

Gamma-rays from nebulae around binary systems containing energetic pulsars

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Abstract: Within compact binary systems, winds from the pulsars and the companion stars have to mix in the region around the orbital planes due to the rotation of the binary systems. As a result of these wind interactions, the electrons can be accelerated at some distance from the binary system. These electrons comptonize thermal radiation from the nearby companion star producing steady fluxes of the high energy gamma-rays. We estimate the expected steady GeV-TeV gamma-ray flux in the case of LS 5039 and the millisecond pulsar binary system PSR J1816+4510. The confrontation of these fluxes with the observed GeV-TeV gamma-ray emission or the sensitivities of the Cherenkov telescopes allows us to put constraints on the escape of relativistic leptons from the binary systems.

Keywords: binaries: general, pulsars: general, radiation mechanisms: non-thermal, gamma-rays: theory

1 Introduction

The winds from pulsars and companion stars collide within the binary systems producing shock structures on which particles can be accelerated to relativistic energies. In fact, some binary systems emit γ -rays in the GeV-TeV energy range, clearly modulated with the period of the binary system which strongly suggests that this emission originates within the binary (Aharonian et al. 2006, Albert et al. 2009). Farther from the binary system, the wind from the pulsar and the companion star has to mix close to the plane of the binary system due to its rotation. As a result, it is expected that such mixed pulsar-stellar winds move together with some specific velocity determined by the energy output from the pulsar and the material content of the stellar wind. Therefore, nebulae around binary systems containing rotation powered pulsars should have different structures than nebulae around isolated pulsars. We propose that binary systems should be surrounded by nebulae composed of the mixture of the pulsar and stellar winds which expands with non-relativistic velocity. In this paper we consider radiation processes occurring in such nebulae. We calculate the γ -ray spectra produced by relativistic electrons in the Inverse Compton (IC) scattering of thermal radiation from the companion star.

2 Nebulae around binary systems

As we have outlined above we consider specific type of nebulae around binary systems containing rotation powered pulsars and companion stars with substantial mass loss rate. In fact, in such type of binaries double shock structures appear already within the binary systems in collisions of the pulsar and stellar winds. They have usually a cone structure characterised by some opening angle. However, due to the rotation of the binary system, the cone should be bound at large distances from the stars (e.g. Dubus 2006, Bosch-Ramon et al. 2012), provided that the velocity of the stellar wind is large in respect to the rotational velocity of the companion star. At some distance both winds mix and move together with some specific ve-

locity. For geometrical details of this scenario see Fig. 1 in Bednarek & Sitarek (2013). Relativistic electrons are accelerated at the collision region of these winds. They are isotropized in the reference frame of a relatively slowly expanding mixed wind. These electrons can interact efficiently with the thermal radiation from the nearby companion star.

Both winds are expected to mix completely at the distance from the binary system which depend on the velocity of the stellar wind and the rotational period of the binary system, $D_{\text{mix}} \approx \tau_{\text{orb}} v_w \approx 8.6 \times 10^{12} \tau_{\text{d}} v_8$ [cm], where the period of the binary system is $\tau_{\text{orb}} = 1 \tau_{\text{d}}$ days and the stellar wind velocity is $v_w = 10^8 v_8$ [cm s⁻¹]. As a result of the mixing process, the pulsar wind becomes uploaded with the stellar wind matter. The mixture of both winds starts to move together with the common velocity, w_{env} , estimated from the energy conservation, $L_{\text{pul}} + L_{\text{sw}} = \dot{M} w_{\text{env}}^2 / 2$, where $L_{\text{sw}} = \dot{M}_w v_w^2 / 2$ is the kinetic power of the stellar wind and the energy loss rate by the pulsar is $L_{\text{pul}} = 10^{36} L_{36}$ erg s⁻¹. If the stellar wind power dominates over the pulsar wind power, then $w_{\text{env}} \approx v_w$. In the opposite case, $w_{\text{env}} = \sqrt{2L_{\text{pul}} / \dot{M}} \approx 5.4 \times 10^8 (L_{36} / M_{-7})^{1/2}$ [cm/s] (where mass loss rate is $\dot{M} = 10^{-7} M_{-7} M_{\odot} \text{ yr}^{-1}$), resulting in a non-relativistic bulk motion of the mixed winds for the assumed above example parameters.

Relativistic electrons accelerated in the inner binary system, either by the pulsar itself or on the shock formed in the pulsar and stellar winds collision, are immersed in the mixed stellar-pulsar wind. We estimate the maximum energies of the electrons for which they are still captured and confined by the mixed wind magnetic field. It is assumed that the magnetic field in the mixed wind is determined by the magnetic field in the stellar wind. The magnetic field strength can be approximated as a function of the distance from the star by the following formula, $B(D) \approx 0.01 B_2 R_{11} / D_{13}$ [G] (Bednarek & Sitarek 2013), where the radius of the star is $R_* = 10^{11} R_{11}$ [cm]. In this formula, the surface magnetic field of the star is $B_* = 100 B_2$ [G], and the distance from the star is expressed as $D = 10^{13} D_{13}$ [cm]. We assume that relativistic electrons are captured by

the wind if their Larmor radius, R_L , is lower than the characteristic distance scale given by the distance from the massive star. $R_L \approx 3 \times 10^2 E_{\text{TeV}}/B(D_{\text{mix}})[\text{cm}] < D_{\text{mix}}$, where $E = 1E_{\text{TeV}}$ [TeV] is the energy of an electron, and $B(D_{\text{mix}})$ (measured in Gauss) is the local magnetic field strength in the mixed wind. We conclude that electrons with energies, $E < 30B_2$ [TeV], should be captured in the mixed stellar-pulsar wind.

Electrons, captured in the magnetic field of the mixed stellar-pulsar wind, are isotropized in the reference frame of the relatively slow wind. They lose energy on the synchrotron radiation and on the IC scattering of the stellar radiation. The importance of the synchrotron energy losses can be evaluated by comparing the synchrotron cooling time scale with the advection time scale with the velocity of the winds. The advection time scale can be estimated from, $\tau_{\text{adv}} = D/w_{\text{env}} = 10^5 D_{13}/w_8$ [s], where $v_{\text{env}} = 10^8 w_8$ [cm/s], and the synchrotron time scale from, $\tau_{\text{syn}} = E_e/\dot{E}_{\text{syn}} \approx 290/(B^2 E)$ [s], where $\dot{E}_{\text{syn}} = (4/3)cU_B \sigma_T E_e^2/m_e^2 \approx 3.5 \times 10^{-3} B^2 E^2$ [TeV/s], $m_e = 511$ keV and electron energy E is expressed in TeV. By comparing the above equations, we get the limit on the electron energy above which the synchrotron energy loss time scale is shorter than the advection time scale, $E_{\text{adv}}^{\text{syn}} \approx 29w_8 D_{13}/(B_2 R_{11})^2$ [TeV]. We conclude that electrons with TeV energies are not able to lose efficiently energy on the synchrotron process during their advection with the mixed pulsar-stellar wind.

As an example, we estimate the parameters of nebulae around the millisecond pulsar J1816+4510 in the redback type binary system, and supposed classical pulsar in the binary system LS 5039 belonging to the class of the TeV γ -ray binaries (see Table 1). The likely parameters of this binary system allows us to estimate the shape of the shock in this binary defined by the parameter η (defined as a ratio of pulsar wind pressure to the pressure of the stellar wind). For $\eta \sim 1.2$ the shock almost divide the volume of the binary in two equal parts. For such geometry, the mixed wind dominates almost at the whole sphere around the binary system, i.e. $\Delta_{\text{mix}} \sim 1$. The energies of electrons accelerated in this system can reach TeV energies (see Table 1).

LS 5039 is a well known binary system containing O type massive star and a compact object which is supposed to be an energetic pulsar (Moldon et al. 2012, Dubus 2006). This binary system has been detected in the TeV γ -rays (Aharonian et al. 2005) and also at GeV energies by *Fermi* (Abdo et al. 2009). For this binary system, the shock structure bends around the pulsar since $\eta \sim 0.08$ (see Table 1). This means that the whole pulsar wind is overtaken by the stellar wind.

3 Relativistic particles in nebulae

We estimate the maximum energies of particles which can be accelerated at the turbulent region at the distance of D_{mix} by comparing their acceleration time scale and their advection time scale from the shock region. The acceleration time scale is given by, $\tau_{\text{acc}} = E_e/\dot{P}_{\text{acc}} \approx 100E_{\text{TeV}}/(\chi_{-3} B)$ [s], where $\dot{P}_{\text{acc}} = \chi cE/R_L$. The acceleration process is parametrised in this case by the acceleration efficiency $\chi = 10^{-3} \chi_{-3}$ which is assumed to be of the order of $\sim (w_{\text{env}}/c)^2$. We estimate the maximum energies of electrons due to their advection from the acceleration region on, $E_{\text{adv}}^{\text{max}} \approx 10\chi_{-3} B_2 R_{11}/w_8$ [TeV]. The

maximum energies of particles, accelerated at the shock at the distance of D_{mix} , can be additionally constrained by their energy losses. Therefore, we compare the acceleration time scale of particles with their energy loss time scale. For the radiation energy loss time scales of electrons in the vicinity of the stars (synchrotron and IC processes), the standard formulae from Blumenthal & Gould (1970) are applied. The comparison of the acceleration and the synchrotron energy loss time scales gives us the maximum energies of electrons due to the synchrotron energy losses, $E_{\text{syn}}^{\text{max}} \approx 19(\chi_{-3} D_{13}/B_2 R_{11})^{1/2}$ [TeV]. The maximum energies due to the Inverse Compton energy losses (in the Thomson regime) are given by, $E_{\text{IC/T}}^{\text{max}} \approx 0.4(\chi_{-3} B_2 D_{13}/R_{11})^{1/2}/T_4^2$ [TeV]. We stress that this second limit is only important in the Thomson regime, i.e. for electrons with energies $< 100/T_4$ GeV. For larger energies, due to the falling of the Klein-Nishina cross-section, the limit is relaxed. The values of the maximum energies of electrons due to their escape with the expansion of the nebula and due to the synchrotron energy losses are shown for the considered binary systems in Table. 1. We conclude that electrons can be accelerated to energies estimated by the lower of the two values: $E_{\text{syn}}^{\text{max}}$ and $E_{\text{adv}}^{\text{max}}$. We assume that electrons are injected into the nebula surrounding the binary system with a power law spectrum extending between $E_e^{\text{min}} = m_e \gamma_e^{\text{pul}}$ and E_e^{max} .

4 Gamma-ray production in nebulae

We calculate the γ -ray spectra produced by relativistic electrons within the nebulae in the IC scattering of the stellar radiation and the Microwave Background Radiation. We assume that relativistic electrons are isotropized in the mixed pulsar-stellar wind at the distances above D_{mix} . We also include the synchrotron energy losses of the electrons in the magnetic field of the winds with the values equal to B_{mix} at the distance D_{mix} . This magnetic field drops with the distance, D , from the binary system as $\propto 1/D$. For example, in the case of J1816+4510, we apply the value $B_{\text{mix}} = 10^{-2}$ G. For this value, the energy density of stellar radiation at the distance D_{mix} overcomes the energy density of the magnetic field by a factor of ~ 200 . Therefore, the synchrotron energy losses can only start to be important at energies above a few hundred GeV, where the IC emission is suppressed by the Klein-Nishina cross-section. The relative importance of the synchrotron energy losses in respect to the IC energy losses, in the case of LS 5039 is similar to that estimated for J1816+4510.

We apply the Monte Carlo method in order to obtain the γ -ray spectra produced by electrons which IC scatter stellar photons. These electrons are advected from the binary system with the velocity of the mixed pulsar-stellar wind w_{env} . The turbulent magnetic field in the mixed pulsar-stellar wind isotropizes the directions of electrons. Therefore, in the reference frame of electrons the stellar radiation from the companion star is isotropic. The γ -ray spectra are calculated applying the formulae for the IC spectra in the general case from Blumenthal & Gould (1970). Two binary systems, J1816+4510 and LS 5039, are selected for more detailed calculations. They seem to be the best candidates for the production of detectable γ -ray fluxes from the nebulae due to the luminous stellar companions and relatively compact nebulae. We assume that relativistic electrons take $\varepsilon = 10\%$ of the rotational power lost by the pulsars.

Table 1: Parameters of the nebulae around binary systems and energies of particles which produce γ -rays.

Name	η	Δ_{mix}	D_{mix} (cm)	B_{mix} (G)	w_{env} (cm/s)	χ_{-3}	$\tau_{\text{IC/T}}$	$E_{\text{syn}}^{\text{max}}$ (TeV)	$E_{\text{adv}}^{\text{max}}$ (TeV)
J1816	1.2	0.95	2×10^{12}	$4 \times 10^{-4} - 0.4$	2.2×10^9	5.4	3.4	12-410	0.05-50
LS 5039	0.08	0.32	8×10^{13}	$8 \times 10^{-3} - 8 \times 10^{-2}$	1.1×10^9	1.3	110	7-24	7.7-77

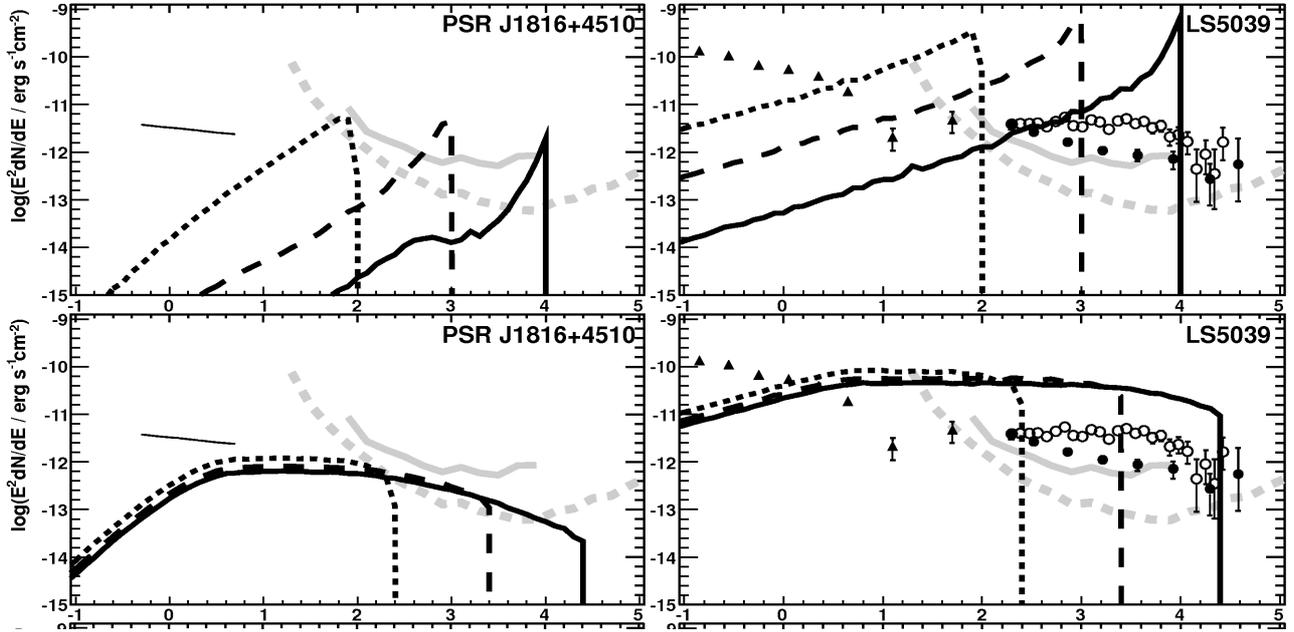


Figure 1: γ -ray SEDs expected from the nebula surrounding the Redback millisecond binary system J1816+4510 (on the left) and the binary system LS 5039 supposed to contain a classical pulsar (on the right). The upper panels show the results for monoenergetic injection of electrons with energy: 10^2 GeV (dotted), 10^3 GeV (dashed), and 10^4 GeV (solid). The bottom panels show the results for a power-law injection with spectral index of -2.1 between $E_{\text{min}} = 10$ GeV and $E_{\text{max}} = 3 \times 10^2$ GeV (dotted), 3×10^3 GeV (dashed), and 3×10^4 GeV (solid). It is assumed that $\Delta_{\text{mix}} \cdot \varepsilon = 10\%$ of the pulsar wind power is converted to relativistic electrons. For the comparison, the 100 hr differential sensitivity of MAGIC (Aleksic et al. 2012) and CTA (Bernlöhr et al. 2012) are also marked by the gray solid and dotted curve respectively. Full and empty data circles show the SED of LS 5039 measured by H.E.S.S. in 2 different orbital phases (Aharonian et al. 2006) and the average spectrum from 30 months of the observations with *Fermi*-LAT is shown with triangles (Hadasch 2012). The thin black line in the left panels show the spectral fit to the *Fermi*-LAT observations of J1816+4510 (Kaplan et al. 2012).

The γ -ray spectra, expected from the nebulae around these two binary systems, are shown in Fig. 1 for the case of the monoenergetic spectrum of electrons (upper figures) and the power law spectra of electrons which were injected with the spectral indices equal to 2.1 (bottom Fig. 1).

The γ -ray spectra, expected at the observer, are compared with the sensitivity of the present generation (e.g. MAGIC) and future (Cherenkov Telescope Array, CTA) imaging atmospheric Cherenkov telescopes (IACTs). Detection of the considered here TeV γ -ray emission from the Redback millisecond binary J1816+4510 with the present instruments is unlikely. However, with a deep exposure of 100 hr, such emission could be detected by CTA as long as the energy conversion efficiency, ε , is at least 10%. The γ -ray spectrum obtained from the *Fermi*-LAT observations of that source does not constrain the product of part of the hemisphere subtracted by the mixed wind and the energy conversion efficiency for this source, i.e. $\Delta_{\text{mix}} \cdot \varepsilon$.

The γ -ray spectra expected from the LS 5039 are ~ 2 orders of magnitude above the expected sensitivity of CTA. With the assumed energy conversion efficiency from the pulsar to relativistic electrons (10%), such emission

should be clearly detected even by the presently operating Cherenkov telescopes. The TeV emission observed from LS 5039 by the H.E.S.S. telescopes is modulated with the orbital period. On the other hand, the emission expected from the presented here model should contribute as a constant component in the whole emission of the system. Therefore, we can use the low state observed by H.E.S.S. telescopes to constrain the parameters which determine the energy transferred to the TeV electrons which escape from the binary system. This power depends on the product of a part of the hemisphere in which the mixed stellar-pulsar wind is confined, Δ_{mix} and the energy conversion efficiency, ε . Derived upper limits on $\Delta_{\text{mix}} \cdot \varepsilon$ are reported in Table. 2 for different spectra of electrons in the case of LS 5039. For the broad range of the model parameters, $\Delta_{\text{mix}} \cdot \varepsilon$ is severely constrained to be $\ll 1\%$.

It is believed that the energy conversion efficiency from the pulsar to relativistic electrons, in the inner pulsar magnetosphere and in the shock acceleration scenario, is of the order of 10%. Then, the part of the hemisphere in which the mixed wind is confined should be also below $\Delta_{\text{mix}} \sim 10\%$. As discussed in Sect. 2, this factor depends

Table 2: The upper limits on the product of the part of the hemisphere overtaken by the mixed pulsar-stellar wind (Δ_{mix}) and the energy conversion efficiency (ϵ) from the pulsar to relativistic electrons for the binary system LS 5039

	Monoenergetic			Power-law, $\alpha = -2.6$			Power-law, $\alpha = -3$		
E_{max} [GeV]	10^2	10^3	10^4	$10^{2.5}$	$10^{3.5}$	$10^{4.5}$	$10^{3.5}$	$10^{4.5}$	$10^{4.5}$
E_{min} [GeV]	10^2	10^3	10^4	10	10	10	100	10	100
$\Delta_{\text{mix}} \cdot \epsilon$	< 0.3%	< 0.05%	< 0.03%	< 0.3%	< 0.3%	< 0.2%	< 0.4%	< 0.3%	< 0.4%

on the half opening angle of the shock within the binary system which is determined by the value of the parameter η . For the value of η , calculated for the supposed shock structure in LS 5039, Δ_{mix} is larger than required above (see Table 1). In fact, different phenomena can affect the estimated value of Δ_{mix} . At first, the value of η might be much larger than ~ 0.08 , i.e. the stellar wind may not effectively confine the pulsar wind. In fact, the winds around Be type massive stars are expected to be aspherical with the dense and slow equatorial wind and the fast and rare poloidal wind. If the pulsar is mainly immersed in the poloidal wind, than the shock structure might even bend around the star (see calculations in Sierpowska-Bartosik & Bednarek 2008). In such case only a part of the pulsar wind can mix with the stellar wind. Second, the electrons could be injected anisotropically from the pulsar or accelerated anisotropically in the pulsar wind. In fact, the pulsar winds are expected to be highly anisotropic with the dominant equatorial component (e.g. Bogovalov & Khangoulian 2002, Volpi et al. 2008). Such aspherical pulsar wind will introduce significant complications to the discussed scenario. More energy in relativistic electrons will be directed to the equatorial regions of the binary system resulting in much larger effective value of η (even larger than unity). However the solid angle, in which mixed stellar-pulsar wind is confined, will become lower. Simple estimations show that the increase of significant effective power of the wind in the equatorial direction results in more power transferred in the form of relativistic electrons to the nebula. However, in such a case a significant part of the particles, accelerated by the pulsar towards the companion star, could not be able to escape from the binary system due to efficient IC interactions with the stellar radiation. Therefore, the final effect of the anisotropic pulsar wind on the energy transferred to nebula in the form of relativistic particles is difficult to estimate without more detailed calculations. The third possibility is that more electrons could be accelerated in the general direction towards the companion star. This might happen in the case of a significant collimation of the relativistic particles in the pulsar winds by the shock structure (e.g. see Dubus et al. 2010, Bogovalov 2008). Then, electrons lose efficiently energy on IC process before they manage to escape into the mixed wind region.

5 Conclusions

We considered nebulae around binary systems which contain rotation powered pulsars and hot companion stars with a relatively large mass loss rate. Due to the efficient mixing of the winds, relativistic electrons are isotropized in the reference frame of the mixed wind relatively close to the binary system. Therefore, they can efficiently comptonize thermal radiation from the companion star. We calculate the γ -ray spectra produced by leptons in the IC scattering

process in the case of the mono-energetic particles (leaving the light cylinder radius of the pulsar) and in the case of the power law spectra of leptons formed as a result of re-acceleration at the shocks produced in the pulsar-stellar wind collisions. Note that this γ -ray emission should be steady, i.e. independent on the phase of the binary system. As an example, we show the predicted γ -ray spectra for the supposed pulsar in the binary system LS 5039 and for the recently discovered Redback type millisecond binary system J1816+4510, containing relatively hot companion star. It is found that if electrons take a part of the pulsar wind energy loss rate defined by the product of the part of the hemisphere, in which the mixed pulsar-stellar wind expands, and for the acceleration efficiency of electrons $\Delta\Omega \cdot \epsilon$ equal to 10%, than the TeV γ -ray emission from the millisecond binary system is comparable to the sensitivity of the Cherenkov Telescope Array (CTA). However, in the case of LS 5039, electrons with such value of $\Delta\Omega \cdot \epsilon$ should produce γ -ray emission on the level clearly above the sensitivity of both the present Cherenkov telescopes and CTA. By comparing the γ -ray spectra predicted for LS 5039 with the TeV γ -ray emission in the low state established by the H.E.S.S. telescopes, and with the average *Fermi*-LAT observations, we put strong limits on $\Delta_{\text{mix}} \cdot \epsilon < 1\%$. Such low limit suggest that either the parameters of the stellar wind are less extreme than considered in the literature or the injection of electrons from the inner pulsar magnetosphere and/or accelerated at the shock is highly anisotropic. Most of relativistic electrons might be directed towards the companion star and lose efficiently energy already within the binary system.

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