CONSTRAINING THE PULSAR POWER IN GAMMA-RAY BINARIES THROUGH THERMAL X-RAY EMISSION

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Gamma-ray binaries are binary systems that show non-thermal broadband emission from radio to gamma rays. If the system comprises a massive star and a young non-accreting pulsar, their winds collide producing non-thermal emission, most likely from the shocked pulsar wind. Thermal X-rays are expected from the shocked stellar wind, with a spectrum akin to the one observed in massive star binaries. The goal of this work is, through the study of the thermal X-ray emission from the shocked stellar wind in pulsar gamma-ray binaries, constrain the pulsar spin-down luminosity and the stellar wind properties. A semi-analytic model is developed to compute the thermal X-ray emission from the shocked stellar wind in pulsar gamma-ray binaries. The model results are compared with XMM-Newton observations of LS 5039, a candidate pulsar gamma-ray binary with a strong stellar wind. Exploring the range of possible values for the stellar mass-loss rate and orbital inclination, we obtain an upper limit on the pulsar spin-down luminosity of $6 \times 10^{36} \text{ erg s}^{-1}$. We conclude that, to explain the non-thermal luminosity of LS 5039 in the pulsar wind scenario, a non-thermal to spin-down luminosity ratio very close to unity may be required.

Keywords: gamma rays: stars; stars: individual (LS 5039); stars: winds, mass-loss; X-rays: binaries

1. Introduction

In the past few years, gamma-ray binaries have emerged as a new category of very high-energy (VHE, $E > 100 \text{ GeV}$) gamma-ray sources. In most of the cases, they comprise a stellar mass compact object orbiting a young, massive star.

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They generally differ from typical X-ray binaries in that they exhibit luminosities at gamma-ray energies at levels similar or above their X-ray luminosity. Five such sources have been already detected: LS 5039¹, PSR B1259–67², LSI+61 303³, HESS J0632+057⁴, and 1FGL J1018.6–5856⁵. Evidence of VHE flaring emission has been found in Cygnus X-1⁶, but at present lacks confirmation.

Whereas the pulsar nature of the compact object in PSR B1259–67 is determined thanks to the detection of radio pulses, this is not possible in the case of LS 5039 and LSI+61 303, in which the radio pulses would be likely free-free absorbed in the stellar wind. Broadband radiation modeling in the microquasar scenario has been able to reproduce the spectral energy distribution of the source^{7,8}, but the lack of accretion signatures, and the similarities with PSR B1259–67, prompted other authors to consider the pulsar wind shock (PWS) scenario for these sources^{9,10,11}.

The emission from the non-thermal particle population accelerated in the PWS scenario has been widely studied in the radio, X-ray, and high energy (HE) and VHE gamma-ray bands^{10,12,13,14}. Furthermore, the possibility of detecting the free pulsar wind from its spectral signature has also been discussed^{14,15}. However, one of the sources of emission that could provide valuable information on the characteristics of gamma-ray binaries has been hitherto overlooked: the thermal X-ray emission from the shocked stellar wind. Here we present the results of a model for the thermal X-rays from pulsar gamma-ray binaries inspired on semi-analytical models of the X-ray emission from massive binary systems^{16,17}. This model, which allows the study of the dependence of the thermal X-ray emission for different stellar and pulsar wind properties, will be applied to the binary LS 5039 in order to constrain the spin-down luminosity of its putative pulsar.

2. The dynamical and emission model

In the PWS scenario, the pulsar wind and the stellar wind collide forming an interaction region bounded on either side by the reverse shocks of the winds. The shocked winds are separated by the contact discontinuity (CD), a surface where the perpendicular velocities of both winds are null. Its location can be approximated as the position where the ram pressure components perpendicular to this surface are in equilibrium: $p_{\star\perp} = p_{p\perp}$. The shape of the CD can be obtained from a purely dynamical point of view following, e.g., the procedure outlined in Ref. 16.

For a strong, steady, standing shock with a compression ratio $\rho_0/\rho_w = v_{w\perp}/v_{0\perp} = 4$ (where the subindices w and 0 indicate the properties of the gas immediately before and after the shock, respectively), the gas will have an immediate postshock temperature of $kT_0 = \frac{3}{16}\mu m_p v_{w\perp}^2$, where $v_{w\perp}$ indicates the preshock speed of the wind component perpendicular to the shock front and μ is the average atomic weight. A value of $\mu = 0.62$ is appropriate for a fully ionized medium with solar abundances¹⁸.

Assuming the shocked gas acts as a calorimeter, in which all the incoming perpendicular kinetic energy is either radiated away as X-ray emission or dissipated

through adiabatic expansion, the fraction of the kinetic energy converted into X-ray emission will be $L_X = (t_{\text{rad}}^{-1}) / (t_{\text{rad}}^{-1} + t_{\text{esc}}^{-1}) \times L_{\text{kin}}^{\text{sh}}$, where t_{rad} is the radiative cooling timescale, t_{esc} is the escape or flow dynamics timescale and $L_{\text{kin}}^{\text{sh}}$ is the incoming kinetic energy.

We used the MEKAL code as implemented in the SPEX software package¹⁹ to generate a look-up table of emission spectra for optically thin hot gas in collisional ionization equilibrium as a function of the gas temperature T . In order to compute the total cumulative emission from the shocked stellar wind we assumed that the X-ray emitter is infinitely thin and located on the CD. Using the method outlined above we computed the luminosity and spectrum of the intrinsic thermal emission and then computed its absorption owing to the stellar wind. The resulting cumulative absorbed spectrum was formatted as a table model to be used as input for an X-ray spectral fitting package.

3. Application of the model to LS 5039

The system LS 5039 is located at 2.5 ± 0.1 kpc and contains a compact object with a mass between 1.4 and $5 M_{\odot}$, orbiting an O6.5V((f)) donor star every 3.90603 ± 0.00017 days²⁰ in a mildly eccentric orbit ($e = 0.24 \pm 0.08$)²¹, with an orbital inclination in the range 20° – 70° ²⁰. The star has a stellar radius of $R_{\star} = 9.3 R_{\odot}$, and its wind has a terminal velocity of $v_{\infty} = 2400 \text{ km s}^{-1}$. The detection of elongated asymmetric emission in high-resolution radio images was interpreted as mildly relativistic ejections from a microquasar jet and prompted its identification with an EGRET HE gamma-ray source^{22,23}. However, recent Very Long Baseline Array observations show morphological changes on short timescales that might be consistent with a pulsar binary scenario²⁴. It shows variable periodic emission in the X-ray, and HE and VHE gamma-ray bands. The X-ray lightcurve has an orbital modulation²⁵, superposed by short timescale features that are quite stable over the years²⁶. The maximum and minimum emission phases in the periodic X-ray lightcurve are located around the inferior and superior conjunctions, so a geometrical effect for the modulation has been suggested. Whereas the VHE gamma-ray lightcurve has a modulation similar to the X-ray one²⁷, the HE gamma-ray flux is lower at the inferior conjunction ($0.45 < \phi < 0.9$) and higher at superior conjunction ($0.9 < \phi < 0.45$). In addition, at superior conjunction it shows a spectral cutoff at $E = 1.9 \pm 0.5$ GeV, not statistically required for inferior conjunction data²⁸.

The radial and powerful wind of LS 5039 makes it an ideal system to apply the model presented in this work. The shocked gas cooling regime will be closer to the radiative than to the adiabatic limit, with radiative timescales of the same order as the escape timescales. Therefore, it seems safe to apply the thermal emission model presented here to LS 5039.

Through optical measurements and studies of lack of X-ray absorption variability^{21,29,30}, we know that the stellar mass-loss rate in LS 5039 is in the range $(0.5\text{--}4.8) \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. The spin-down luminosity of the putative pulsar has not

Fig. 1. *Left:* Sketch of the orbit of the compact object around the companion star in LS 5039. The star (but not the pulsar) is at scale. The two marked positions correspond to periastron (P) and apastron (A). For each of these positions the shape of the CD is shown for $\eta_\infty = 0.0025, 0.025$ and 0.25 (blue, red, and green lines, respectively). *Right:* Spin-down luminosity upper limits as a function of orbital inclination and stellar mass-loss rate.

been detected directly, but energetic considerations constrain it to be strictly above $2 \times 10^{35} \text{ erg s}^{-1}$, and considering a reasonable emission scenario for the GeV emission this lower limit increases up to $\sim 3 \times 10^{36} \text{ erg s}^{-1}$. A sketch of the orbit of the compact object can be seen in Figure 1 left. The position of the CD is shown at periastron and apastron for different values of the ratio of the stellar and pulsar ram pressures $\eta_\infty = (L_{\text{sd}}/c)/(\dot{M}v_\infty)$.

LS 5039 has been observed at different positions along its orbit by many X-ray observatories³¹. Recently, a very long observation with *Suzaku* provided an uninterrupted lightcurve of the source during an orbit and a half²⁵, and a comparison with previous observations indicated that it was quite stable over periods of up to a decade²⁶. We have chosen to compare the output of our model with two deep observations of the source with *XMM-Newton* during periastron (phase range 0.02–0.05) and apastron (0.49–0.53). We processed the data through the standard procedure and extracted spectra from the three detectors aboard *XMM-Newton* for each of the two observations. We did an spectral analysis considering a source model comprised of a non-thermal component (absorbed power-law) and a thermal component. The non-thermal component was left as free parameter, but the thermal component was computed directly from our model of the thermal emission from the shocked stellar wind. We were the able to compute for which values of the model the thermal component was relevant in the total spectrum and disagreed with the observed data.

4. Results

To derive the upper limits of the pulsar spin-down luminosity, we chose to explore the stellar mass-loss rate values in the range obtained through the various determination methods^{21,29,30}: from $5 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1}$ to $4.25 \times 10^{-7} \text{ M}_\odot \text{ yr}^{-1}$. The orbital

inclination ($i = 20^\circ\text{--}70^\circ$)²⁰ affects the importance of circumstellar absorption at periastron in the emitted spectrum. The result of the pulsar spin-down luminosity upper limit determination, for the whole ranges of mass-loss rate and orbital inclination, is shown in Figure 1 right. We found that pulsar spin-down luminosities above $6 \times 10^{36} \text{ erg s}^{-1}$ are excluded by the lack of spectral thermal features in the observed periastron and apastron spectra, for any combination of mass-loss rate and orbital inclination. This upper limit corresponds to the extreme inclination of 70° , and for moderate orbital inclinations the upper limit is at all times below $5.5 \times 10^{36} \text{ erg s}^{-1}$. The reduced absorption at low mass-loss rates also results in constraining upper limits even though the wind kinetic luminosity is lower.

5. Discussion

The found upper limits of the pulsar spin-down luminosity pose strong constraints on further modeling of the PWS scenario for non-thermal emission. The pulsar spin-down luminosity should be at least a few times $10^{36} \text{ erg s}^{-1}$ in order to account for the GeV emission. The upper limit we have found from the thermal X-ray emission ($L_{\text{sd}} < 6 \times 10^{36} \text{ erg s}^{-1}$) indicates that the spin-down luminosity must be very close to this value in order for the PWS scenario to be consistent. A detailed modeling of the GeV emission from LS 5039 is required to accurately check the consistency of the observed GeV luminosity and the PWS scenario. Unfortunately, the structure and location of the GeV emitter is not well known, and IC emission is very sensitive to the θ_{IC} -value, which makes difficult to obtain conclusive results. Nevertheless, a robust enough limit can be derived for L_e in the IC scenario³² and it shows that, likely, $L_e/L_{\text{sd}} \rightarrow 1$. We note that the constraint on the efficiency is slightly less restrictive for high orbital inclinations ($i \gtrsim 45^\circ$) and low stellar mass-loss rates ($\dot{M} \lesssim 2 \times 10^{-7} M_\odot \text{ yr}^{-1}$).

The acceleration and emission processes responsible for the high efficiency in the conversion from spin-down luminosity to HE gamma-ray emission are currently unknown. IC emission from particles accelerated beyond the light cylinder in the striped pulsar wind is one of the proposed emission processes³³. However, when applied to the recent GeV flare of PSR B1259–67³⁴, this process can only account for the low-flux state before periastron, and is unable to explain the high luminosity detected after the periastron passage without the invocation of additional seed photon sources apart from the stellar companion. The extremely high efficiency required for LS 5039, similar to the high-flux state of PSR B1259–67, indicates that this process might not be responsible for its HE gamma-ray emission.

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