Doppler-boosting emission from a high-mass gamma-ray binary with a non-accreting pulsar

Author: Ariadna Gutiérrez Arbonés
*Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.**

Advisor: Dr. Valentí Bosch-Ramon

Abstract: Gamma-ray binaries are bright sources of γ-ray emission in the Galaxy. Here, we study the Doppler-boosting effects on the radiation from these sources in a simplified scenario. By modelling the structure of the shocked stellar and pulsar winds, we study the changes in the observed luminosity with variations in the orbital phase and in the angle with respect to the structure symmetry axis. The obtained results show how the orbital position of the pulsar, and the orientation of the observer, affect the radiation that can be observed.

I. INTRODUCTION

Gamma-ray binaries are astrophysical systems characterized by their very-high-energy emission. They are formed by a massive star and a compact object, which in our case is a pulsar. The pulsar loses rotational energy through the emission of relativistic particles and electromagnetic waves, which both can be considered components of the pulsar's relativistic wind. The star also generates a strong wind. The stellar and the pulsar winds interact shocking each other and that are separated by a surface called Contact Discontinuity (CD) (see the thick solid line in Fig. 1).

Gamma-ray binaries are sources of γ-ray, X-ray and radio emissions from the shock of the relativistic wind of the pulsar formed at the interaction with the non-relativistic stellar wind [1]. Relativistic electrons accelerated at the pulsar wind termination shock interact via inverse-Compton scattering with the optical photons from the star, which is the reason why there is γ-ray emission. These electrons also produce synchrotron emission interacting with the magnetic field [2].

Because of the interaction of the stellar and pulsar winds, a shocked flow structure is formed around the pulsar. For simplicity, we consider here that this structure has the same shape as the CD. Due to the relativistic nature of the pulsar wind, the radiation from the shocked pulsar wind will be affected by Doppler-boosting [3], which is the main focus of our study.

II. PHYSICAL SCENARIO

The binary system we are studying is composed by a massive star and a pulsar of spin-down luminosity of $L_{sd} = 10^{37}$ erg/s. The pulsar orbit around the star is considered circular with a radius of $D = 3 \cdot 10^{12}$ cm, which is the binary separation distance (see Fig. 1). This orbit is an approximation valid for moderately ellyptic systems, and it is adopted in order to simplify calculations.

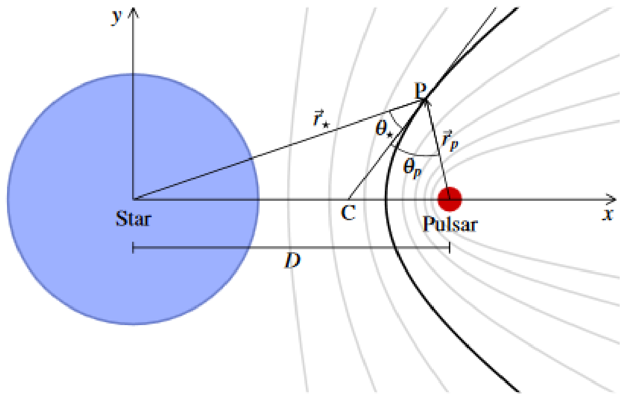

FIG. 1: Two-dimensional visualization of the system. Adapted from Zabalza, Bosch-Ramon & Paredes 2011 [4].

The coefficient η is the ratio between the momentum rate of the pulsar wind and the momentum rate of the stellar wind:

$$\eta(x, y) \equiv \frac{L_{sd} \backslash c}{\dot{M} v(r_\star)} \tag{1}$$

We assume that both winds are radial and isotropic. The components of the ram pressure perpendicular to the CD are in equilibrium on this surface.

Because the spin-down luminosity is the measured loss rate of the rotational energy, we assume it is the power of the relativistic pulsar wind. In addition, we assume a typical mass-loss rate and velocity of the stellar wind of $\approx 3 \cdot 10^{-7}$ $M_\odot$/s and 2000 km/s, respectively. In consequence, a spin-down luminosity of 10^{37} erg/s means $\eta \approx 0.1$. The used parameter values are not very

*Electronic address: agutiear7@alumnes.ub.edu

different from those of real known systems [5].

The reason why the pulsar wind becomes relativistic very quickly after being shocked is because there is a gradient of pressure that produces a force, which means that there is an acceleration of the particles of the wind [6]. As mentioned before, electrons emit energy via inverse-Compton scattering and synchrotron radiation. This radiation is affected by Doppler-boosting due to the relativistic nature of the electrons of the pulsar wind.

Our radiative model is simple, and we do not specify the emission synchrotron or inverse-Compton. We assume that particles homogeneously cover the emitting fluid lines. They also radiate uniformly, which implies that each segment of the emiting fluid lines along the CD has the same radiative properties. We assume that on average particles lose a 10% of their energy when they leave the emission region. Doppler-boosting introduces strong changes in luminosity [7]:

$$L_{obs} = \frac{\delta^3}{\gamma} L' \tag{2}$$

where L' is the luminosity in the reference frame of the fluid, δ is the fluid Doppler factor (see below), and γ the Lorentz factor.

III. CALCULATIONS

We adopt the condition $p_{\star\perp} = p_{p\perp}$, and the symmetries of our system. The shape of the CD on the xy-plane is obtained using a method of numerical integration called Runge-Kutta for Equation (3) below [4], where x and y represent the coordinates of each point in relation to the center of the star; $r_\star$ and r_p are the distance to each point in the structure from the center of the star and from the center of the pulsar, respectively, as shown in Fig. 1. We considered $\eta = 0.1$, as mentioned in the previous section.

$$\frac{dx}{dy} = \frac{1}{y}\left[x - \frac{D r_\star^2(x,y)\sqrt{\eta(x,y)}}{r_\star^2(x,y)\sqrt{\eta(x,y)} + r_p^2(x,y)}\right] \tag{3}$$

Regarding the boundary conditions, we imposed that $x_0 = D/(1+\sqrt{\eta})$, which is obtained from the continuity of the derivative when y tends to zero: $(dx/dy)_{y\to 0} \to 0$.

Once we obtained $x(y)$ using the method of Runge-Kutta, we converted the one-dimensional structure of the CD into a two-dimensional surface. In order to do so, we assumed cylindrical symmetry in our system. We maintained the same values for x, whereas for each y value we obtained two different quantities by multiplying the mentioned y values by the sine and the cosine of a cylindrical angle α. This angle corresponds to $\alpha = n \cdot 2\pi/500$ where n is the number of steps. We repeated this process 500 times in order to obtain an equally-spaced well sampled distribution of emitting lines on the two-dimensional surface. Such a high number of iterations is meant to reduce the noise in the results as much as possible.

Then, we proceeded to study the changes in the observed luminosity of the structure caused by the variation of ϕ (orbital phase) and θ (angle with respect to the normal of the orbit inclination). The orbital phase, ϕ, is defined in the range [0,1], whereas i is defined in [0°,180°].

We model the Line Of Sight (LOS), which we rotate along the orbit instead of the whole structure. As is shown in Equation (4), the LOS has a dependence with the orbital phase: $\varphi = 2\pi\phi$, which is the azimuthal angle.

$$\widehat{n} = (cos(\varphi)sin(i), sin(\varphi)sin(i), cos(i)) \tag{4}$$

To compute the observed luminosity we used Equation (5), which is a variation of Equation (2), where δ_i is the Doppler factor for each one of the N segments of the structure (Equation 6) and L_{sd} is the spin-down luminosity of the pulsar. In our system, the Lorentz factor is fixed: γ= 10 [6], which at the same time determines the value of β.

$$L_{obs} = \frac{0.1{\cdot}L_{sd}}{\gamma^3}\frac{\sum_{i=1}^{N}\delta_i^3}{N} \tag{5}$$

$$\delta = \frac{1}{\gamma(1-\beta cos\theta_{obs})} \tag{6}$$

Here, θ_{obs} is the angle between the velocity of the particles of the structure and the LOS.

To obtain the dependence of the luminosity with ϕ and i, we varied the orbital phase for different i-values. We also computed the dependence with θ, which is the angle with respect to the symmetry axis of the CD.

IV. RESULTS

The shape of the Contact Discontinuity we obtained from converting the results of the integration of Equation (3) into a cylindrical structure is a cone-like struture with the x-axis as symmetry axis (Fig. 2).

When the pulsar is in its inferior conjunction ($\phi = 0$ or $\phi = 1$), the observed luminosity is in its maximum. However, when the pulsar is in its superior conjunction ($\phi = 0.5$), L_{obs} is in its minimum, for the cases with a low value of i (Fig. 3). However, this does not occur for $i = 60°$ and $90°$. In these two cases, there are two

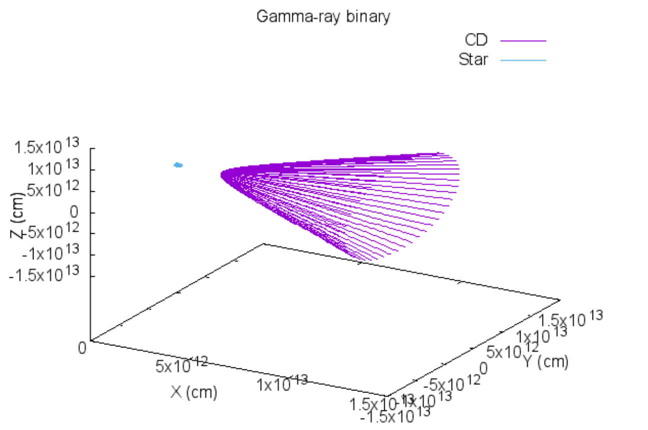

FIG. 2: Two-dimensional structure of the CD with a reduced number of lines to ease visualization.

maximums and two minimums. This is due to the fact that for high values of i, the LOS crosses twice the boundaries of the cone-like structure of the CD along the orbit. It is worthy to emphasise the fact that when the pulsar is in the nodes of its orbit ($\phi = 0.25$ and $\phi = 0.75$), L_{obs} is the same for all values of i.

We display two full orbits of the pulsar around the massive star. A strong symmetry in the lightcurve around the inferior conjunction is clearly visible (Fig. 3).

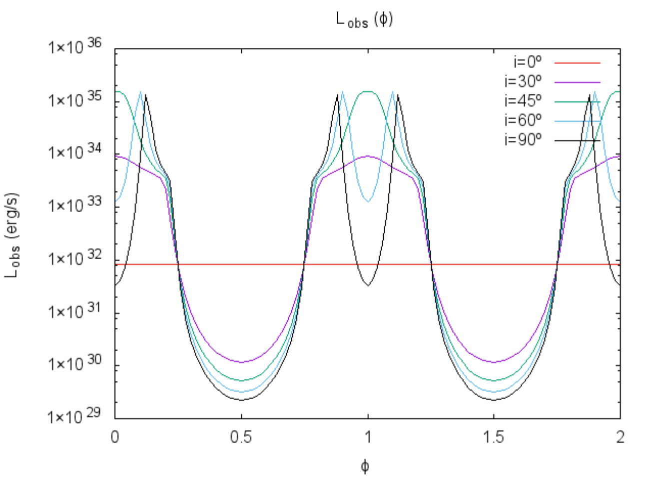

FIG. 3: Dependence of the observed luminosity with the orbital phase for several values of i, for two full orbits around the star.

As for the dependence of L_{obs} with θ, its behaviour is similar to the one shown in Fig. 3 for the case of $\theta = 90°$ for the interval $[0, 0.5]$. It has a maximum in $\theta = 45°$ and two minimums: one relative minimum when the angle is null (LOS pointing along the symmetry axis) and the absolute one when θ has its maximum value ($\theta = 180°$, LOS pointing in the opposite direction) (Fig. 4).

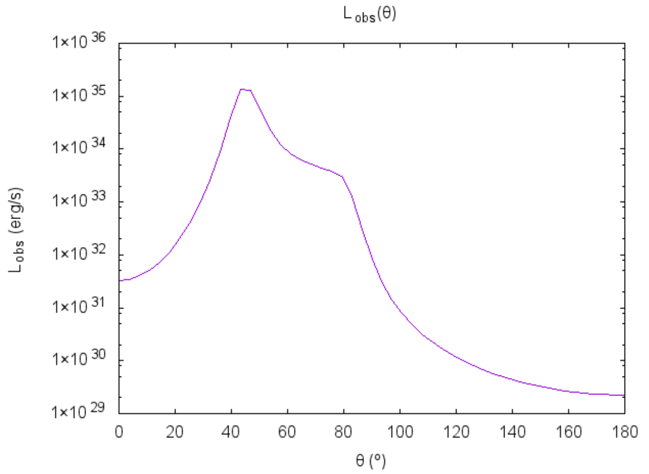

FIG. 4: Dependence of the observed luminosity with the angle with respect to the structure symmetry axis (θ).

Because the shape of the CD is a two-dimensional surface, our results differ from the ones obtained from a jet or a linear emitter along the symmetry axis. The dependence of L_{obs} with ϕ for a jet is always the same: one maximum and one minimum, except for the case where $\theta = 0°$, which gives a constant lightcurve (Fig. 5). These differences are obtained for the CD for low values of i, because when we rotate the LOS we do not cross the boundaries of the structure. The most visual difference is in the dependence of L_{obs} with θ. For a jet, L_{obs} starts with a maximum when θ has its minimum value, it decreases strongly, and reaches a minimum when θ is at its maximum value (Fig. 6). Our results (Fig. 4) resemble the fast decrease only when $\theta > 100°$.

V. CONCLUDING REMARKS

The Doppler-boosting effects in the radiation of gamma-ray binaries are important and need to be taken into account. The emitter geometry renders a lightcurve more complex than that of a jet, with symmetry around inferior conjunction for large i-values.

Our simplification of the model gives us a cone-like structure which appears to be a reasonably good approximation of the obtained results for the Contact Discontinuities in more complex studies close to the binary [8] (see Fig 2).

Doppler-boosting effects appear to add to other factors that give variability to this kind of systems.

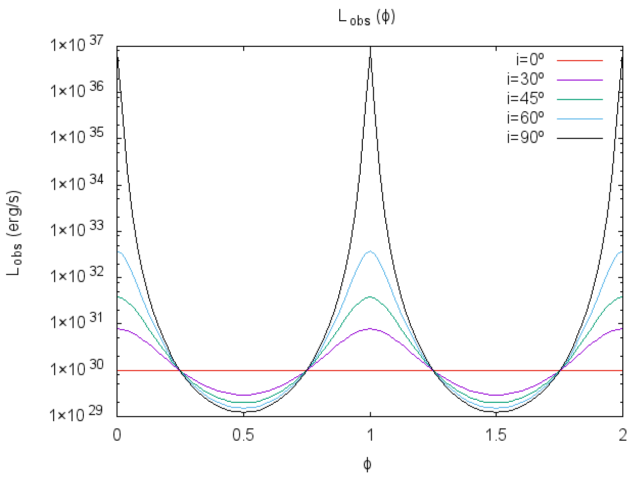

FIG. 5: Dependence of the observed luminosity with the orbital phase for several values of i, for two full orbits around the star, for a jet.

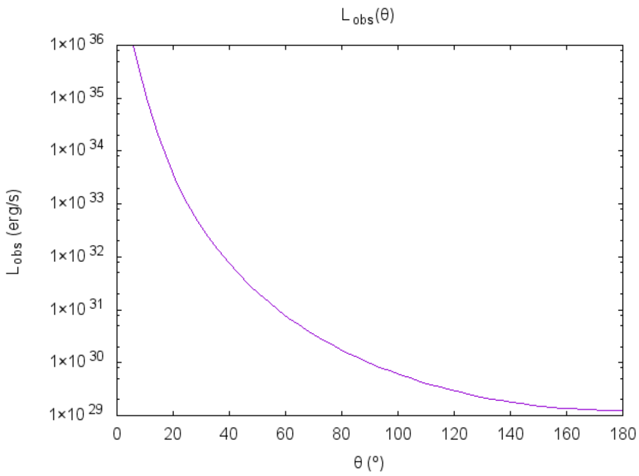

FIG. 6: Dependence of the observed luminosity with the angle with respect to the structure symmetry axis (θ) for a jet.

However, Doppler boosting could be dominant shaping the lightcurve.

We have found a resemblance between the behaviour of $L_{obs}(\phi)$ for $i = 90°$ and $L_{obs}(\theta)$. It is due to the fact that in that case both, LOS and CD, have cylindrical symmetry around the symmetry axis.

In order to obtain as little noise as possible in our results, we increased the number of iterations, which, in consequence, increased the run time of the program. Even though that for our purposes it worked fine, if we were to make a more sophisticated research, the code of the program would need to be improved. The same could be said for all the approximations that we used in this project. However, the obtained results are reasonable and similar to the ones obtained in real systems (see [5]).

Acknowledgments

I would like to thank my advisor, Dr. Valentí Bosch-Ramon, for his guidance and valuable advice; and for providing clarifications whenever I needed them and for always believing in me.

I would also like to thank my friends and family for their never-ending support and for the fact that they never doubted I could finish this project, despite the difficulties I encountered along the way.

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