Gamma-rays from Compact Massive Binaries

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Some massive binaries should contain energetic pulsars which inject relativistic leptons from their inner magnetospheres. If the binary system is compact enough, then these leptons initiate inverse Compton (IC) $e^{\pm}$ pair cascades in the anisotropic radiation field of a massive star. γ-rays can be produced in a pulsar wind region and above the shock in a massive star wind region where the propagation of leptons is determined by the structure of a magnetic field around the massive star. For a binary system with specific parametres, we calculate phase dependent spectra and fluxes of γ-rays as a function of the inclination angle of the system and for different assumptions on injection conditions of the primary leptons. These γ-rays should be observed by future AGILE and GLAST satellites and low threshold Cherenkov telescopes.

1. INTRODUCTION

Numerical simulations of the evolution of binary systems containing neutron stars show that a fraction of them with non-accreting pulsars may become several percent of the total number of massive binaries [8], e.g. PSR B1259-63 with the period of 47.8 ms or A0538-66 with the period of 69.2 ms. It is expected that such binaries are sites of high energy processes in which particles can be accelerated to relativistic energies. In fact, some of such compact binary systems are coincident with the EGRET sources e.g. LSI +61 303 (2EG J0241+6119), Cyg X-3 (2EG J2033-4112), and LS 5039 (3EG J1824-1514). One of them, PSR 1259-63/Be, has been recently observed by the HESS group at energies ~ 400 GeV on the level of 5% of the Crab [9].

We consider in details a very compact binary system of a young pulsar and OB or WR type star which volume is separated by the shock wave into two regions with different properties. The shock appears as a result of collisions between the pulsar and the massive star winds. Massive companion is able to create soft radiation field in which the optical depths for accelerated leptons can be much larger than unity. For details of the model see [10].

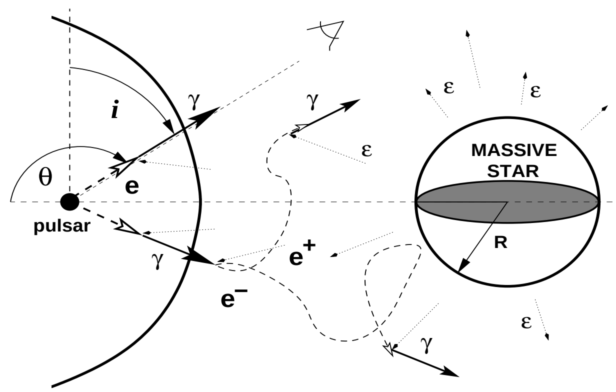

Figure 1: The schematic scenario of the interacting neutron star and massive companion inside the compact binary system. Primary leptons are injected by the pulsar and propagate inside the pulsar wind region (PWZ) along direction defined by the angle θ, comptonizing soft radiation from the massive star. Secondary γ-rays can be absorbed in the same radiation field either inside the PWZ or, after passing the pulsar wind termination shock, in the massive star wind region (MSWR), triggering an electromagnetic cascade. Leptons propagate radially inside the PWZ but follow the magnetic field structure inside the MSWR.

2. A PULSAR CLOSE TO A MASSIVE STAR

Let us assume that the energy loss rate of the pulsar, $L_{\rm rot}$, is high enough that the matter from the massive companion can not accrete onto the pulsar surface neither from the outflow through the Lagrangian point or from the dense stellar wind. The pulsar is on a circular orbit around the massive star with the radius $R_{\rm s}$, effective surface temperature $T_{\rm s}$, and surface magnetic field $B_{\rm s}$. The star creates the wind which has the termination velocity v_∞ and is characterized by the mass loss rate $\dot{\rm M}$. The separation of the stars is D. As a result of the interaction of the pulsar and stellar winds a double shock structure is formed, separated by the contact discontinuity, at the distance determined by the above mentioned parameters of the stars (see Fig. 1). The pulsar and stellar winds are symmetric. We apply the simplified model for the structure of the colliding winds based on momentum conservation [5].

In order to perform detailed calculations in the case of specific binary we apply as an example the parameters expected for the massive WR star in the Cyg X-3 system. This is a short period compact binary, $\tau = 4.8$ hr, with the massive star radius $< 3 - 6R_\odot$, surface temperature $T_{\rm s} > (7-9)\times 10^4$ K, separation of the components $3.2 < D/R_\odot < 5.6$, and the mass loss rate $\dot{M} \sim 1.1\times 10^{-5} M_\odot\ yr^{-1}$ [4]. The orbital inclination of the system with respect to the observer at the Earth is $i > 60^{\rm o}$ [6]. The infrared observations by [13] are consistent with the high orbital inclination, $i = 74^o$, and the mass loss rate in the range $\dot{M} \sim 1.2\times10^{-4} M_\odot$ yr^{-1} and $\dot{M} \sim 0.6\times10^{-5} M_\odot$ yr^{-1}. The stellar wind has terminal velocity $V_\infty = 1.45\times10^3$ km s^{-1}. The mass of the compact object has been constrained by $< 3.6 M_\odot$, and the mass and radius of the stellar companion by $< 7.3 M_\odot$ and $R_s < 1.6 R_\odot$ [11]. We adopt the following parameters for our specific binary system. A Wolf-Rayet type star with a radius $R_s = 1.6 \times R_\odot$, an effective temperature, $T_{\rm eff} = 1.36 \times 10^5$K, and a typical surface magnetic field, $B_s \sim 10^2 - 10^3$G [12]. The mass loss rate is $\dot{M} \sim 0.8-8.0\times10^{-5}$ $M_\odot$ yr^{-1}, the velocity of the stellar wind at infinity $v_\infty \sim (1-5)\times10^8$ cm s^{-1}, and the star rotational velocity $v_{rot} \sim (0.1-0.2)v_\infty$. The pulsar has a period $P = 12.59$ ms and a surface magnetic field $B = 4.95 \times 10^{11}$ G [3]. It is on a circular orbit, with a separation of $D = (3.6 \pm 1.2)R_\odot = 2.25 \times R_s$ [11]. For these parameters, the pulsar energy loss rate is,

$$L_{\rm rot} \approx 6 \times 10^{43}\ B_{12}^2\ P_{\rm ms}^{-4}\ {\rm erg\ s^{-1}} \approx 6 \times 10^{38}\ {\rm erg\ s^{-1}}, \quad (1)$$

where $P = 10^{-3} P_{\rm ms}$ s and $B = 10^{12} B_{12}$. For the above mentioned parameters of the massive companion in the Cyg X-3, the value of the parameter η, which determines the shape of the shock, is in the range $0.067 < \eta < 0.67$ [5]. We apply the average value $\eta = 0.3$.

Leptons which move through the PWZ interact efficiently with the soft radiation of the massive companion initiating IC $e^\pm$ pair cascade. The optical depths for IC scattering of massive star thermal radiation and for γ-rays absorption process in the same radiation are much larger than unity (see 2). γ-rays with energies above a few GeV have high probability of interaction for all directions (optical depth larger than unity). The charged products of this cascade arrive finally to the shock region in the pulsar wind and follow the flow along the shock surface. The power in these secondary leptons is relatively low with respect to the power in secondary cascade γ-rays in the case of very close binary systems considered in this paper. The secondary γ-rays move into the massive star wind region. Some of them escape from the binary system but a significant part can be converted into the next generation of $e^\pm$ pairs which have to follow the complex structure of the magnetic field present in the stellar wind. These pairs can trigger further cascading processes producing next generation of γ-rays at directions which depend not only on the injection geometry of primary leptons but also on the geometry of the magnetic field.

We consider two models for the primary spectra of leptons injected into the radiation field of the massive star: (i) The power law spectrum of injected leptons between 100 MeV and 500 GeV and the spectral index -1.2, as envisaged in the recent calculations of the spectra of leptons escaping from the inner magnetoshere performed by [7]. (ii) The monoenergetic injection of leptons with energies 10^6 MeV corresponding to the Lorentz factors of the pulsar wind with the parameters typical for the Crab pulsar. These leptons have very similar energies to those ones expected for the supposed pulsar in Cyg X-3 binary system due to the similar value of B/P^2.

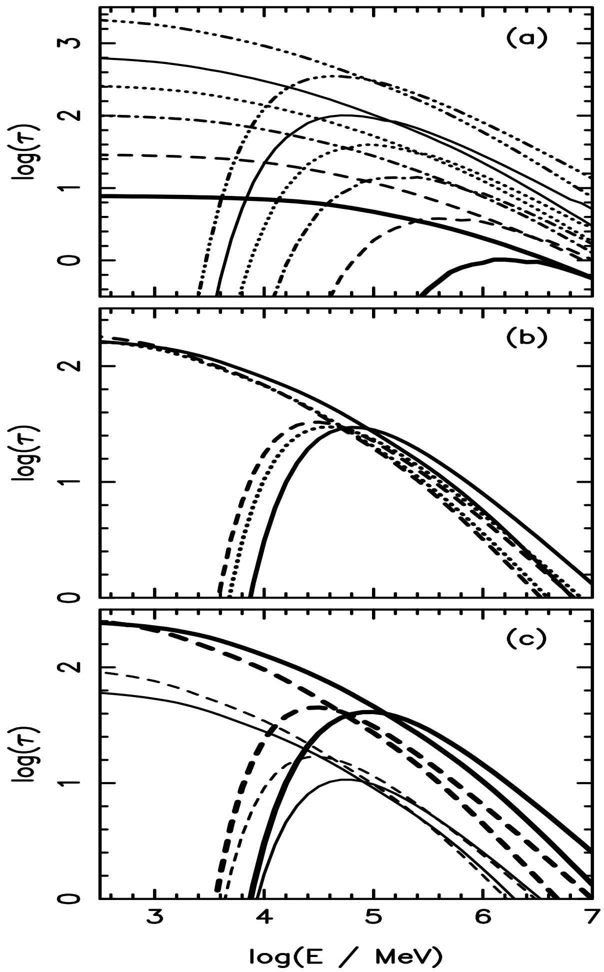

Figure 2: The optical depths for leptons on ICS and for γ-rays on $e^\pm$ pair production in the anisotropic radiation of the massive star during their rectilinear propagation from the injection place (at the distance $D = 2.25$R$_s$ from the massive star) up to the infinity (figure (a)) are shown as a function of particles energies for the case of their injection at the angle: $\theta = 0^o$ (thick full curves), 30^o (dashed), 60^o (dot-dashed), 90^o (dotted), 120^o (thin full), and 150^o (dot-dot-dot-dashed). (b) As in (a) but for particles propagating only to the termination shock defined by $\eta = 0.3$ and for the injection angles 90^o (solid lines), 120^o (dotted lines) and 150^o (dashed lines). (c) As in (b) but for two specific locations of the shock defined by $\eta = 0.06$ and 0.6 and for the injection angles of primary leptons equal to 90^o (solid lines) and 150^o (dashed lines).

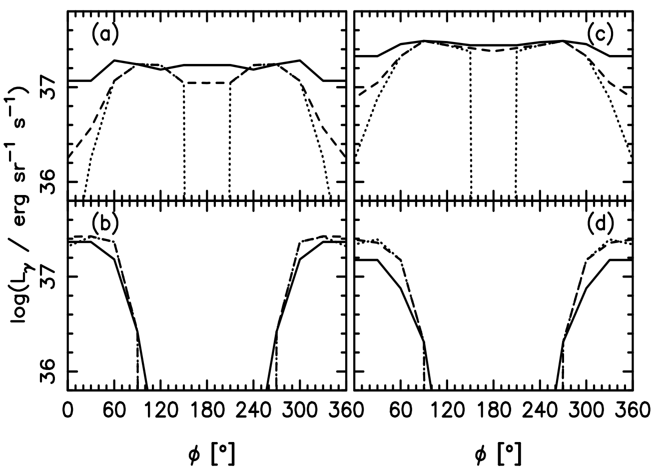

Figure 3: The γ-ray light curves in two energy ranges, $0.1 - 10$ GeV ((a) and (c)) and $10 - 10^3$ GeV ((b) and (d)), produced in the cascade process occurring inside the PWZ. The cascade is initiated by leptons with the monoenergetic (figures on the left) and the power law spectra (on the right) for selected values of the inclination angles $i = 30^o$ (solid curve), 60^o (dashed), and 90^o (dotted) measured from the normal to the plane of the binary system.

3. PULSAR WIND REGION

Energetic leptons are injected from the vicinity of the pulsar light cylinder and propagate radially from the pulsar almost at rest with respect to the pulsar wind. In this case we neglect the synchrotron losses of leptons during their propagation up to the pulsar wind shock. Leptons develop IC $e^\pm$ pair cascade whose efficiency depends on the injection parameters of these primary particles (initial energies of leptons, their injection directions and parameters of the binary system and massive star). We assume that the cascade initiated by specific primary lepton in the PWZ develops in one dimension, i.e. in the direction of propagation of the primary particle. Such one-dimensional cascade develops up to the pulsar wind shock. The secondary γ-rays pass through the shock into the massive star wind region where they can be additionally absorbed producing next generation of energetic $e^\pm$ pairs. For considered large optical depths, only the γ-rays with energies below the threshold for $e^\pm$ pair production escape freely from the binary system. The secondary $e^\pm$ pairs which are produced in the PWZ are captured by the magnetic field of the shock region and move along its surface with the pulsar wind plasma. However, in the case of compact binary systems such as Cyg X-3, we can neglect the contribution of secondary $e^\pm$ pairs to the total escaping γ-ray spectrum, because the part of energy of the primary leptons transfered to the secondary $e^\pm$ pairs is relatively low compared to that one transfered to the secondary γ-rays, as we show later.

We follow the development of such IC $e^\pm$ pair cascade in the anisotropic radiation of the massive star assuming that the primary particles are injected in the place corresponding to the location of the pulsar in the binary system. The procedure for the cascade Monte Carlo simulations in the PWZ is generally the same as used before [1, 2], except for the assumption on the local isotropisation of secondary $e^\pm$ pairs applied in previous papers. It is assumed that the secondary cascade $e^\pm$ pairs follow the direction of the parent γ-rays.

The γ-ray spectra have been obtained for two, mentioned above, distributions of primary leptons and the location of the shock defined by $\eta = 0.3$. The basic features of the γ-ray spectra observed at infinity, i.e. after their partial absorption in the radiation field of the MSWR, can be easily understood. Only primary leptons propagating in the outward direction (with respect to the massive star) can produce γ-ray fluxes above ~ 100 GeV, being potentially detectable by telescopes operating at very high energies (VHE). On the other hand, the γ-ray spectra escaping in the inward directions, i.e. close to the limb of the massive star, have comparable intensities at energies below 10 GeV (HE range) within a factor of 2-3. Moreover, these spectra show cut-offs close to ~ 10 GeV which are determined by the surface temperature of the massive star. Therefore, the anticorrelation between the γ-ray emission in the HE and VHE ranges is expected from such compact luminous binaries. It is evident that the high energy part of the γ-ray spectrum produced in the PWZ is strongly absorbed during propagation through the MSWR if the primary leptons are injected in the hemisphere containing the massive star, i.e. for the angles $\theta > 90^o$.

In order to investigate in more details the angular dependence of the γ-ray emission produced in the cascade inside the PWZ, we calculate the γ-ray light curves which should be observed at different inclination angles of the binary system. The results are shown for the two, HE and VHE, energy ranges (i.e. $0.1-10$ GeV and $10-10^3$ GeV) in the case of primary leptons injected into the PWZ with the monoenergetic and power law distributions (see Fig. 3). The γ-ray luminosities are calculated after normalization of the power in primary leptons to the rotational energy lost by the pulsar, $L_e = L_{\rm rot}$. Clear anticorrelation in the γ-ray curves is observed between these two energy ranges for both initial spectra of primary leptons. The VHE emission is mainly limited to the phases when the pulsar is in front of the massive star ($\varphi = 0^o$). In contrast, the HE emission is much more uniform with significant decrease at phases around 0^o at which the VHE emission is the strongest. The disappearance of γ-ray emission for large inclination angles of $i > 90^o - \alpha$ (where $\alpha = 26.4^o$ is the angular extend of the massive companion observed from the distance of the binary separation) and at the phase close to 180^o,

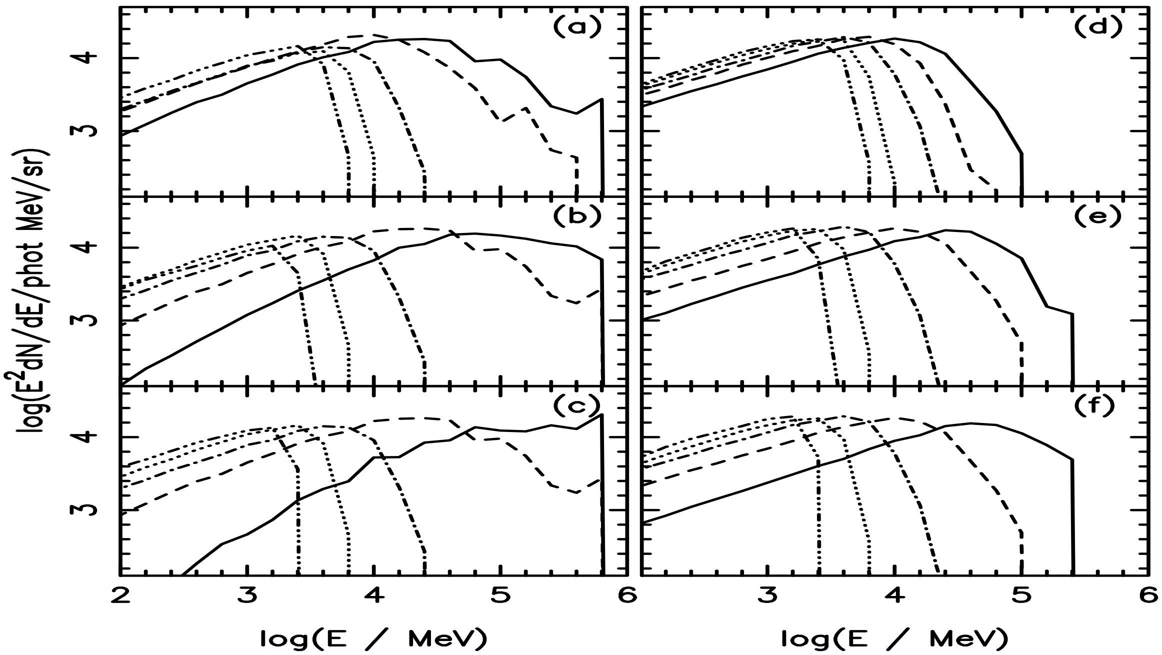

Figure 4: The γ-ray spectra escaping from the binary system for different phases of the pulsar on its orbit around the massive star (measured with respect to the location of the observer), $\varphi = 30^o$ (solid curve) 60^o (dashed), 90^o (dot-dashed), 120^o (dotted), 180^o (dot-dot-dot-dashed), and different inclination angles of the binary system $i = 30^o$ ((a) and (d)), 60^o ((b) and (e)), and 90^o ((c) and (f)). γ-rays are produced in the PWZ cascade by primary leptons with the monoenergetic (figures on the left) and the power law spectrum (on the right).

is connected with the total eclipse of the pulsar by the massive companion. The γ-ray spectral shapes do not differ significantly below a few GeV (spectral index close to -1.5) for half of the pulsar phases, independently on the inclination angle of the binary system. The level of this emission vary only by a factor of 2-3. In contrast, the VHE emission is limited to a relatively small range of phases with clear dependence on the inclination angle of the binary.

4. MASSIVE STAR WIND REGION

As we have shown above, a significant part of γ-rays from the PWZ which passed the termination shock is effectively absorbed in the MSWR by dense radiation field of the massive star. However, the next generation of $e^{\pm}$ pairs is forced to follow the local magnetic field lines and their directions of propagation can change significantly with respect to the directions of their parent γ-rays. Therefore, the development of the cascade in the MSWR becomes much more complicated, determined by the complex magnetic field structure and the cascade is not further one-dimensional. The next generation γ-rays are usually produced at completely different angles than the initial directions of the PWZ cascade γ-rays. In these cascade calculations it is assumed that synchrotron energy losses of the cascading $e^{\pm}$ pairs can be neglected with respect to their energy losses on the ICS. In fact, the comparison of energy densities of the magnetic field $\sim 2.5 \times 10^{16}$ eV cm^{-3} (for the surface magnetic field of the star $B_{\rm s} = 10^3$ G) and the thermal radiation $\sim 8.5 \times 10^{17}$ eV cm^{-3} (for the temperature of the star $T_{\rm s} = 1.36 \times 10^5$ K) shows that the IC losses should clearly dominate over the synchrotron process. Further from the star the energy density of radiation drops with the square of the distance and the energy density of magnetic field drops with the forth power of the distance. Therefore, if the IC losses dominate at the stellar surface it has to dominate everywhere above the star.

The magnetic field in the wind of the massive star can have complicated structure. In the region very close to the massive star surface it is characterized by dipolar component. At a certain distance, the radial component starts to dominate due to the presence of the ionized plasma, and at larger distances the magnetic field becomes toroidal due to the rotation of the massive star. The strength of the magnetic field as a function of distance from the center of the massive star is described by [12].

Let us investigate the angular distribution of secondary γ-rays produced by secondary $e^{\pm}$ pairs which in turn originate in the absorption process of γ-rays from PWZ cascade. These $e^{\pm}$ pairs propagate in the magnetic field and anisotropic soft radiation. As before, we consider two cases of the monoenergetic and power law injection of primary leptons. The basic features of the angular distribution of the secondary

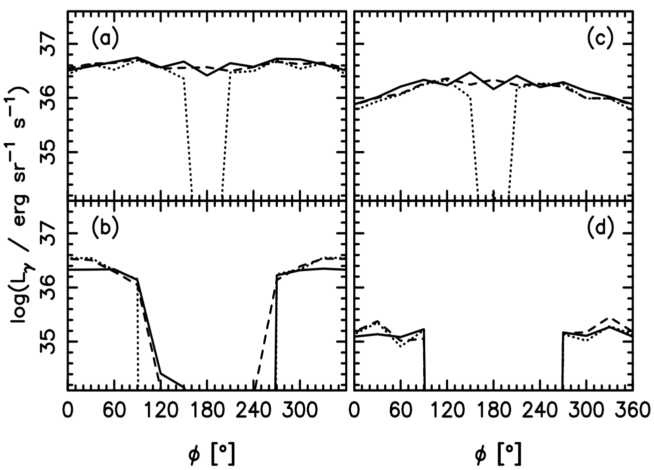

Figure 5: As in Fig. 2 but for the MSWR cascade initiated by secondary γ-rays which are in turn produced in the cascade in the PWZ initiated by primary leptons with the monoenergetic (figures on the left) and the power law distributions (on the right). γ-rays are collected within the range of the cosine of inclination angles of the system $0.76 < \cos i < 0.88$ (contains $i = 30^o$ - solid curve), $0.41 < \cos i < 0.53$ (60^o - dashed), and $-0.06 < \cos i < 0.06$ (90^o - dotted).

γ-rays are determined by the structure of the magnetic field in the MSWR. For the parameters considered in this work, the magnetic field is radial in the main region above the shock. For the primary leptons injected at the angle $\theta = 90^o$, the γ-rays from cascade inside the MSWR are produced inside the cone centred along the direction of the magnetic field lines which cross the direction of propagation of γ-rays produced inside the PWZ. Since the magnetic field lines are radial, the angles at which the secondary γ-rays escape are limited to relatively small part of the sphere. For primary leptons injected at larger angles the cone of secondary γ-ray production inside the MSWR becomes broader on the sky. Most efficient production occurs for directions which are tangent to the massive star limb. In this case a significant part of secondary γ-rays fall onto the surface of the massive star which angular dimensions, seen from the location of the neutron star, are equal to 26.4^o. If the primary leptons are injected towards the massive star, then the secondary $e^\pm$ leptons, which originate in the MSWR in absorption of secondary γ-rays from PWZ, move along the radial magnetic field. Most of the γ-rays produced in MSWR fall then onto the massive star. The secondary $e^\pm$ pairs reach finally the dipole part of the magnetic field, which is close to the massive star, and may produce low energy γ-rays at wide angles in the plane of the binary system.

The angular distribution of γ-rays produced in the MSWR in the case of monoenergetic and power law distributions of primary leptons is similar since it is determined by the radial structure of the magnetic field. However, the numbers of produced γ-rays are a factor of a few larger in the case of monoenergetic injection of primary leptons. This is due to the fact that γ-rays produced in the PWZ by monoenergetic leptons have on average higher energies. Therefore, they transport more energy to the MSWR. The energies and numbers of secondary $e^\pm$ pairs, from their absorption inside the MSWR, are larger allowing more efficient production of next generation of γ-rays in the MSWR.

The γ-ray light curves of photons produced in the MSWR for two energy ranges, $0.1 - 10$ GeV and 10 GeV - 1 TeV, are shown in Figs. 5, after its normalization to the total energy loss rate of the considered here pulsar. The observer is located at different inclination angles i to the plane of the binary system. The general features of the γ-ray light curves produced in the MSWR are similar to these ones shown above for the γ-rays produced in the PWZ (see for comparison Figs. 5). However, the total γ-ray power is usually lower (typically by a factor of three) than expected in the case of γ-rays produced in the PWZ. Only in the range of phases around 0^o and large inclination angles, the power of the γ-rays from the MSWR can dominate over the PWZ γ-rays in the GeV energy range. The power emitted in GeV energies is quite uniform with the phase of the pulsar provided that the inclination angle is small enough that the binary system is not eclipsing. The power emitted at TeV energies is limited to the range of phases $\pm 60^o$ around the phase 0^o which correspond to the position of the pulsar in front of the massive star.

Figs. 6 show the γ-ray spectra produced in the MSWR for selected phases and inclination angles of the binary system. The basic differences between these spectra and the γ-ray spectra produced in the PWZ are due to the fact that cascade in the MSWR is initiated by leptons for which the total optical depths are higher. Therefore, these γ-ray spectra are steeper, with the spectral index close to -2, in contrast to the spectral index of the spectra produced in the PWZ which are close to -1.5. Although, the power emitted in γ-rays from the MSWR is a factor of a few lower, it can still significantly contribute to the total γ-ray spectrum observed at some range of phases and at energies below ~ 1 GeV for the case of monoenergetic injection of primary leptons. Moreover, as already noted above, this GeV emission is much more uniform over the sky. At energies > 10 GeV the contribution of the γ-rays from the MSWR (produced by monoenergetic primary leptons) becomes negligible with respect to the γ-rays from the PWZ for the considered location of the shock inside the binary system defined by $\eta = 0.3$. The γ-rays produced inside the MSWR by primary leptons with the power law spectrum do not contribute significantly to the γ-rays produced in the PWZ. Primary leptons with the power law spectrum

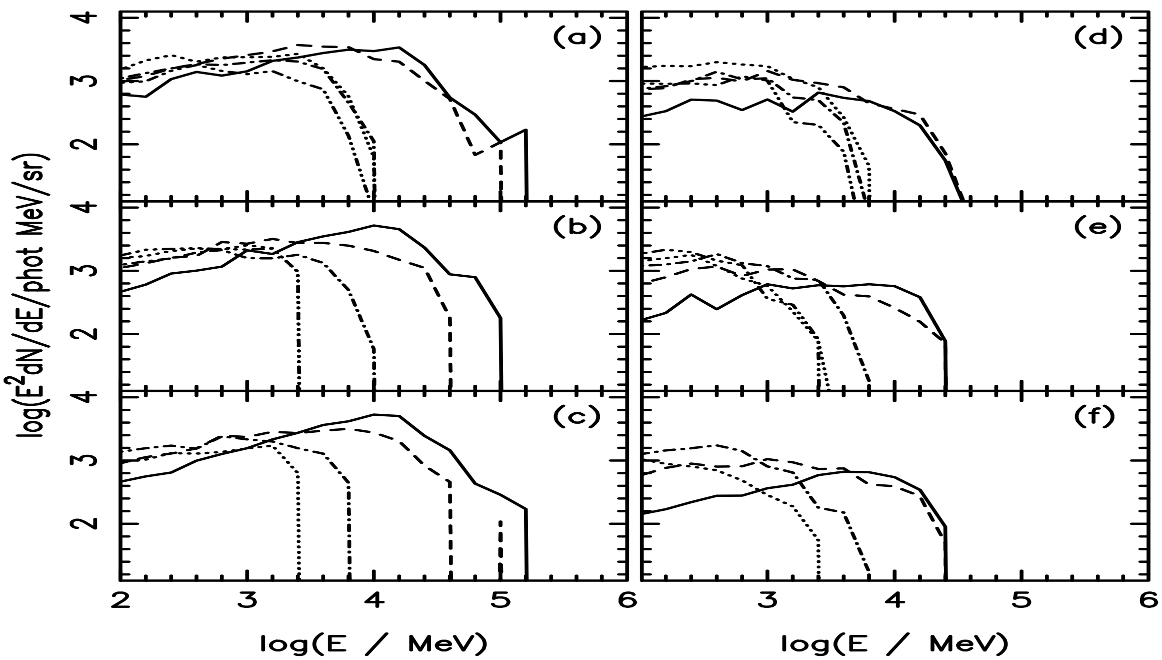

Figure 6: As in Fig. 4 but for the MSWR and three ranges of the cosine of the inclination angle of the binary $0.76 < \cos\alpha < 0.88$ (centered on $i = 30^o$ - (a) and (d)), $0.41 < \cos\alpha < 0.53$ (60^o - (b) and (e)), and $-0.06 < \cos\alpha < 0.06$ (90^o - (c) and (f)).

produce on average more secondary γ-rays already inside the PWZ.

5. CONCLUSIONS

Most of energy of primary leptons propagating in the pulsar wind zone (PWZ) is transfered to the secondary γ-rays for both the monoenergetic and the power law primary spectra of leptons (shock location is defined by $\eta = 0.3$). The γ-ray light curves for photons escaping from the PWZ at lower energies (range $0.1 - 10$ GeV) are anticorrelated with the γ-ray light curves at higher energies (> 10 GeV) for both discussed primary spectra of leptons independently on localizations of the shock within the binary system. The γ-ray spectra extend to higher energies for the monoenergetic primary leptons but are less intense at lower energies than in the case of leptons injected with the power law spectrum. A part of γ-rays produced in the PWZ (typically one third to half) is converted to secondary $e^{\pm}$ pairs in the MSWR. Therefore, the contribution of γ-rays produced in the MSWR is usually lower than γ-rays produced in the PWZ. The complex magnetic field in the MSWR has significant effect on propagation directions of secondary cascade $e^{\pm}$ pairs and, as a consequence, on the distribution of γ-rays on the sky. This distribution also strongly depends on the injection directions of primary leptons. The γ-ray fluxes produced in the MSWR are weakly dependent on the phase of the pulsar and the inclination angles of the binary system due to the propagation effects of secondary $e^{\pm}$ pairs in the magnetic field mentioned above.

Acknowledgments

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References

[1] Bednarek, W., A&A 322, 523, 1997.
[2] Bednarek, W., A&A 362, 646, 2000.
[3] Brazier, A., et al., ApJ 350, 745, 1990.
[4] Cherepashchuk, A., Moffat, A., ApJ 424, 53, 1994.
[5] Girard, T., Wilson, L.A., A&A 183, 247, 1987.
[6] Hanson, M. et al., ApJ 541, 308, 2000.
[7] Hibschman, J.A., Arons, J., ApJ 560, 871, 2001.
[8] Lipunov, V.M., *Astrophysics of Neutron Stars*, Stringer-Verlag (Berlin), 1990.
[9] Schlenker, S. et al., Proc. Int.Symp.High Energy Gamma-Ray Astronomy (Heidelberg, Germany), AIP, submitted, 2004.
[10] Sierpowska, A., Bednarek, W., MNRAS, 356, 711, 2005.

[11] Stark, M., Saia, M., ApJ 587, L101, 2003.
[12] Usov, V.V., Melrose, D.B., ApJ 395, 575, 1992.
[13] van Kerkwijk, M.H. et al., A&A 314, 521, 2002.