS2883 at energies > 380 GeV (Aharonian et al. 2005). The spectrum of leptons has the spectral index 2.5 and the magnetization parameter of the pulsar wind is $\sigma = 10^{-4}$. The period when the pulsar crosses the massive star equatorial wind are marked by the thick perpendicular lines. The γ -ray light curve obtained in model I but for different orientation of the orbital plane and the plane of the equatorial wind ($\omega_p = 148^{\circ}$) is shown in (c).



Figure 18: The differential γ -ray spectra (SED) for subsequent pulsar phases calculated in terms of the model I (with $\sigma = 10^{-4}$). The calculated γ -ray spectra are compared in figures (a) and (b)) with the γ -ray spectrum observed by the HESS telescopes from the binary system PSR B1259-63/SS2883 (with errors marked by the gray lines). The spectral index of primary leptons is $\alpha_i = 2.5$. The spectra are calculated for the phases before periastron ($\varphi = -90^{\circ}$ (dotted line), $\varphi = -60^{\circ}$ (dot-dashed), $\varphi = -30^{\circ}$ (dashed), $\varphi = 0^{\circ}$ (solid red line)) are shown in (a) and after periastron ($\varphi = 30^{\circ}$ (dashed line), $\varphi = 60^{\circ}$ (dot-dashed), $\varphi = 90^{\circ}$ (dotted) and $\varphi = 105$ (dot-dot-calculated)) in (b). γ -ray spectra calculated in terms of the model II are shown in (c) and (d).

<u>WR 20a</u>

• Nuclei present in the stellar winds can be accelerated at such shock structure to maximum Lorentz factors either due to the magnetic field reconnection

$$\gamma_{\text{max}} \approx \frac{ZeB_{sh}L_{rec}v_{\mathbf{A}}}{Am_{\mathbf{n}}c} \approx 2.6 \times 10^6 \frac{B_3^2 L_{12} v_3^{1/2}}{r^3 \dot{M}_{-5}^{1/2}},\tag{7}$$

or at the diffusive shock acceleration with the power law with the cut-off at

$$\gamma \mathbf{max} = \frac{3eZB_{\mathbf{sh}}R_{\mathbf{sh}}v_{\mathbf{w}}}{cAm_{\mathbf{p}}} \approx 4 \times 10^6 \frac{R_{12}B_3v_3}{r}.$$
 (8)

• The accelerated heavy nuclei lose nucleons due to the photo-disintegration process in collisions with the thermal photons from the massive stars provided that,

$$\gamma_{\min} \approx 8 \times 10^4 / T_5 (1 + \cos \theta). \tag{9}$$

- Significant fraction of neutrons from disintegration of nuclei, η , move towards the surface of the massive stars. These neutrons interact with the matter of stellar atmospheres. The average value η is estimated on 0.2.
- The relativistic nuclei take a fraction, ξ , of the kinetic power of the two stellar winds,

$$P_{\mathbf{A}} = \xi \dot{M} v_{\mathbf{W}}^2 \approx 6 \times 10^{37} \xi \dot{M}_{-5} v_3^2 \quad \text{erg s}^{-1}.$$
 (10)



Summary

The gamma-ray emission from massive binaries:

clearly modulated with the period of the binary systems TeV γ -ray binaries are very compact

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Production of γ -rays:

has to occur in dense radiation of the massive star cascade processes in the anisotropic radiation

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anisotropic IC e^{\pm} pair cascade model:

predicts correctly the basic features of the TeV emission from these binaries

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predicts unticorrelation of the GeV and TeV emission

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soon will be tested by the GLAST telescope