GAMMA-RAY SIGNAL FROM THE PULSAR WIND IN THE BINARY PULSAR SYSTEM PSR B1259−63/LS 2883

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ABSTRACT

Binary pulsar systems emit potentially detectable components of gamma-ray emission due to Comptonization of the optical radiation of the companion star by relativistic electrons of the pulsar wind, both before and after termination of the wind. The recent optical observations of binary pulsar system PSR B1259−63/LS 2883 revealed radiation properties of the companion star which differ significantly from previous measurements. In this paper, we study the implications of these observations for the interaction rate of the unshocked pulsar wind with the stellar photons and the related consequences for fluxes of high energy and very high energy (VHE) gamma rays. We show that the signal should be strong enough to be detected with Fermi close to the periastron passage, unless the pulsar wind is strongly anisotropic or the Lorentz factor of the wind is smaller than 10^5. The higher luminosity of the optical star also has two important implications: (1) attenuation of gamma rays due to photon–photon pair production and (2) Compton drag of the unshocked wind. While the first effect has an impact on the light curve of VHE gamma rays, the second effect may significantly decrease the energy available for particle acceleration after termination of the wind.

Key words: binaries: close – gamma rays: stars – pulsars: individual (PSR B1259−63)

Online-only material: color figures

1. INTRODUCTION

Three binary systems containing a massive star and a compact object—LS 5039, LS I +61 303, and PSR B1259−63—have been clearly detected in TeV energy band (see http://tevcat.uchicago.edu/ for the updated information). While the nature of the compact companion in LS 5039 and LS I +61 303 is not yet established (Casares et al. 2005a, 2005b; Sarty et al. 2011), the detection of the pulsed radio emission from PSR B1259−63 indicates the presence of a 47.7 ms pulsar in the system (Johnston et al. 1992). The pulsar orbits a luminous star in a very eccentric orbit with the following orbital parameters: eccentricity $e = 0.87$, period $P_{orb} = 1237$ days, and semimajor axis $a_2 = 7.2$ AU (see Negueruela et al. 2011, and references therein). The system displays variable broad nonthermal radio, X-ray, and TeV gamma-ray emission close to periastron passage (Johnston et al. 2005; Uchiyama et al. 2009; Chernyakova et al. 2009; Grove et al. 1995; Aharonian et al. 2005, 2009). Also a weak GeV signal during the periastron passage in 2010 December as well as a strong gamma-ray flare several weeks after the periastron have been detected by the Fermi gamma-ray observatory (Tam et al. 2011; Abdo et al. 2011).

Recently, optical observations with VLT UT2 Kueyen discovered that the optical star LS 2883 corresponds to a late O star and has a significantly higher luminosity of $L_\odot = 2.3 \times 10^{33} \text{ erg s}^{-1}$ than previously thought (Negueruela et al. 2011). Because of fast rotation the star is significantly oblated with equatorial radius of $R_{eq} = 9.7 R_\odot$ and polar radius of $R_{pole} = 8.1 R_\odot$. This leads as well to a strong gradient of the star’s surface temperature with $T_{eq} = 27,500$ K and $T_{pole} = 34,000$ K. The star’s rotation axis is inclined by $i_\star \approx 33^\circ$ with respect to the line of sight (Negueruela et al. 2011). The distance to the system is now estimated to be $2.3 \pm 0.4$ kpc. Moreover, the observations favored an orbital inclination value of $i \approx 25^\circ$, which is remarkably smaller than the previously obtained value of $\sim 35^\circ$ (Johnston et al. 1994). All these new parameters together should have an important impact on the multiwavelength properties of this system.

The orbital separation distance, pulsar spin-down luminosity, and the lack of the accretion features suggest a realization of the compactified nebula scenario, i.e., the source contains two distinct regions: the relativistic pulsar wind and the terminated flow (Tavani & Arons 1997; Bogovalov et al. 2008). The very high energy (VHE) emission is expected to originate in the post termination shock region, and a number of models have been proposed invoking both hadronic (Kawachi et al. 2004; Neronov & Chernyakova 2007) and leptonic (Kirk et al. 1999; Khangulyan et al. 2007) radiation mechanisms. In the framework of the hadronic scenario, the two humped TeV light curves observed with the High Energy Stereoscopic System (HESS) of Cerenkov telescopes in 2004 (Aharonian et al. 2005) have been interpreted as the enhancement of the production rate due to the pulsar passage through the dense stellar disk. However, the recent report of a more complicated TeV gamma-ray light curve by HESS with more humps and dips disfavors, to a large extent, the hadronic scenario (Aharonian et al. 2009). In the case of a leptonic origin of the emission, there are a number of additional effects, which may significantly affect the production rate of the nonthermal emission in the post shock region (Khangulyan et al. 2007).

Importantly, within the standard ultrarelativistic cold pulsar wind scenario, one expects a specific inverse Compton (IC) radiation from the unshocked pulsar wind. A line-like bulk
Comptonization component from this region has been predicted for isolated pulsars like the Crab pulsar (Bogovalov & Aharonian 2000) and for the binary pulsar system PSR B1259−63 (Ball & Kirk 2000; Ball & Dodd 2001; Khangulyan et al. 2007). It is difficult to overestimate the importance of observational proof of this radiation component; it offers a unique opportunity of detecting a direct signal from the pulsar wind. The HESS observations already exclude the range of bulk motion Lorentz factors exceeding 10^6, but the most meaningful constraints in this regard can be obtained in the 0.1−100 GeV region. Therefore, the observations with *Fermi* and *AGILE* gamma-ray telescopes close to the periastron passage are of great interest; any result (flux upper limit or detections of a signal) can greatly contribute to our understanding of the physics of pulsar winds.

Since the interaction of the pulsar wind with the stellar photon field does not occur in the *saturation regime*, the production rate is very sensitive to the properties of the photon field. In this paper, we present new calculations of the radiation signal from the pulsar wind taking into account the new properties of the optical star (Negueruela et al. 2011) and using results of detailed hydrodynamical modeling of the interaction between the pulsar and stellar winds in PSR B1259−63/LS 2883 (Bogovalov et al. 2008). In addition to the optical radiation from the companion star, a non-negligible contribution to the IC gamma rays can be provided by the reprocessed near-infrared radiation in the stellar disk (O. de Jager 2010, private communication; van Soelen & Meintjes 2011).

### 2. PULSAR WIND IN A BINARY PULSAR SYSTEM

In the framework of the generally accepted paradigm (Kennel & Coroniti 1984), pulsars launch cold ultrarelativistic winds which are terminated due to external pressure. At the termination shock, the wind electrons can be accelerated to multi-TeV energies. The radiation of these electrons results in a phenomenon called pulsar wind nebula. Since the wind is cold, i.e., particles remain at rest in the wind comoving system, no synchrotron emission is expected from the wind before its termination. On the other hand, the Comptonization of the ultrarelativistic wind by external radiation fields, through which the wind propagates, can lead to detectable gamma-ray emission. This effect is relatively weak in isolated pulsars and can achieve a reasonable efficiency only in powerful pulsars, provided that the particle-dominated wind is formed close to the light cylinder (Bogovalov & Aharonian 2000). In binary systems, the process operates with an enhanced efficiency thanks to the presence of the dense radiation field of the optical companion (Ball & Kirk 2000; Ball & Dodd 2001). The interaction rate in this channel depends on different parameters characterizing the system: (1) luminosity and temperature of the optical star, (2) orbital separation and inclination, (3) distance to the system, (4) size of the region occupied by the pulsar wind, and (5) pulsar wind bulk Lorentz factor.

Remarkably, the recent optical observations of PSR B1259−63 have significantly revised the parameters (1)−(3) in favor of higher temperature and luminosity, smaller inclination angle and more distant system location. The wind bulk Lorentz factor remains a highly uncertain parameter.

The depth to which the pulsar wind can penetrate depends on the ratio η of the ram pressures of the pulsar and stellar winds (Bogovalov et al. 2008; Cerutti et al. 2008). Since the pulsar spin-down luminosity is known, one can calculate the ram pressure of the pulsar wind

\[ P_{\text{pw}} = \frac{L_{\text{sd}}}{4\pi r^2 c}, \]

where \( L_{\text{sd}} = 8 \times 10^{35} \text{ erg s}^{-1} \) and \( r \) are the spin-down luminosity of the pulsar and the distance to the pulsar, respectively. It should be noted that this relation ignores the possible effects related to the anisotropy of the pulsar wind. Although the level of the anisotropy may be quite high at large distances from the pulsar, e.g., in the case of the Crab-like pulsars (Bogovalov & Khangulyan 2002), in this paper we limit our consideration to the case of an isotropic wind.

To obtain the ram pressure of the stellar wind, one needs detailed information about the properties of the optical star, including the mass-loss rate and wind velocity profile, which are currently not firmly established. For the given optical star luminosity, the mass-loss rate can be estimated at the level of \( M = 6 \times 10^{-8} M_\odot \text{ yr}^{-1} \) (Vink et al. 2000). Accounting for the wind velocity at the interaction point \( V_w < V_{\infty} = 1350 \pm 200 \text{ km s}^{-1} \) (McCullum 1993), one can estimate the \( \eta \)-parameter

\[ \eta = \frac{L_{\text{sd}}}{M c V_w} = 5 \times 10^{-2} \left( \frac{M}{6 \times 10^{-8} M_\odot \text{ yr}^{-1}} \right)^{-1} \times \left( \frac{V_w}{1350 \text{ km s}^{-1}} \right)^{-1}. \]

We should note, however, that there are several factors which may introduce significant uncertainties in the \( \eta \)-parameter. In particular, the wind porosity may result in overestimation of the mass-loss rate of the star by a factor of five or more (Owocki & Cohen 2006). Consequently, this would lead to a significant underestimate of the \( \eta \)-parameter. An opposite situation may occur when the pulsar wind interacts with the stellar wind close to the star’s equatorial plane, where a dense Keplerian disk is formed. Since the disk outflow is expected to have a mass-loss rate comparable to the polar wind, but with the radial velocity as low as \( V_r \simeq 1 \text{ km s}^{-1} \), the pressure in this region would be larger by three orders of magnitude. Thus, accounting for the disk typical velocity at the distance \( r \) (i.e., Keplerian velocity) of

\[ v_{\text{disk}} \simeq 200 \left( \frac{r}{10^{13} \text{ cm}} \right)^{-1/2} \text{ km s}^{-1}, \]

one can see that the disk effective ram pressure may significantly exceed the polar wind pressure. This implies that the \( \eta \)-parameter can be smaller than the estimate given by Equation (2) by a factor up to 30. Moreover, because of the disk rotation and pulsar orbital velocity, the structure of the wind termination shock, with respect to the observer direction, may be rather different for two pulsar–disk interaction points. Finally, we note that the physical properties of the stellar disk may be significantly changed by the pulsar wind (Okazaki et al. 2011). Because of these uncertainties, below we will consider a fairly broad range of the \( \eta \)-parameter.

In Figure 1, the shapes of the termination shock obtained for three different values of the \( \eta \)-parameter are shown, using the results of numerical modeling performed by Bogovalov et al. (2008), for \( \eta = 1 \) (squares), \( \eta = 0.05 \) (filled circles), and \( \eta = 1.1 \times 10^{-3} \) (open circles). Here the value of \( \eta = 1 \) corresponds to the upper limit case, which can be approached in the case of very small mass-loss rates in the polar wind, e.g., the “weak case” in Okazaki et al. (2011). The value \( \eta = 0.05 \)
Here, \( d \) is the distance to the system, \( d \sigma/dE \) is the differential anisotropic IC cross-section (Aharonian & Atoyan 1981), \( r \) is the energy-dependent optical depth due to the gamma–gamma interactions from the point of gamma-ray production to the observer, and \( dN_{\text{ph}}/d\epsilon_{\text{ph}}dV \) is the target photon density at the given location. The term representing the electron energy distribution in the cold pulsar wind has the following form:

\[
\frac{dN_e}{dE_{\gamma}d\epsilon_{\text{ph}}} = \frac{L_{\text{sd}}}{\Gamma_0 mc^2} \delta \left( E_{\gamma} - \Gamma_0 mc^2 - \int_0^1 dl' \dot{E}/c \right),
\]

where \( \Gamma_0 \) is the initial wind bulk Lorentz factor and \( \dot{E} \) describes the electron energy loss rate.\(^6\) Note that the integration of Equation (8) along the line of sight gives a broadening of the energy distribution of electrons instead of monoenergetic electrons in the case of absence of the Compton drag.

The integration of Equation (7) is performed over the line of sight from the pulsar location to the pulsar wind termination shock. Obviously, the integration path depends strongly on the orbital phase. In Figure 1, the lines of sight for three different orbital phases (−6, 0, and 6 days to periastron passage) are shown by dashed lines.

Another effect, which may lead to an additional orbital phase dependence, is the shape of the optical star and temperature change between different regions of the star. To study this effect we performed a calculation for the precise properties of the star, i.e., assuming the star to be an oblate spheroid with a linear gradient of the surface temperature as a function of the zenith angle. The orientation of the star with respect to the observer is defined by inclination angle, i.e., the angle between the star’s rotation axis and line of sight, which was assumed to be \( i_\ast = 33^\circ \), as inferred by Negueruela et al. (2011). To fix the star’s orientation an additional angle is required, namely the angle which describes the turn in the plane of the sky. This angle was assumed to be a free parameter, and its influence was studied. Numerical calculations show (see Figures 2 and 3) that independently of this parameter, the emission is well described by a model with a spherical star of radius \( R_\ast = 6.2 \times 10^{11} \text{ cm} \) and surface temperature \( T_\ast = 3 \times 10^4 \text{ K} \). Given the uncertainties related to the orientation of the star, in what follows we perform calculations for the spherical star with the inferred parameters. Finally, the circumstellar disk can affect the flux level, leading to sudden changes in light curve. This important issue will be discussed elsewhere (Khargulyan et al. 2011).

In Figure 2, we show the spectral energy distributions expected at the orbital phase corresponding to the periastron passage for \( \eta = 1 \) (solid lines), \( \eta = 0.05 \) (dotted lines), and \( \eta = 1.1 \times 10^{-3} \) (dashed line). In calculations we have adopted the following values of the initial wind Lorentz factors: \( \Gamma_0 = 10^4, 4.6 \times 10^4, 2.2 \times 10^5 \), and \( 10^6 \). In Figure 3, we show a similar plot, but for the orbital phase corresponding to the epoch of 30 days before the periastron passage. For a rather broad range of the wind bulk Lorentz factors around \( \Gamma_0 = 10^4 \), the obtained flux level is above the Fermi sensitivity level (unless the \( \eta \)-parameter is small \( \eta \ll 0.05 \)).

Due to the orbital phase dependence of several key parameters, in particular, separation distance, the location of the termination shock, the gamma–gamma optical depth, and the electron–target photon interaction angle, the pulsar wind signal

\(^6\) In the calculations shown in Figures 2, 3, and 4 we assumed an enhancement of the kinetic luminosity of the wind by a factor of 1.5 due to the anisotropy of the pulsar wind (see Bogovalov & Khargulyan 2002, for details). We note that the flux level depends linearly on this parameter.
has an orbital phase dependence. Since the light curves for different energies are quite similar, we show just a few examples. In particular, the light curve for 10 GeV gamma rays is shown in Figure 4. Here we assumed for the initial pulsar wind Lorentz factor $\Gamma_0 = 4.6 \times 10^4$. In calculations we used two different values of the $\eta$-parameter: $\eta = 1$ (solid line) and $\eta = 0.05$ (dotted line). We note that this parameter may affect not only the flux level, but also the location of the light-curve maximum: in the case of small $\eta$ the maximum is located close to the periastron passage, while in the case of larger values of $\eta$ the maximum is located a few days before the periastron passage.

In the case of large bulk Lorentz factor, $\Gamma_0 \sim 10^6$--$10^7$, the IC signal from the pulsar wind may appear at energies beyond the range of Fermi/Large Area Telescope (LAT). In this energy band, the atmospheric Cerenkov telescope arrays are more appropriate tools for probing the wind Lorentz factor (note that for this specific source, currently only the HESS array is able to monitor PSR B1259--63). In Figure 4, we show a light curve of 0.4 TeV gamma rays calculated for the $\eta$-parameter $\eta = 1$ and for the bulk Lorentz factor $\Gamma_0 = 10^6$.

3. IMPACT OF THE HIGHER LUMINOSITY OF THE OPTICAL STAR

In addition to gamma radiation of the unshocked pulsar wind, we expect gamma rays (at higher energies) from the Compton scattering of shock-accelerated electrons (Kennel & Coroniti 1984). If the optical radiation density exceeds the density of the magnetic field, the IC gamma-ray production proceeds in the saturation regime, thus the increased luminosity of the optical star does not lead to amplification of the VHE gamma-ray signal. On the other hand, for the recently reported luminosity of the optical star (Negueruela et al. 2011), the gamma–gamma opacity for VHE photons traveling from the pulsar to the observer may be as large as 0.5, thus emission may be attenuated by a factor of 1.6. In Figure 5, we show the corresponding optical depth as a function of the phase for five different energies of gamma rays: $\gamma = 0.05$, 0.15, 0.4, 1, and 5 TeV. Note that the gamma-ray absorption is strongest at the energy of 0.4 TeV, while at energies below 100 GeV and at multi-TeV energies it becomes negligible. We note however that the actual absorption...
level depends on the location of the production region, while the calculations in Figure 5 assume that the production occurs in the pulsar location. In particular, in Figure 4 two light curves for 0.4 TeV gamma rays are shown. The thick dash-dotted line corresponds to the flux level corrected for the gamma–gamma attenuation, while thin dash-dotted line shows the intrinsic flux level. It can be seen that the attenuation is somewhat weaker than is expected from the opacity shown in Figure 5. The reason for that is rather simple, namely since the gamma-ray production occurs along the line of sight in the pulsar wind zone (see Equation (7)), some gamma-ray photons suffer a weaker attenuation than the one shown in Figure 5.

Another important implication of the enhanced optical luminosity of the companion star for the production of VHE gamma rays is related to the so-called effect of Compton drag which corresponds to the flux level corrected for the gamma–gamma attenuation, while thin dash-dotted line shows the intrinsic flux level. It can be seen that the attenuation is somewhat weaker than is expected from the opacity shown in Figure 5. The reason for that is rather simple, namely since the gamma-ray production occurs along the line of sight in the pulsar wind zone (see Equation (7)), some gamma-ray photons suffer a weaker attenuation than the one shown in Figure 5.

Motivated by the recent revision of optical properties of LS 2883, the companion star of PSR B1259–63 (Negueruela et al. 2011), we present new calculations of high energy gamma-ray fluxes using a realistic termination shock geometry as described in Bogovalov et al. (2008). Calculations show that the higher optical star luminosity is compensated, to a large extent, by the new estimate of the distance to the source. Thus, the new calculations of gamma-ray fluxes are quite close to previous predictions based on the old gamma-ray parameters of the optical star (see in Khangulyan et al. 2007). According to Figure 2, the 0.1–10 GeV gamma-ray fluxes calculated for epochs close to the periastron passage are below the current upper limits obtained with EGRET (Tavani et al. 1996), and above the minimum fluxes detectable by Fermi/LAT for observation time of about one month. The pulsar wind radiation component can be identified by its distinct spectral shape.

Another important feature of pulsar wind emission is the expected modulation with the pulsar period on the top of the smooth orbital phase dependence. Indeed, since the emitting electrons move toward the observer almost with the speed of light, the gamma-ray signal should have the second modulation reflecting the time structure of the striped pulsar wind. Although, a detailed shape of the fine light curve can be hardly obtained given a lack of any consistent description of the striped pulsar wind, a detailed search for this effect looks quite important for a consistent interpretation of the results obtained with Fermi/LAT (Tam et al. 2011; Abdollahi et al. 2011).

The most important implication of detection of this component of gamma radiation would be the unique opportunity to measure the Lorentz factor of the pulsar wind. On the other hand, in the case of failure to detect this component at GeV and/or TeV energies, the conclusions could be equally interesting and important. The possible reasons for non-detection of gamma rays from the unshocked wind could be (1) an extremely powerful stellar wind, i.e., very low values of the η-parameter and (2) unconventional, i.e., very small (Γ0 ≪ 104) or very large (Γ0 ≳ 105) values of the pulsar wind bulk Lorentz factor. The first condition requires the pulsar to interact with the stellar disk over the whole orbit. This implies a very specific realization in the sense of orientation of the stellar disk (namely the orbital plane and the disk plane should almost coincide), which contradicts the current expectations (see Melatos et al. 1995; Bogomazov 2005; Bogovalov et al. 2008; Kerschhaggl 2011, and the shadowed regions in Figure 4). However, we should note that one cannot exclude that the pulsar wind is strongly anisotropic. If so, the gamma-ray signal should be anisotropic as well. This can be another reason for reduction of the gamma-ray flux, which unfortunately would make the conclusions concerning the range of parameters Γ0 and η less robust. Finally, one should mention that if the pulsar wind is not absolutely cold, electrons in the frame of the wind might have a rather broader distribution. This would make the gamma-ray spectrum less distinct and smoother compared to the ones shown in Figures 2 and 3.

Regarding VHE energy gamma rays produced after termination of the wind, the new optical observations of Negueruela et al. (2011) imply a significant reduction of the flux of IC gamma rays produced by shock-accelerated electrons. All three
The main factors related to (1) the larger distance to the source, (2) the gamma–gamma attenuation, and (3) the Compton drag of the pulsar wind work in the same (negative) direction, reducing the gamma-ray flux by a factor of up to 10. Given that the previous studies based on the old optical observations already have required a significant fraction of the spin-down luminosity (5%–10%) to be released in TeV gamma rays, the revised energy requirements become almost unbearable. A possible solution to the energy budget crisis could be the Doppler boosting of radiation as suggested in Khangulyan et al. (2008). This important issue will be discussed elsewhere.

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