X-ray mapping of the stellar wind in the binary PSR J2032+4127/MT91 213

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ABSTRACT

PSR J2032+4127 is a γ-ray binary system (Lyne et al. 2015) and associated with the source TeV J2032+4130 (Camilo et al. 2009). The compact object of the binary is PSR J2032+4127 (Abdo et al. 2009), a young (∼0.2 Myr) pulsar with spin-down luminosity $L_{sd} \simeq 1.7 \times 10^{37} \text{ erg s}^{-1}$ and spin period $P = 143$ ms yielding a magnetic field strength of ∼2 × 10^{12} G. The companion is most likely a Be star (MT91 213; Massey & Thompson 1991) that belongs to the Cygnus OB2 association at a distance $d = 1.33 \pm 0.60$ kpc (Kiminki et al. 2015). The pulsar is on a highly eccentric orbit ($e \sim 0.93–0.99$) around its companion with an orbital period of $P_{orb} \sim 44–49$ yr (Ho et al. 2017). The long $P_{orb}$ and short spin period make the system an outlier of the $P$–$P_{orb}$ diagram for Be X-ray binaries (Corbet 1984). However, we note many similarities between this system and PSR B1259-63/LS 2883 (Chernyakova et al. 2014).

X-ray monitoring of the system with Swift has revealed a gradual increase of the X-ray luminosity which we attribute to the synchrotron emission of the shocked pulsar wind. We use Swift X-ray observations to infer a clumpy stellar wind with $r^{-2}$ density profile and constrain the Lorentz factor of the pulsar wind to $10^{5} < \gamma_{w} < 10^{6}$. We investigate the effects of an axisymmetric stellar wind with polar gradient on the X-ray emission. Comparison of the X-ray light curve hundreds of days before and after the periastron can be used to explore the polar structure of the wind.

Key words: radiation mechanisms: non-thermal – stars: massive – pulsars: individual: PSR J2032+4127 – X-rays: binaries.

1 INTRODUCTION

PSR J2032+4127/MT91 213 is a γ-ray binary system (Lyne et al. 2015) and associated with the source TeV J2032+4130 (Camilo et al. 2009). The compact object of the binary is PSR J2032+4127 (Abdo et al. 2009), a young (∼0.2 Myr) pulsar with spin-down luminosity $L_{sd} \simeq 1.7 \times 10^{37} \text{ erg s}^{-1}$ and spin period $P = 143$ ms yielding a magnetic field strength of ∼2 × 10^{12} G. The companion is most likely a Be star (MT91 213; Massey & Thompson 1991) that belongs to the Cygnus OB2 association at a distance $d = 1.33 \pm 0.60$ kpc (Kiminki et al. 2015). The pulsar is on a highly eccentric orbit ($e \sim 0.93–0.99$) around its companion with an orbital period of $P_{orb} \sim 44–49$ yr (Ho et al. 2017). The long $P_{orb}$ and short spin period make the system an outlier of the $P$–$P_{orb}$ diagram for Be X-ray binaries (Corbet 1984). However, we note many similarities between this system and PSR B1259-63/LS 2883 (Chernyakova et al. 2014).

X-ray monitoring of the system with Swift has revealed a gradual increase of the X-ray luminosity combined with episodes of flaring activity (Ho et al. 2017; Li et al. 2017). The enhancement of the X-ray emission is believed to arise from the interaction between the relativistic wind of the pulsar and the outflowing wind of the companion Be star. Within this scenario, Takata et al. (2017) have recently argued that the Swift X-ray light curve (LC) can be explained by either a variation in the momentum ratio of the two winds along the orbit or with a pulsar wind magnetization that depends on the distance from the pulsar.

In this letter, we provide analytical expressions connecting the X-ray luminosity of the binary system with properties of the stellar wind and the relativistic wind of the pulsar. We assume that the observed X-ray emission results from synchrotron emitting pairs which are accelerated at the termination shock formed in the relativistic wind of the pulsar. We search for deviations from the typical $r^{-2}$ density profile of the companion Be star and also provide model X-ray LCs for scenarios where the stellar wind properties have polar and radial dependences.

The upcoming periastron, occurring in 2017 mid-November, provides a unique opportunity to observe variations in the emission of the system from X-rays up to TeV γ-rays. Follow-up X-ray observations after the periastron passage will allow us to explore anisotropies in the wind properties of a massive star.

2 MODEL SET-UP

We adopt the scenario where the observed X-ray emission from PSR J2032+4127/MT91 213 is attributed to the synchrotron radiation from relativistic electrons and positrons (i.e. pairs). These are accelerated at the termination shock formed by the interacting winds.

The shock terminates at a distance $r_{t}$ from the neutron star, which can be derived by balancing the ram pressures of the pulsar and stellar winds (e.g. Lipunov et al. 1994; Tavani, Arons & Kaspi 1994):

$$r_{t} = \sqrt{\frac{L_{ad}}{4\pi c \rho_{w} v_{t}^{2}}} \approx \sqrt{\frac{L_{ad}}{4\pi c \rho_{w}}},$$

(1)
where \( p_w = \rho_w v_w^2 \) is the ram pressure of the stellar wind and \( v_w \approx v_{w,t} \) is the relative velocity of the two winds along the orbit. The shocked pulsar wind moves with a mildly relativistic speed (\( \sim c/2 \)), while it may accelerate to superfast magnetosonic speeds due to sideways expansion (Bucciantini, Amato & Del Zanna 2005). The relevant expansion time-scale is:

\[
\tau_{\text{exp}} \sim \frac{2r_l}{c}
\]  

(2)

In general, \( p_w \) is expected to vary with radial distance, thus leading to changes of \( r_l \) and \( \tau_{\text{exp}} \) along the pulsar’s orbit. The magnetic field of the shocked pulsar wind can also be expressed in terms of \( p_w \) as follows:

\[
B \approx \sqrt{8\pi \varepsilon_p p_w},
\]  

(3)

where the dimensionless parameter \( \varepsilon_p \) is related to the wind magnetization \( \sigma \) (Kennel & Coroniti 1984) as \( \varepsilon_p = 4\sigma \). At the termination shock, pairs are expected to accelerate and obtain a non-thermal energy distribution typically described by a power law with slope \( p > 2 \). The pair injection rate into the shocked pulsar wind region can be written as (e.g. Christie et al. 2017):

\[
Q(\gamma) \approx \varepsilon_{\text{ps}} \gamma \frac{L_{\text{sd}}(p-2)}{\gamma_{\text{min}}^2 \rho_{\text{me}} c^2} \left( \frac{\gamma}{\gamma_{\text{min}}} \right)^{-p}, \quad \gamma \geq \gamma_{\text{min}},
\]  

(4)

where \( \varepsilon_{\text{ps}} \leq 1 \) is the fraction of the pulsar’s spin-down power transferred to relativistic pairs and \( \gamma_{\text{min}} \) is the minimum Lorentz factor of the pairs, \( \gamma_{\text{min}} = \gamma_p (p-2)/(p-1) \). Among the free parameters of the model, \( \gamma_{\text{min}} \) is the most uncertain one with values in the range \( 10^2-10^6 \) (e.g. Montani & Bernardini 2014; Porth, Komissarov & Keppens 2014).

Henceforth, we assume equipartition between particles and magnetic fields in the downstream region of the shock, i.e. \( \varepsilon_e = \varepsilon_B = 0.5 \) (e.g. Porth et al. 2014). Synchrotron photons of energy \( \epsilon_e \) will be produced by pairs with Lorentz factor:

\[
\gamma_{\text{s}} \approx 3 \times 10^6 \rho_{w,4}^{-1/4} \left( \frac{\epsilon_{e}}{5 \text{ keV}} \right)^{1/2} \left( \frac{\varepsilon_{\text{B}}}{0.5} \right)^{-1/4},
\]  

(5)

where \( \rho_{w} = 10^{-4} \rho_{w,4} \text{ g cm}^{-2} \text{ s}^{-2} \). As long as the synchrotron cooling time-scale of the X-ray emitting pairs is smaller than \( \tau_{\text{exp}} \) (slow cooling regime), the X-ray synchrotron luminosity emitted over a frequency range \([\nu_1, \nu_2] \) will be given by:

\[
L_{\nu} = C_{\nu} L_{\text{sd}}^{3/2} \gamma_{\text{min}}^{-2} \varepsilon_e \frac{\rho_{w,4}^{1/4}}{\rho_{w,4}^{1/4}},
\]  

(6)

where \( C_{\nu} = (v_{w}^{\beta+1} - v_{\nu_2}^{\beta})/(\beta - 1), \beta = (p - 1)/2, \) and \( C = \sigma_t(8\pi)^{1/2}(2\pi m_e c/e)^{1/2}(p - 2)/(6\pi m_e c^3 \sqrt{4\pi}) \). For the derivation of equation (6), we used the \( \delta \)-function approximation for the synchrotron emissivity, the relation \( N(\gamma) = Q(\gamma) \tau_{\text{exp}} \), and equations (1)–(4).

A transition from the slow cooling to the fast cooling regime can result in a softening of the X-ray spectrum and in the saturation of the system’s X-ray luminosity, seen as a plateau in the LC, at a fraction of \( \varepsilon_{\text{s}}, L_{\text{sd}} \), namely:

\[
L_{\text{s}\nu} \approx 2 \times 10^{34} \text{ erg s}^{-1} p_{w,4}^{1/4} \frac{L_{\text{sd}}}{10^{35} \text{ erg s}^{-1}} \times \left( \frac{\rho_{w,4}}{10^6} \right)^{1/4} \left( \frac{\varepsilon_e}{0.5} \right)^{1/4} \left( \frac{\gamma_{\text{min}}}{1 \text{ keV}} \right)^{-1/2},
\]  

(7)

where equation (5) and \( p = 3 \) were used.

1 The pulsar moves at most with \( \sim 100 \text{ km s}^{-1} \) at periastron, whereas \( v_w \sim 10^3 \text{ km s}^{-1} \).

3 X-RAY OBSERVATIONS

Swift /XRT observations can provide a detailed X-ray LC of the system while available XMM–Newton, Chandra, and NuSTAR observations can be used to derive accurate spectral properties. We note that all available observations yield compatible spectral properties within errors, apart from a single combined XRT/NuSTAR spectrum that appears to be much softer (Ho et al. 2017; Li et al. 2017).

The Swift/XRT LC (up to MJD 58033.4) was produced following the instructions described in the Swift data analysis guide (http://www.swift.ac.uk/analysis/xrt/). We used xrtpipeline to generate the Swift/XRT products, and extracted events by using xselect (HEASoft FTOOLS; Blackburn 1995). The LC was also compared for consistency with the automated Swift/XRT online products (Evans et al. 2007). None of the Swift/XRT observations during the monitoring campaign of the system yielded sufficient statistics to allow a meaningful study of the spectrum. We therefore used fixed spectral parameters for converting the XRT count rates to flux. In particular, to transform the Swift/XRT rates to unabsorbed luminosities, we assumed a distance of 1.3 kpc and a power-law spectrum with photon index \( \Gamma = 2 \) and column density \( N_H = 7.7 \times 10^{21} \text{ cm}^{-2} \) (see table 4 in Ho et al. 2017).

4 SPHERICAL STELLAR WIND

The X-ray luminosity depends on the following model parameters: \( p, \varepsilon_e, \varepsilon_B, \gamma_{\text{w}}, \) and \( p_w, \) see equation (6). We benchmark the power-law index of the pair distribution to \( p = 2 \) (see Section 3), assuming that the pairs emitting in the Swift energy band (0.3–10 keV) are slow cooling. The validity of our assumption will also be checked by comparing a posteriori the synchrotron cooling and shock expansion time-scales. If energy is shared equally between particles and magnetic fields (i.e. \( \varepsilon_e = \varepsilon_B = 0.5 \)), we can derive \( p_w \) by matching equation (6) to the unabsorbed Swift X-ray luminosity for different values of \( \gamma_{\text{w}} \). In Fig. 1, we show the results for \( \gamma_{\text{w}} = 10^6 \) although these can be scaled accordingly for other parameter values using the analytical expressions of Section 2.

The first two panels from the top show, respectively, the Swift X-ray LC and the inferred ram pressure of the stellar wind, \( \rho_w \propto L_{\text{sd}}^{3/2} \gamma_{\text{w}}^{-2} \varepsilon_e^{-2} \). The magnetic field, which can be derived by equation (3), can be as high as \( \sim 0.1 \text{ G} \) in agreement with Takata et al. (2017). The temporal variability of \( \rho_w \) may originate from changes in the wind’s velocity and/or density. Simulations of line-driven winds from massive stars have shown that both their velocity and density are strongly variable close to the stellar surface (e.g. Feldmeier 1995; Lobel & Blomme 2008). The wind velocity is typically less variable than the density, which may vary more than two orders of magnitude (see Fig. 1; Bozzo et al. 2016). In addition, at the distances of interest (i.e. \( r \gg R_{\odot} \)), the stellar wind is expected to move with its terminal velocity. As a zeroth-order approximation, we thus attribute the changes of \( \rho_w \) (second panel from top) to changes of the wind’s density and assume that \( v_w \) is constant with radius and equal to its terminal value (\( \sim 10^7 \text{ km s}^{-1} \)).

Assuming spherical symmetry, the mass-loss rate of the wind can be estimated as \( \dot{M} = 4\pi r^2 \rho_0 v_w \), where \( r \) is the separation distance of the binary members. The mass-loss rate fluctuates around an average value of \( \sim 10^{-9} \dot{M}_{\odot} \text{ yr}^{-1} \) that falls within the value range for B stars (Martins et al. 2008; Krtiˇcka 2014). Interestingly, the inferred mass-loss rate is compatible with \( \rho_w \propto r^{-2} \) (magenta dashed line in Fig. 1), while density enhancements giving rise to X-ray flares (top panel in Fig. 1) can be explained by a clumpy wind (e.g. Oskinova, Feldmeier & Kretschmar 2012). Because of the scaling \( p_w \propto \gamma_{\text{w}}^{-2} \).
Equation (8) also suggests that neither \( \epsilon_M \) nor \( \epsilon_e \) can be much smaller than unity, as very large values of the pulsar wind’s Lorentz factor are necessary to explain the observed \( L_x \).

The extended atmosphere of a Be star can, in general, be divided into two regions: the equatorial (decretion) disc region and the wind region (Okazaki et al. 2011). The former is described by a geometrically thin Keplerian disc with high plasma density (for a slow pulsar wind with \( \gamma \leq 1 \) or the star’s mass-loss rate \( \dot{M} \gg 10^{-7} M_\odot \) yr\(^{-1} \)) would be necessary to explain the observed \( L_x \).

The synchrotron cooling time-scale of pairs emitting at energy \( \epsilon_e \) is \( \tau_{\text{syn}} \propto \epsilon_e^{-3/2} L_x^{-1/2} \epsilon_B^{-1} \gamma_0 \epsilon_e \epsilon_\gamma (\gamma_0 \epsilon_e \epsilon_\gamma)^{1/2} \) (see equations 3 and 5) and is longer than \( \tau_{\text{exp}} \) for the adopted parameters (bottom panel in Fig. 1). Transition to the fast cooling regime during the period of \( \text{Swift} \) observations would be relevant for \( \gamma_w < 10^5 \), which would, in turn, imply very high mass-loss rates in contradiction to the expected values for B stars as discussed above (see also equation 8). Although synchrotron cooling is not relevant for the X-ray emitting pairs during the period of \( \text{Swift} \) observations, we discuss the possibility of inverse Compton (IC) cooling in Section 6.

5 Axisymmetric Stellar Wind with Polar Gradient

The extended atmosphere of a Be star can, in general, be divided into two regions: the equatorial (decretion) disc region and the wind region (Okazaki et al. 2011). The former is described by a geometrically thin Keplerian disc with high plasma density (for a slow pulsar wind with \( \gamma \leq 1 \) or the star’s mass-loss rate \( \dot{M} \gg 10^{-7} M_\odot \) yr\(^{-1} \)) would be necessary to explain the observed \( L_x \).

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along its orbit. Additionally, the \( G \) parameter can mimic the effect of different angles between the pulsar’s orbital plane and the Be disc plane. The parameter \( m \) determines the confinement of the wind to the equatorial plane of the star. Changes in \( m \) do not strongly affect the LC close to periastron, but have an impact on the LC shape hundreds of days before or after. A radial wind profile that deviates from the standard one (i.e. \( r^{-2} \)) may masquerade an axisymmetric stellar wind with polar variations, namely \( n = 2 \) and \( m > 0 \) (see equation 9), but cannot explain asymmetric LCs around periastron.

6 DISCUSSION

The \textit{Swift} X-ray data indicate the presence of a clumpy stellar wind whose density scales, on average, as \( \sim r^{-2} \). The latter can explain the gradual increase of the X-ray luminosity as the pulsar approaches periastron, while the X-ray flares are attributed to clumps of dense matter (Section 4). Relativistic hydrodynamic simulations of an inhomogeneous stellar wind interacting with a pulsar wind show that the two-wind interaction region can be perturbed by clumps (see e.g. Paredes-Fortuny et al. 2015). These perturbations may enhance the energy dissipation of the pulsar wind at the termination shock, strengthen the post-shock magnetic field, or change the direction of motion of the shocked pulsar wind, thus giving rise to X-ray flares (de la Cita et al. 2017).

Synchrotron cooling is not relevant for X-ray emitting pairs in the 0.3–10 keV band during the period of \textit{Swift} observations, as shown in Fig. 1. This holds also for more energetic pairs that emit \( \sim 0.2 \) g cm\(^{-2} \) s\(^{-1} \) close to periastron, which requires \( \rho \gtrsim 3 \times 10^{-16} \) g cm\(^{-3} \) at periastron. Still, accretion on to the rapidly rotating neutron star will be halted by the propeller effect (Illarionov & Sunyaev 1975), unless the accretion rate is extremely high, i.e. \( M_t = (2–20) \times 10^{18} \) g s\(^{-1} \) corresponding to \( L_x = (5–50) \times 10^{36} \) erg s\(^{-1} \) (Campana et al. 2002).

Although a type-I outburst is unlikely to happen close to periastron (see e.g. Okazaki & Negueruela 2001), further phenomenology is expected. The pulsar spins down due to electromagnetic torque \( N_{\text{EM}} = -\mu^2 \Omega^2 / c^5 \), where \( \Omega \) and \( \mu \) are the pulsar’s angular spin frequency and magnetic moment, respectively. Close to the periastron, the pulsar may experience an additional spin-down due to the propeller effect on the plasma ‘held’ outside the corotation radius (e.g. Illarionov & Sunyaev 1975; Ghosh 1995). We adopt the conservative expression of Illarionov & Sunyaev (1975) for the propeller torque (for details, see Papitto, Torres & Rea 2012): \( N_{\text{prop}} = - M \sqrt{GM R_{\text{in}} \Omega_k / R_p} \), where \( \Omega_k \) is the Keplerian velocity, \( R_{\text{in}} = \xi (\mu^2 / 2 G M_{\text{NS}} M_t^2)^{1/7} \) is the magnetospheric radius, and \( \xi \approx 0.5–1 \) (see Chashkina, Abolmasov & Poutanen 2017, and references therein). The total spin-down torque acting upon the
pulsar will be at least doubled, if $\dot{M}_a \gtrsim 4 \times 10^{17}$ g s$^{-1}$. Assuming that the propeller torque acts upon the pulsar for $\sim 10^5$ d, we expect a spin-frequency change of $-4 \times 10^{-6}$ Hz, i.e. an antiglitch (Şaşmaz Muş, Aydin & Göğüş 2014). The predicted effect could be detectable by *Fermi*-LAT which has already measured a pulsar glitch with $\Delta \nu = 1.9 \times 10^{-6}$ Hz (Lyne et al. 2015).

The upcoming periastron passage of PSR J2032+4127 offers a unique opportunity to observe the system across the electromagnetic spectrum. In this letter, we focused on the non-thermal X-ray emission of the system and showed how it can be used to map the wind properties of the stellar companion. Comparison of the X-ray LC hundreds of days before and after the periastron will allow us to explore the polar structure of the wind while changes in the pulsar’s spin-down rate close to the periastron may probe the rate of mass captured by the neutron star.

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