The major role of eccentricity in the evolution of colliding pulsar-stellar winds

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Abstract

Binary systems that host a massive star and a non-accreting pulsar can be powerful non-thermal emitters. The relativistic pulsar wind and the non-relativistic stellar outflows interact along the orbit, producing ultrarelativistic particles that radiate from radio to gamma rays. To properly characterize the physics of these sources, and better understand their emission and impact on the environment, careful modelling of the outflow interactions, spanning a broad range of spatial and temporal scales, is needed. Full 3-dimensional approaches are very computationally expensive, but simpler approximate approaches, while still realistic at the semi-quantitative level, are available. We present here the results of calculations done with a quasi 3-dimensional scheme to compute the evolution of the interacting flows in a region spanning in size up to a thousand times the size of the binary. In particular, we analyze for the first time the role of different eccentricities in the large scale evolution of the shocked flows. We find that the higher the eccentricity, the closer the flows behave like a one-side outflow, which becomes rather collimated for eccentricity values \( \gtrsim 0.75 \). The simulations also unveil that the pulsar and the stellar winds become fully mixed within the grid for low eccentricity systems, presenting a more stochastic behavior at large scales than in the highly eccentric systems.

1 Introduction

Binary systems hosting a massive star and a non-accreting pulsar, or pulsar high-mass binaries (PHMB), can be powerful sources of gamma rays. The objects of this kind capable of gamma-ray emission pertain to the wider class of gamma-ray binaries, in which most of the non-stellar radiation is released in the gamma-ray energy range (see, e.g., Dubus, 2013; Paredes and Bordas, 2019a,b, for these and related sources). The radiation is produced through the interaction of a relativistic pulsar wind and the outflows ejected by the star: Massive stars
produce strong non-relativistic winds of supersonic nature and, in cases of very fast stellar rotation, quasi-Keplerian equatorial disks (or decretion disks) that flow outwards at subsonic speeds. These outflows interact with the pulsar wind and later on interstellar matter in a process in which ultrarelativistic particles are accelerated and produce emission from radio to gamma rays (see, e.g., Tavani and Arons, 1997; Sierpowska and Bednarz, 2005; Dubus, 2006; Neronov and Chernyakova, 2007; Khangulyan et al., 2007; Kong et al., 2012; Zabalza et al., 2013; Dubus et al., 2015; Molina and Bosch-Ramon, 2020; Huber et al., 2021; Lyutikov et al., 2020; Khangulyan et al., 2021).

The pulsar wind-stellar outflow interactions are complex, and different regions that can influence each other are relevant when trying to understand the evolution of the shocked flows. Even the associated radiation and its reprocessing can feedback on the flow dynamics, making the whole physical system highly non-linear. At small scales, there is the region right between the star and the pulsar in which flows are stopped and shocked by colliding against each other. After the collision, the flows become subsonic and hot, and start moving symmetrically sideways while pressure gradients lead to their reacceleration, getting supersonic again. This picture is roughly similar in both sides of the contact discontinuity separating the stellar and the pulsar shocked flows. Later on, the respective evolution of the flows largely differs due, for instance, to very different wind momentum rates and initial velocities, plus orbital effects.

Due to the large momentum rate of stellar winds, the stellar wind confines the pulsar wind, which bends over the pulsar. Shocked winds form an approximately axisymmetric curved structure that becomes conical further away from the binary. On those larger scales, if orbital motion were neglected, the shocked winds would move ballistically and form a conical shell made of shocked pulsar wind, surrounded by another shell of shocked stellar wind. The half-opening angle of the conical contact discontinuity would converge to a value that can be derived from the pulsar-to-stellar wind momentum rate ratio (Bogovalov et al., 2008):

$$\eta = \frac{L_{sd}}{\dot{M}_w v_w c},$$

where \(L_{sd}\) is pulsar spin-down luminosity, \(\dot{M}_w\) and \(v_w\) are the stellar mass-loss rate and wind speed, respectively. Following Eichler and Usov (1993) and Bogovalov et al. (2008), the contact discontinuity of the cone-like structure has an approximate opening angle of

$$\phi_c \approx \frac{\pi}{6} \left(4 - \eta^{2/5}\right) \eta^{1/3}.$$
contact surface gets partially disrupted, stellar wind mixes with the shocked pulsar wind, and the latter develops strong turbulence and decelerates. The result is that the shocked flow structure shape becomes a one-arm spiral that fills much of the volume and is expected to disrupt after a few turns.

Between the apex of the interaction structure, located at the two-shocked flow stagnation point (Bogovalov et al. 2012), and the starting point of the Coriolis shock, on the leading edge of the interaction structure, the shocked pulsar wind gets compressed and thus heated by the Coriolis force-related lateral pressure of the stellar wind. This can weaken the mentioned shocked flow reacceleration caused by pressure gradients. On the other hand, in the trailing edge of that interaction structure, the shocked pulsar wind quickly expands and accelerates through rarefaction waves.

The presence of decretion disks can significantly alter the geometry of the interaction structure, which must develop now embedded in a much more complex circumstellar environment. Nevertheless, the disk is rather massive and marginally bounded to the star, so part of the material may not even escape the binary. In addition, the accumulated disk mass can be in fact just comparable to that of the stellar wind. Thus, on large scales, the shocked flow dynamics is likely dominated by the pulsar and the stellar wind, the disk and radiation processes can be important for flow dynamics on small and middle scales. Assuming then that the disk is mostly relevant closer to the binary, and neglecting the role of the magnetic field, the system eccentricity may turn out to be as important as η to describe the evolution of the shocked flows on large scales. In particular, [Bosch-Ramon et al. 2017; Barkov and Bosch-Ramon 2018] show that for very high eccentricities the shocked pulsar wind becomes strongly focused along the periastron-apastron direction, as it gets deflected by the stellar wind in that direction for most of the orbit. To date, however, an exploration of how different eccentricity values affect the large-scale shocked flow structure is missing, mainly, at which eccentricities one-sided outflows form.

In this work, we perform a numerical study of how the shocked flows from PHMB evolve, and propagate, up to large distances from the binary for different eccentricities. Our major goal is to find for which orbit eccentricity the mentioned one-sided outflow forms. The study is carried out using the quasi 3-dimensional (3D) calculation scheme developed by [Barkov and Bosch-Ramon 2016], used to study PSR B1259–63, and HESS J0632+057 (Bosch-Ramon et al. 2017; Barkov and Bosch-Ramon 2018). The advantage of this method, which employs spherical coordinates, is that it focuses on the orbital plane, but sacrifices resolution for zenithal angles far from that plane. Furthermore, the shocked flow geometry just outside the binary turns out to be amenable to be simplified such that the colliding-wind apex region does not need to be modelled, which allows a computationally much cheaper resolution. All this largely reduces the cost of the simulations, allowing one to probe a large region surrounding the binary. The accuracy of the method is appropriate at a semiquantitative level, as shown by comparison with results obtained using full 3D calculations encompassing overlapping regions (Bosch-Ramon et al. 2015).

The article is organized as follows: In Sect. 2 the simulations are described, and in Sect. 3 their results presented. Then, in Sect 4 the simulations results are summarized and discussed.
2 Numerical model

Quasi-3D simulations of PHMB wind-wind collisions with different orbit eccentricities were performed using the PLUTO code\footnote{Link http://plutocode.ph.unito.it/index.html} [Mignone et al., 2007]. PLUTO is a modular Godunov-type code entirely written in C and intended mainly for astrophysical applications and high Mach number flows in multiple spatial dimensions. Spatial parabolic interpolation, a 3rd order Runge-Kutta approximation in time, and an HLLC Riemann solver were used (Li, 2005). The simulations were performed on the CFCA XC30 cluster of the National Astronomical Observatory of Japan (NAOJ). To reduce computing costs, the flow was approximated by a simple equation of state enough for our purposes: that of an ideal relativistic gas with adiabatic index $4/3$. We adopted spherical coordinates $(R, \theta, \phi)$, with 768 cells in both the radial and the azimuthal directions. To reduce the computation costs, we took only 3 cells in the zenithal direction. The domain size was taken to be $R \in [1,500]R_{\text{min}}$, $\theta \in [\pi/4,3\pi/4]$ and $\phi \in [0,2\pi]$. We set $R_{\text{min}} = 2(1 - e^2)a$, with $a$ being the semi-major axis of the orbit, and $e$ its eccentricity; thus, the scales captured by the simulations are larger than a few times the orbital separation distance at periastron. The computational grid was made logarithmic in the radial direction, that is, cells grow with a constant aspect ratio. Our treatment of the $\theta$-direction allows a reasonably realistic characterization of the orbital plane physics on scales beyond the pulsar, where the interaction structure expansion becomes approximately linear with distance, although a more quantitative account would require a complete 3D treatment (see Barkov and Bosch-Ramon, 2016; Bosch-Ramon et al., 2017; Barkov and Bosch-Ramon, 2018).

In the quasi-3D calculation scheme adopted here the injected pulsar wind has a half-opening angle $\phi_c$, which depends on the momentum rate relation, which is set to $\eta = 0.1$, an intermediate value for this parameter, to restrict the degrees of freedom of the problem. This $\eta$-value corresponds to $\phi_c = 0.87$ radians, so the computational domain was divided in two non-equal parts. The first one, in which $\phi \in (\phi_c,2\pi - \phi_c)$, was filled by a radial stellar wind with velocity value $v_w = 2400$ km s$^{-1}$. The second part, in which $\phi \in [-\phi_c,\phi_c]$, was filled by a radial pulsar wind with Lorentz factor $\Gamma = 1.9$. Despite this Lorentz factor being just moderately relativistic, the calculations are enough relativistic for our purposes because internal energy density already plays a significant inertial role (see Bosch-Ramon et al., 2012, 2015). The winds were assumed to be highly supersonic at injection, with Mach numbers $M_w = 6.9$ and $M_j = \gamma p/v_s \sqrt{c_s} = 14$ for the stellar and the pulsar wind, respectively, where "s" refers to the sound speed. For simplicity, any wind azimuthal velocity component, coming for instance from object rotation and angular momentum conservation, was neglected in our calculations as its value would be well below $v_w$ and $c$. Also, as discussed in Sect.1, we neglected the role of a decretion disk, although more quantitative studies should include it.

The initial pulsar position is at the left of the computational domain, which means that the simulated pulsar wind cone is also initially directed to the left, which corresponds to the periastron-apastron direction. The adopted orbital period is $T_{\text{orb}} = 16.6$ days, and the stellar masses are $M_{\text{MS}} = 31$ M$_\odot$ and $M_{\text{PSR}} = 1.44$ M$_\odot$ for the star and the pulsar, respectively, so from Kepler’s
third law the corresponding orbital semi-major axis is \( a = 6 \times 10^{12} \text{ cm} \). During the simulation, the \( \phi \)-intervals within which the pulsar and the stellar winds are injected rotate along the orbit with the pace and sense of the corresponding orbital velocity. The studied cases have orbit eccentricities \( e = 0, 0.25, 0.5 \) and 0.75. Simulations with even larger \( e \)-values can be found in Barkov and Bosch-Ramon (2016); Bosch-Ramon et al. (2017); Barkov and Bosch-Ramon (2018). These \( e \)-values are characteristic of the different known high-mass gamma-ray binaries, although we note that a pulsar has been confirmed to be present only in PSR B1259−63 and PSR J2032+4127 (e.g. Aharonian et al. 2005; Lyne et al., 2015). On the other hand, the simulated orbital period is significantly shorter than those of HESS J0632+057, PSR B1259−63 and PSR J2032+4127. This was done as previous studies already explored cases with long periods (Barkov and Bosch-Ramon, 2016; Bosch-Ramon et al., 2017; Barkov and Bosch-Ramon, 2018). It is worth noting that the asymmetry of the interaction structure on large scales should not depend significantly on \( T_{\text{orb}} \), because what characterizes this asymmetry is the relative change with \( \phi \) of the shocked pulsar wind energy rate along the orbit, which is independent of \( T_{\text{orb}} \). We note that a potential \( v_\phi \) component of the stellar wind would affect the angular distribution of the flow, but since \( v_\phi \propto 1/R \) this component will become negligible at \( R \gg R_{\text{min}} \).

3 Results

Maps of the density distributions and the velocity vector fields in the orbital plane are presented in Fig. 1 for the different eccentricities studied. Regardless of the eccentricity, the spiral structure starts to disrupt after one orbital turn, and after 2-3 orbital turns, spiral structure disruption leaves a more or less uniform medium with randomly located density and velocity irregularities. In particular, the velocity field shows spiral motion in the first turns and, farther away from the system, it mostly shows a radial outflow. Asymmetry of the interaction structure on the orbital plane starts to become significant for \( e \gtrsim 0.5 \). In the case of \( e = 0.75 \), the effect becomes extreme, with the density (velocity) in the periastron-apastron direction being much smaller (larger) than in the other directions. For \( e = 0.5 \), this effect is also present, but not so strong. A fluid property used to track fluid motion – the tracer behavior, shown in Fig. 2 – is similar to that of the density, and one can see there as well that the spiral structure disappears after 2-3 orbital turns regardless of eccentricity. The higher the \( e \)-value, the more prominent the pulsar wind becomes in the periastron-apastron direction. The pressure spatial distribution is presented in Fig. 3 showing the same trends as density and tracer. In addition, pressure shows a smooth drop after spiral structure disruption. As for density and tracer, the main difference between cases with low and high eccentricities is that pressure falls anisotropically, its decrease being slightly shallower in the periastron-apastron direction when \( e \) is large enough.

We averaged, weighting in mass, the radial velocity and the Mach number in three \( \phi \)-ranges, or sectors: s1, with \( \phi_{s1} \in [150^\circ, 210^\circ] \); s2, with \( \phi_{s2} \in [290^\circ, 350^\circ] \); and s3, with \( \phi_{s3} \in [60^\circ, 120^\circ] \). We also performed the mass-weighted average of the radial velocity in \( R \), where \( R \in [350a, 435a] \). The mass-weighted value,
Figure 1: Maps for the whole computational domain of the logarithm of the density distribution on the orbital plane by color, with colored arrows representing the velocity field, for different eccentricities: $e = 0$ (top-left panel); $e = 0.25$ (top-right panel); $e = 0.5$ (bottom-left panel); and $e = 0.75$ (bottom-right panel). The radius of the circular grid region shown is $1000(1 - e^2)a$, and units of the legend scales are $a = 6 \times 10^{12}$ cm. The periastron-apastron direction is to the left.
Figure 2: The same as in Fig. 1 but for tracer, where 1 and -1 correspond to the injected pulsar and stellar winds, respectively.
Figure 3: The same as in Fig. but for pressure.
averaged over a certain $R$- or $\phi$-range, was calculated as

$$< q(\phi) > = \frac{\int_{R \in [R_1, R_2]} q(R, \phi) \rho(R, \phi) dR}{\int_{R \in [R_1, R_2]} \rho(R, \phi) dR}$$

(3)

and

$$< q(R) > = \frac{\int_{\phi \in sX} q(R, \phi) \rho(r, \phi) d\phi}{\int_{\phi \in sX} \rho(r, \phi) d\phi}$$

(4)

respectively, where $\rho$ is density, $q$ the value being averaged, and $sX$ the corresponding sector.

The radial distributions of $v_r$ averaged over $s1$, $s2$, and $s3$, at simulation time $T = 1.11 \times 10^5$ are presented in Fig. 4. We note that time in this work is given in simulation units, which are $\left(\frac{a}{c}\right) = 200$ s and are implicit. The figure includes the case for $s1$ at $T = 1.09 \times 10^5$ as well to illustrate short-term variability on top of the longer term behavior. Independently of the eccentricity, there are strong spatial variations in the radial velocity up to $R \sim 300 a$ that are related to the spiral interaction structure. Beyond $R \sim 300 a$, there is a gradual acceleration of the flow, which is at that point already made of a mixture of pulsar and stellar winds. This acceleration is equally prominent for all sectors when $e = 0$, although the higher the eccentricity, the stronger the acceleration becomes for $s1$, around the periastron-apastron direction, and weaker for $s2$ and $s3$. This is also seen in Fig. 5, which displays the dependence of the sector-averaged $v_r$ with $e$ at $R = 400 a$. In general, the acceleration slows down at $R \sim 400 - 600 a$ depending on $e$, which is expected as the flow becomes highly supersonic. In Fig. 6, the radial distribution of averaged Mach number is also shown. At smaller radii, $R \lesssim 300 a$, large variations of this quantity are related to the spiral structure, whereas at larger radii the flow averaged Mach number approaches $\sim 6$ (being still strongly variable for high $e$). Despite the shallower drop of pressure in $s1$ shown above (see Fig. 5), $v_r$ grows faster in that direction because more energy is invested in the flow motion whereas the average density is lower.

To illustrate the temporal evolution of the system, color maps of sector-averaged radial velocity and Mach number in the $R$ ($y$-axis) versus $T$ ($x$-axis) plane are presented in Figs. 7 and 8 respectively. These maps show two different colour regions that indicate the transition at $R < 300 a$ from a spiral structure to a more homogeneous, mixed, outflow at larger radii. This effect is very prominent in all directions for low eccentricities, both in averaged $v_r$ and Mach number, whereas for high eccentricities the same effect is much more prominent in $s1$ (around the periastron-apastron direction) than in $s2$ and $s3$ for $v_r$, whereas for Mach number the opposite happens, although less dramatically. The slower increase in the $s1$-averaged Mach number for high $e$-values is related to the presence of shocks that reheat the flow. The contrast of shocked flow behavior depending on $e$ is also illustrated in Fig. 5 which shows the whole $\phi$-averaged in sector $s1$ $v_r$ versus $T$ at $R = 400 a$ for different eccentricities. The velocity jumps grow with eccentricity and became more pronounced for $e \geq 0.5$.

The radial velocity, averaged over $R$ in the interval $[350 a, 435 a]$, versus $\phi$ is shown in Fig. 10. The radial velocity is also color mapped on the $\phi$ ($y$-axis) versus $T$ ($x$-axis) plane in Fig. 11. Consistently with previous figures, one sees that the low $e$ cases present a quasi-isotropic flow with significant stochastic
Figure 4: Radial velocity, averaged over sectors $s_1$, $s_2$ and $s_3$, versus $R$ and different orbital eccentricities: $e = 0$ (left top panel); $e = 0.25$ (right-top panel); $e = 0.5$ (left-bottom panel); and $e = 0.75$ (right-bottom panel). An additional curve for the $s_1$ case at a slightly earlier time, is also shown to illustrate the quick variability of the flow properties on top of its longer term behavior.

behavior on top of the longer term behavior, whereas high $e$-cases show faster flows concentrate around the periastron-apastron direction ($\phi = \pi$).

4 Summary and discussion

In this article, we have presented a detailed analysis of the results obtained by the simulation of colliding pulsar and stellar winds. For the first time, cases with different eccentricities are systematically explored, so the impact of this prediction can be assessed. The further development of these models should impact the studies of very powerful sources such as HMPB or microquasars (Dubus et al., 2010; Zdziarski et al., 2018; Sinitsyna and Sinitsyna, 2021; Massi et al., 2020). We note that the first simulation of a jet-stellar wind interaction in a microquasar along a full orbit has been already done in Barkov and Bosch-Ramon (2022).

The evolution of the shocked pulsar and stellar winds was studied analytically in Bosch-Ramon and Barkov (2011). The mixed-wind eventual velocity
Figure 5: Radial velocity, averaged over sectors s1, s2 and s3 at $R = 400a$, versus orbital eccentricity.

Figure 6: The same as in Fig. 5 but for Mach number.
Figure 7: Color map of $v_r$ (in light speed units), averaged over sectors s1, s2 and s3, in the $R$ ($y$-axis) versus $T$ ($x$-axis) plane. Rows from top to bottom correspond to $e = 0$, 0.25, 0.5 and 0.75, and columns from left to right to s1, s2 and s3.
Figure 8: The same as in Fig. 7 but for Mach number.

Figure 9: Radial velocity, averaged over s1, versus $T$ at $R = 400a$ for different eccentricities.
Figure 10: Radial velocity, averaged over $R$ in the interval $[350a, 435a]$, versus $\phi$ for different eccentricities.

Figure 11: Map of $v_r$, averaged over $R$ in the interval $[350a, 435a]$, in the $\phi$ ($y$-axis) versus $T$ ($x$-axis) plane, at $R = 400a$, for different eccentricities: $e = 0$ (left-top panel); $e = 0.25$ (right-top panel); $e = 0.5$ (left-bottom panel); and $e = 0.75$ (right-bottom panel).
away (expel) from the binary can be estimated as:

\[ v_{\text{exp}} = \sqrt{\frac{2L_{\text{sd}}}{M_w}} \approx 0.04 \, c \eta^{-1/2}; \]  

(5)

where \( \eta_{-1} = \eta/10^{-1} \), and our numerical results, \( v_{\text{exp}} = 0.40 \pm 0.03 \, c \) (see Fig. 1), confirm this prediction.

In our numerical calculations, we find that the shocked flow structure on large scales is a slowly-accelerating, supersonic mixture of shocked stellar and pulsar winds, with an approximately isotropic propagation in \( \phi \). We note that the simulations could not properly probe the expansion in \( \theta \) due to low resolution, although 3D simulations by Bosch-Ramon et al. (2015) suggest that on scales \( \gg a \) the shocked structure can become wider in that direction than conical expansion predicts because of internal energy confinement. The present work also shows that this mixed supersonic wind is very clumpy in density and velocity, so particle acceleration may easily occur in such an environment.

Our results are fully consistent with those obtained by Barkov and Bosch-Ramon (2016); Bosch-Ramon et al. (2017), who showed for the first time the dramatic impact that eccentricity can have on the evolution of the shocked flows on large scales (non-thermal processes were discussed in Barkov and Bosch-Ramon 2018). In addition to that, the present work also characterizes the eccentricity of a transition between an approximately isotropic supersonic wind, made of shocked stellar and pulsar wind (for small \( e \)), and a sort of two-component structure, one fast, light and collimated, directed along the periastron-apastron direction, and the other slow, dense and broad, directed elsewhere (for high \( e \)). In particular, we find that the transition is somewhere between \( e = 0.5 \) and 0.75, probably close to the latter.

As mentioned in Sect. 2, our results should not be sensitive to the orbital period on large scales. This implies that at a semi-quantitative level, our predictions can be extrapolated to wider systems. However, higher accuracy in the estimate of the eccentricity associated to a structure geometry transition requires fully 3D calculations. On the other hand, the magnetic field could also play an important role in the evolution of the shocked flows, and should be included in future stages of this research. Moreover, future numerical work should tackle the issue of how the shocked mixed flows interact with the interstellar medium, both in the low \( e \) (see Bosch-Ramon 2011 for analytical predictions) and the high \( e \) regimes. Finally, the consequences of the eccentricity dependence of the shocked flow evolution with respect to non-thermal emission should be studied in more detail than what has been done so far.

All authors have read and agreed to the published version of the manuscript. Barkov M. performed the numerical simulation and data analysis. Bosch-Ramon and Barkov worked on the text of the manuscript.

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Data availability
The original data and its analysis can be requested by email.

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References
Dubus, G. Gamma-ray binaries and related systems. *A&A Rev* 2013, 21, 64, [arXiv:astro-ph.HE/1307.7083] doi:10.1007/s00159-013-0064-5.

Paredes, J.M.; Bordas, P. Phenomenology of gamma-ray emitting binaries. *arXiv e-prints* 2019, p. [arXiv:1902.09898] [arXiv:astro-ph.HE/1902.09898].

Paredes, J.M.; Bordas, P. Broad-band Emission from Gamma-ray Binaries. Frontier Research in Astrophysics - III. 28 May - 2 June 2018. Mondello (Palermo, 2019, p. 44, [arXiv:astro-ph.HE/1901.03624].

Tavani, M.; Arons, J. Theory of High-Energy Emission from the Pulsar/Be Star System PSR 1259-63. I. Radiation Mechanisms and Interaction Geometry. *ApJ* 1997, 477, 439–464, [arXiv:astro-ph/astro-ph/9609086]. doi:10.1086/303676.

Sierpowska, A.; Bednarek, W. γ-rays from cascades in close massive binaries containing energetic pulsars. *MNRAS* 2005, 356, 711–726, [arXiv:astro-ph/astro-ph/0410304] doi:10.1111/j.1365-2966.2004.08490.x.

Dubus, G. Gamma-ray binaries: pulsars in disguise? *A&A* 2006, 456, 801–817, [arXiv:astro-ph/astro-ph/0605287] doi:10.1051/0004-6361:20054779.

Neronov, A.; Chernyakova, M. Radio-to-TeV γ-ray emission from PSR B1259-63. *Ap&SS* 2007, 309, 253–259, [arXiv:astro-ph/0610139] doi:10.1007/s10509-007-9454-3.

Khangulyan, D.; Hnatic, S.; Aharonian, F.; Bogovalov, S. TeV light curve of PSR B1259-63/SS2883. *MNRAS* 2007, 380, 320–330, [arXiv:astro-ph/0605663] doi:10.1111/j.1365-2966.2007.12075.x.

Kong, S.W.; Cheng, K.S.; Huang, Y.F. Modeling the Multiwavelength Light Curves of PSR B1259-63/LS 2883. II. The Effects of Anisotropic Pulsar Wind and Doppler Boosting. *ApJ* 2012, 753, 127, [arXiv:astro-ph.HE/1205.2147] doi:10.1088/0004-637X/753/2/127.
Zabalza, V.; Bosch-Ramon, V.; Aharonian, F.; Khangulyan, D. Unraveling the high-energy emission components of gamma-ray binaries. *A&A* 2013, *551*, A17, [arXiv:astro-ph.HE/1212.3222] doi:10.1051/0004-6361/201220589

Dubus, G.; Lamberts, A.; Fromang, S. Modelling the high-energy emission from gamma-ray binaries using numerical relativistic hydrodynamics. *A&A* 2015, *581*, A27, [arXiv:astro-ph.HE/1505.01026] doi:10.1051/0004-6361/201425394

Molina, E.; Bosch-Ramon, V. A dynamical and radiation semi-analytical model of pulsar-star colliding winds along the orbit: Application to LS 5039. *A&A* 2020, *641*, A84, [arXiv:astro-ph.HE/2007.00543] doi:10.1051/0004-6361/202038417

Huber, D.; Kissmann, R.; Reimer, O. Relativistic fluid modelling of gamma-ray binaries. II. Application to LS 5039. *A&A* 2021, *649*, A71, [arXiv:astro-ph.HE/2103.00995] doi:10.1051/0004-6361/202039278

Lyutikov, M.; Barkov, M.V.; Giannios, D. FRB Periodicity: Mild Pulsars in Tight O/B-star Binaries. *ApJ* 2020, *893*, L39, [arXiv:astro-ph.HE/2002.01920] doi:10.3847/2041-8213/ab87a4

Khangulyan, D.; Barkov, M.V.; Popov, S.B. High-frequency radio synchrotron maser emission from relativistic shocks. *arXiv e-prints* 2021, p. arXiv:2106.09858 [arXiv:astro-ph.HE/2106.09858].

Bogovalov, S.V.; Khangulyan, D.V.; Koldoba, A.V.; Ustyugova, G.V.; Aharonian, F.A. Modelling interaction of relativistic and non-relativistic winds in binary system PSR B1259-63/SS2883 - I. Hydrodynamical limit. *MNRAS* 2008, *387*, 63–72, [arXiv:astro-ph.HE/0710.1961] doi:10.1111/j.1365-2966.2008.13226.x

Eichler, D.; Usoskin, G. Particle Acceleration and Nonthermal Radio Emission in Binaries of Early-Type Stars. *ApJ* 1993, **402**, 271. doi:10.1086/172130

Bosch-Ramon, V.; Barkov, M.V.; Perucho, M. Orbital evolution of colliding star and pulsar winds in 2D and 3D: effects of dimensionality, EoS, resolution, and grid size. *A&A* 2015, *577*, A89, [arXiv:astro-ph.HE/1411.7892] doi:10.1051/0004-6361/201425228

Bogovalov, S.V.; Khangulyan, D.; Koldoba, A.V.; Ustyugova, G.V.; Aharonian, F.A. Modelling the interaction between relativistic and non-relativistic winds in the binary system PSR B1259-63/SS2883- II. Impact of the magnetization and anisotropy of the pulsar wind. *MNRAS* 2012, **419**, 3426–3432, [arXiv:astro-ph.HE/1107.4831] doi:10.1111/j.1365-2966.2011.19983.x

Bosch-Ramon, V.; Barkov, M.V.; Mignone, A.; Bordas, P. HESS J0632+057: hydrodynamics and non-thermal emission. *MNRAS* 2017, **471**, L150–L154, [arXiv:astro-ph.HE/1708.00066] doi:10.1093/mnrasl/slx124

Barkov, M.V.; Bosch-Ramon, V. A hydrodynamics-informed, radiation model for HESS J0632 + 057 from radio to gamma-rays. *MNRAS* 2018, **479**, 1320–1326, [arXiv:astro-ph.HE/1806.05629] doi:10.1093/mnras/sty1661
Barkov, M.V.; Bosch-Ramon, V. The origin of the X-ray-emitting object moving away from PSR B1259-63. *MNRAS* 2016, 456, L64–L68, [arXiv:astro-ph.HE/1510.07764](https://arxiv.org/abs/1510.07764) doi:10.1093/mnrasl/slv171

Mignone, A.; Bodo, G.; Massaglia, S.; Matsakos, T.; Tesileanu, O.; Zanni, C.; Ferrari, A. PLUTO: A Numerical Code for Computational Astrophysics. *ApJS* 2007, 170, 228–242, [arXiv:astro-ph/0701854](https://arxiv.org/abs/astro-ph/0701854) doi:10.1086/513316

Li, S. An HLLC Riemann solver for magneto-hydrodynamics. *Journal of Computational Physics* 2005, 203, 344–357. doi:10.1016/j.jcp.2004.08.020

Bosch-Ramon, V.; Barkov, M.V.; Khangulyan, D.; Perucho, M. Simulations of stellar/pulsar-wind interaction along one full orbit. *A&A* 2012, 544, A59, [arXiv:astro-ph.HE/1203.5528](https://arxiv.org/abs/1203.5528) doi:10.1051/0004-6361/201219251

Aharonian, F.; Akhperjanian, A.G.; Aye, K.M.; et al.. Discovery of the binary pulsar PSR B1259-63 in very-high-energy gamma rays around periastron with HESS. *A&A* 2005, 442, 1–10, [arXiv:astro-ph/0506280](https://arxiv.org/abs/astro-ph/0506280) doi:10.1051/0004-6361:20052983

Lyne, A.G.; Stappers, B.W.; Keith, M.J.; Ray, P.S.; Kerr, M.; Camilo, F.; Johnson, T.J. The binary nature of PSR J2032+4127. *MNRAS* 2015, 451, 581–587, [arXiv:astro-ph.HE/1502.01465](https://arxiv.org/abs/1502.01465) doi:10.1093/mnras/stv236

Dubus, G.; Cerutti, B.; Henri, G. The relativistic jet of Cygnus X-3 in gamma-rays. *MNRAS* 2010, 404, L55–L59, [arXiv:astro-ph.HE/1002.3888](https://arxiv.org/abs/1002.3888) doi:10.1111/j.1745-3933.2010.00834.x

Zdziarski, A.A.; Malyshev, D.; Dubus, G.; Pooley, G.G.; Johnson, T.; Frankowski, A.; De Marco, B.; Chernyakova, M.; Rao, A.R. A comprehensive study of high-energy gamma-ray and radio emission from Cyg X-3. *MNRAS* 2018, 479, 4399–4415, [arXiv:astro-ph.HE/1804.07460](https://arxiv.org/abs/1804.07460) doi:10.1093/mnras/sty1618

Sinitsyna, V.G.; Sinitsyna, V.Y. Cyg X 3: A gamma ray binary. *Astronomische Nachrichten* 2021, 342, 337–341. doi:10.1002/asna.202113930

Massi, M.; Chernyakova, M.; Kraus, A.; Malyshev, D.; Jaron, F.; Kiehlmann, S.; Dzib, S.A.; Sharma, R.; Migliari, S.; Readhead, A.C.S. Evidence for periodic accretion-ejection in LS I +61°303. *MNRAS* 2020, 498, 3592–3600, [arXiv:astro-ph.HE/2010.08598](https://arxiv.org/abs/astro-ph.HE/2010.08598) doi:10.1093/mnras/staa2623

Barkov, M.V.; Bosch-Ramon, V. Relativistic hydrodynamical simulations of the effects of the stellar wind and the orbit on high-mass microquasar jets. *MNRAS* 2022, 510, 3479–3494, [arXiv:astro-ph.HE/2112.04202](https://arxiv.org/abs/astro-ph.HE/2112.04202) doi:10.1093/mnras/stab3609

Bosch-Ramon, V.; Barkov, M.V. Large-scale flow dynamics and radiation in pulsar γ-ray binaries. *A&A* 2011, 535, A20, [arXiv:astro-ph.HE/1105.6236](https://arxiv.org/abs/astro-ph.HE/1105.6236) doi:10.1051/0004-6361/201117235

Bosch-Ramon, V. Radio emission from high-mass binaries with non-accreting pulsars. *ArXiv e-prints* 2011, [arXiv:astro-ph.HE/1103.2996](https://arxiv.org/abs/astro-ph.HE/1103.2996)