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Stellar wind velocity of the massive component in the high mass X-ray binary OAO 1657−415

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Abstract. The parameters of the wind-fed accretion process in the massive X-ray binary OAO 1657−415 are discussed. We show that the X-ray luminosity of an accreting pulsar in this system can be explained only if the velocity of the stellar wind of the massive component in the orbital plane of the binary system is in the range of 200–500 km/s.

Keywords: stars: pulsars: general, winds, outflows; X-rays: binaries; accretion; individual: OAO 1657−415

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1 Introduction

Delgado-Martí et al. (2001) showed that the stellar wind velocity of the massive star in the X-ray binary X Persei in the orbital plane does not exceed 150 km/s. Otherwise, the amount of material captured by the neutron star from the wind of its companion is insufficient to explain the observed X-ray luminosity of the system. Their estimate is almost an order of magnitude lower than a typical wind velocity of hot massive stars and is several times smaller than the wind velocity of a star derived from observations of spectral lines in the UV.

In this work, we follow the technique proposed by Delgado-Martí et al. (2001) to estimate the stellar wind velocity of a massive component in the X-ray binary OAO 1657−415.

2 Stellar wind velocity

OAO 1657−415 (hereafter OAO 1657) is a close massive X-ray binary system (see Table 1). It is one of the best studied bright eclipsing quasi-equilibrium accreting X-ray pulsars. The massive component of the system does not fill its Roche lobe and the mass-exchange between the system components operates in accordance with the wind-fed accretion scenario. This implies that the neutron star captures gas from the wind of its massive companion at a rate

$$\dot{\mathfrak{M}}_c = \frac{L_x R_{\rm ns}}{GM_{\rm ns}} = \pi r_G^2 \rho_w v_{\rm rel} = \frac{4\pi (GM_{\rm ns})^2 \rho_w}{v_{\rm rel}^3}, \qquad (1)$$

where

$$r_{\rm G} = \frac{2GM_{\rm ns}}{v_{\rm rel}^2}$$

is the radius of gravitational capture (the so-called Bondi radius) by the neutron star and ρ_w is the density of the stellar wind in the region of its interaction with the neutron star. The velocity of a neutron star relative to the wind in the interaction region is generally estimated by

$$v_{\rm rel} = \left(v_{\rm orb}^2 + v_w^2 + c_{s(w)}^2\right)^{1/2}, \qquad (2)$$

where $v_{\rm orb}$ is the orbital velocity of the neutron star, $v_{\rm w}$ is the stellar wind velocity, and $c_{s(w)}$ is the sound speed in the stellar wind.

Under the conditions of interest, the sound speed in the eq. (2) can be neglected (assuming that the temperature of the stellar wind does not exceed several million

Table 1. Observed parameters of the pulsar OAO 1657-415 (for details see Ikhsanov et al. 2024 and references therein).

Sp opt.	$M_{\rm opt}$ $M_\odot$	$P_{\rm orb}$ days	a AU	$P_{\rm s}$ sec	$L_{\rm x}$ erg/s	d kpc
Ofpe [a]	14.3±0.8	10.45	0.24	37.3	(1–20)$\times 10^{36}$	6.4±1.5

degrees). The minimum possible value of the relative velocity of a neutron star in this case is determined by the value of its orbital velocity, which, taking into account a small value of the orbit eccentricity and the inequality $M_{\rm ns} \ll M_2$ implemented in the system, can be approximated by the Keplerian velocity, i.e. $v_{\rm rel} \geq v_k^{\rm ns}(a)$, where

$$v_k^{\rm ns}(a) = \left(\frac{GM_2}{a}\right)^{1/2} \simeq 240 \text{ km/s} \left(\frac{M_2}{15\,M_\odot}\right)^{1/2} \left(\frac{a}{0.24\,\text{AU}}\right)^{-1/2}. \qquad (3)$$

Here M_2 is the mass of the optical component of the system and a is the orbital separation (close to the radius of the neutron star's orbit). Substituting this velocity into eq. (1) and solving it with respect to ρ_w, we find $\rho_w \geq \rho_0$, where

$$\rho_0 = \frac{L_x R_{\rm ns}}{4\pi\,(GM_{\rm ns})^3} \left(\frac{GM_2}{a}\right)^{3/2} \simeq 10^{-16}\,\text{g}\,\text{cm}^{-3}\, L_{36} R_6 m^{-3} \left(\frac{M_2}{15\,M_\odot}\right)^{3/2} \left(\frac{a}{0.24\text{ AU}}\right)^{-3/2}, \qquad (4)$$

where $L_{36} = L_x \times 10^{-36}$ erg/s, $R_6 = R_{\rm ns} \times 10^{-6}$ cm and $m = M_{\rm ns}/1.4\,M_\odot$.

Assuming, on the other hand, that the stellar wind velocity exceeds the orbital velocity of the neutron star within the approximation of a spherically symmetric outflow of stellar wind from a massive component of the system, we estimate, following the method proposed by Delgado-Martí et al. (2001), the X-ray luminosity of the pulsar as $L_x \leq L_0$, where

$$L_0 = \frac{\dot{\mathfrak{M}}_{\rm out}(GM_{\rm ns})^3}{a^2 R_{\rm ns} v_w^4}. \qquad (5)$$

Here $\dot{\mathfrak{M}}_{\rm out}$ is the rate of mass loss by the optical component of the system in the form of stellar wind. Solving this equation for v_w, we find $v_w \leq v_{\rm max}$, where

$$v_{\rm max} \simeq 440 \text{ km/s} \times m^{3/4} R_6^{-1/4} L_{36}^{-1/4} \left(\frac{a}{0.24\text{ AU}}\right)^{-1/2} \left(\frac{\dot{\mathfrak{M}}_{\rm out}}{10^{-7}\,M_\odot/\text{ year}}\right)^{1/4}. \qquad (6)$$

The X-ray luminosity of the source in this equation is normalized to the value obtained under the assumption that the object we are studying is located at a distance of the order of 6 kpc. Using an estimate of the minimum possible distance to the source $d \geq 2.5$ kpc, based on Gaia observations (Saavedra et al. 2022), it can be argued that the stellar wind velocity in the orbital plane of the system does not exceed 700 km/s.

3 Conclusions

Our analysis of the wind-fed accretion process in the massive X-ray binary system OAO 1657−415 indicates that the neutron star velocity relative to the stellar wind of its massive companion in this system can be limited as $v_k^{\rm ns}(a) \leq v_{\rm rel} \leq v_{\rm max}$. The lower and upper limits here are determined, respectively, by the eq. (3), (6). The lower limit to the relative velocity is fixed relatively well. The estimate of the upper limit is model dependent. It has been obtained under the assumption about a spherically symmetric outflow of the wind from the massive component of the system with a velocity significantly exceeding the orbital velocity of the neutron star. The estimate of this velocity, in addition, depends on the distance to the object, which is still a subject of debate. At the same time, the value we obtained, represented by the eq. (6), can be further used to analyze the structure of the accretion flow and the accretion pattern as a whole.

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