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Stellar Wind Parameters of Massive Stars in Accretion-Powered High-Mass X-Ray Binary Pulsars

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Abstract: The process of mass exchange between the components of High-Mass X-ray Binary (HMXB) systems with neutron stars undergoing wind-fed accretion is discussed. The X-ray luminosity of these systems allows us to evaluate the mass capture rate by the neutron star from the stellar wind of its massive companion and set limits on the relative velocity between the neutron star and the wind. We found that the upper limit to the wind velocity in the orbital plane during the high state of the X-ray source is in the range of 120–1000 $\mathrm{km\,s^{-1}}$, which is by a factor of 2–4 lower than both the terminal wind velocity and the speed of the wind flowing out from the polar regions of massive stars for all the objects under investigation. This finding is valid not only for the systems with Be stars, but also for the systems in which the optical components do not exhibit the Be phenomenon. We also show that the lower limit to the radial wind velocity in these systems can unlikely be smaller than a few percent of the orbital velocity of the neutron star. This provides us with a new constraint on the mass transfer process in the outflowing disks of Be-type stars.

Keywords: accretion; pulsars; high-mass X-ray binary; stellar wind; neutron star; magnetic field

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1. Introduction

Delgado-Martí et al. [1] highlighted that High-Mass X-ray Binaries (HMXBs) harboring neutron stars can, under certain conditions, serve as natural laboratories for studying stellar winds generated by early spectral-type stars. The neutron star in these systems can be considered as a probe. As it orbits through the stellar wind of its massive companion, the neutron star captures gas via its gravitational field and accretes it onto its surface. The properties of the X-ray source produced by this process allow us to infer the amount of gas being captured by the neutron star in unit time. Combining this information with the observed parameters of the binary system and the characteristics of its massive component enables us to evaluate the physical conditions in the stellar wind emanating from the massive star in the orbital plane of the system.

Using their proposed methodology, Delgado-Martí et al. [1] analyzed the Be/X-ray binary system X Persei. They have found that the velocity of the wind which the Be star ejects within the orbital plane of the system is unlikely to exceed 150 $\mathrm{km\,s^{-1}}$. If the velocity were higher, the amount of material captured by the neutron star from the wind of its companion would be insufficient to explain the observed X-ray luminosity of the pulsar.

This result was not quite unexpected, since Be-type stars are known to be surrounded by the outflowing gaseous disk in which the radial velocity of material is a factor of 3–5 smaller than the wind velocity in the polar regions (see, for example, ref. [2], and references therein) and is almost an order of magnitude lower than the typical terminal wind velocity of hot massive stars. This situation is just realized in X Persei, where the wind velocity of the Be star measured through observations of the UV lines (about 800 $\mathrm{km\,s^{-1}}$) exceeds the velocity of the wind within the orbital plane by at least a factor of a few [1].

An attempt to apply the method proposed in [1] to the HMXB OAO 1657-415, in which the massive star does not show a Be-type phenomenon, has been made in our previous paper [3]. The object of our analysis was one of the best-known eclipsing HMXB systems containing a bright quasi-steady accretion-powered X-ray pulsar with orbital parameters and X-ray flux determined with high confidence. The only uncertainty in its X-ray luminosity arises from conflicting distance estimates to the source. However, it is well-established that the massive component does not fill its Roche lobe, and mass transfer between the components occurs via the wind-fed accretion scenario. Our derived upper limit for the wind velocity of the massive star in OAO 1657-415 ejected within the orbital plane is in the interval of 200–500 $\mathrm{km\,s^{-1}}$. It is higher than the wind velocity obtained by Delgado-Martí et al. [1] for X Persei but remains well below both a typical terminal wind velocity of early-type stars (about 2000 $\mathrm{km\,s^{-1}}$ for O-type stars [4,5] and 500–1500 $\mathrm{km\,s^{-1}}$ for B-type super-giants [6,7]) and the wind velocity evaluated from the properties of UV lines observed in these objects [8]. This raises a question about the structure of stellar wind of massive early-type stars which do not show the Be-phenomenon. In particular, is the velocity of wind ejected by these stars within the orbital plane smaller than the wind velocity in the polar regions?

In order to answer this question we consider in this paper a sample of HMXBs in which a neutron star undergoing wind-fed accretion is orbiting its massive companion which does not show Be-phenomenon. Measuring the intensity of X-rays generated in this process allows us to estimate the rate of gas accretion onto the surface of the neutron star and, accordingly, the minimum rate at which it captures gas from the wind of its companion. Incorporating this finding with observational data on the massive component of the system, we arrive at an estimate of the neutron star's velocity relative to the stellar wind of the massive star, which is expelled in the orbital plane of the system (see Section 2). Using the conditions of the steady accretion process we also set a lower limit to the radial velocity of the outflowing matter (see Section 3). Following these methods, we expand the list of objects under study and present our estimates of the relative velocity of the neutron star in some of the most thoroughly studied HMXBs (see Section 4). The assumptions we made in our analysis and some of the implications of the results presented are briefly discussed in Section 5.

2. Upper Limit to the Relative Velocity

The luminosity of a source arising due to the accretion of gas onto the surface of a neutron star is estimated by the expression below (see, for example, ref. [9] and references therein).

$$L_\mathrm{a} = \dot{\mathfrak{M}}_\mathrm{a} \frac{GM_\mathrm{ns}}{R_\mathrm{ns}}. \tag{1}$$

Here, $\dot{\mathfrak{M}}_\mathrm{a}$ is the mass accretion rate, that is, the amount of matter falling per unit time onto the surface of a neutron star, whose mass and radius are, respectively, M_ns and R_ns. In the scenario of accretion onto a neutron star with a strong magnetic field (which corresponds to the case of accretion we are considering for X-ray pulsars), the energy of the accretion source is predominantly emitted in the "classical" part of the X-ray range (with photon energies ∼1–10 keV). This creates the most favorable opportunity to evaluate the accretion rate onto the surface of neutron stars,

$$\dot{\mathfrak{M}}_{\rm a} = \frac{L_{\rm x} R_{\rm ns}}{G M_{\rm ns}}, \tag{2}$$

through measurements of X-ray luminosity of the object, $L_{\rm x}$. A precise evaluation of $\dot{\mathfrak{M}}_{\rm a}$ requires only information about the distance to the source under investigation, while the mass and radius of neutron stars are constrained within a relatively narrow range of possible values ($R_{\rm ns}$∼8–12 km and $M_{\rm ns}$∼1–2 $M_{\odot}$) by their equation of state [10]. Because of the latter property, neutron stars prove to be a really good probe.

The rate at which a neutron star captures gas as it moves through the stellar wind of its companion is estimated by the following expression:

$$\dot{\mathfrak{M}}_{\rm c} = \pi r_{\rm G}^2 \rho_{\rm w} v_{\rm rel} = \frac{4\pi (G M_{\rm ns})^2 \rho_{\rm w}}{v_{\rm rel}^3}, \tag{3}$$

where

$$r_{\rm G} = \frac{2 G M_{\rm ns}}{v_{\rm rel}^2} \tag{4}$$

is a so-called Bondi radius [11] which represents the maximum possible distance from the center of the neutron star to the point at which it is able to capture material as it moves through the stellar wind at the relative velocity

$$v_{\rm rel} = \left(v_{\rm orb}^2 + v_{\rm w}^2 + c_{\rm s(w)}^2 \right)^{1/2}. \tag{5}$$

Here, $v_{\rm orb}$ is the orbital velocity of the neutron star, $v_{\rm w}$ is the stellar wind velocity in the reference frame of the massive star, and $c_{\rm s(w)}$ is the sound speed in the stellar wind. Finally, $\rho_{\rm w}$ is the density of the stellar wind at the Bondi radius, which in the approximation of a spherically symmetric wind outflow can be expressed as follows:

$$\rho_{\rm w} = \frac{\dot{\mathfrak{M}}_{\rm opt}}{4\pi a^2 v_{\rm w}}. \tag{6}$$

Here, $\dot{\mathfrak{M}}_{\rm opt}$ is the mass loss rate of the optical component of the system (i.e., the massive star) in the form of the stellar wind, and a is the orbital separation (distance between the system's components).

Combining Expressions (3) and (6) under the approximation $v_{\rm rel} \approx v_{\rm w}$ and solving the inequality $\dot{\mathfrak{M}}_{\rm a} \leq \dot{\mathfrak{M}}_{\rm c}$ for $v_{\rm rel}$, we find $v_{\rm rel} \leq v_{\rm max}$, where

$$v_{\rm max} \simeq 650\,{\rm km\,s^{-1}} \times L_{36}^{-1/4} R_6^{-1/4} m^{3/4} \left(\frac{a}{0.1\,{\rm AU}} \right)^{-1/2} \left(\frac{\dot{\mathfrak{M}}_{\rm opt}}{10^{-7}\,{\rm M_{\odot}\,year^{-1}}} \right)^{1/4} \tag{7}$$

is the maximum possible value of the stellar wind velocity in the orbital plane of a neutron star. Here, $L_{36} = L_{\rm x}/10^{36}\,{\rm erg\,s^{-1}}$, $R_6 = R_{\rm ns}/10^6$ cm and $m = M_{\rm ns}/1.4\,M_{\odot}$.

3. Lower Limit to the Wind Radial Velocity

Studies of HMXBs also open the unique possibility of evaluating the minimum possible value of radial velocity of the stellar wind ejected by the massive star within the orbital plane of the system. The distance at which a neutron star in a HMXB system is able to capture gas as it moves through the wind of its massive companion in general case is limited to

$$r_{\rm cap} \le \begin{cases} r_{\rm G}, & \text{for } v_{\rm rel} > v_0, \\ R_{\rm L_{ns}}, & \text{for } v_{\rm rel} \le v_0, \end{cases} \tag{8}$$

where

$$R_{\rm L_{ns}} \simeq 3 \times 10^{11}\,{\rm cm} \left(\frac{a}{0.1\,{\rm AU}}\right) \tag{9}$$

is the radius of the Roche lobe of the neutron star and the velocity

$$v_0 \simeq 370\,{\rm km\,s^{-1}}\, m^{1/2} \left(\frac{a}{0.1\,{\rm AU}}\right)^{-1/2} \tag{10}$$

is defined by equation $r_{\rm G}(v_0) = R_{\rm L_{ns}}$ (for details see, e.g., [12] and references therein). As a neutron star orbits its companion with the relative velocity $v_{\rm rel} \le v_0$ it captures all material located inside the impact parameter, which in the case considered is equal to $R_{\rm L_{ns}}$. A stationary accretion process can be realized in this case only if the distance in the radial direction which the stellar wind is able to pass on a timescale of the orbital period is comparable to or exceeds the scale of the impact parameter. Otherwise, the amount of gas located at the orbit of the neutron star would not be sufficient to produce observed luminosity of the X-ray pulsar. This condition implies that the stationary accretion can be realized if the radial velocity of the stellar wind is limited as $v_{\rm w(r)} \ge v_{\rm f}$, where

$$v_{\rm f} = \frac{R_{\rm L_{ns}}}{P_{\rm orb}} \simeq 1.2\,{\rm km\,s^{-1}} \times \left(\frac{R_{\rm L_{ns}}}{10^{11}\,{\rm cm}}\right) \left(\frac{P_{\rm orb}}{10\,{\rm d}}\right)^{-1} \tag{11}$$

turns out to be in the interval 2–12 km/s for all the systems presented in Table 1.

Table 1. Estimation of the maximum possible values of stellar wind velocity in the orbital plane of the binary system in the HMXBs along with their key parameters (see [13–15] and references therein) used in our calculations (see text above for details).

Object	$P_{\rm orb}$ **Day**	**a AU**	**Massive Star**	$M_{\rm opt}$ $M_\odot$	$\dot{\mathfrak{M}}_{\rm opt}$ $10^{-7}\,M_\odot$**/yr**	$L_{\rm x}^{\rm max}$ 10^{36} **erg/s**	$v_{\rm max}$ **km/s**
Cen X-3	2.03	0.08	O6.5 II-III	20	50	14	1010
4U 1538-52	3.73	0.11	B0.2 Ia	20	12	4.3	810
Vela X-1	8.96	0.23	B0.5 Ia	26	40	0.10	610
OAO 1657-415	10.45	0.21	Ofpe/WNL	14	1	20	210
2S 0114+650	11.6	0.26	B1 Ia	16	30	12	510
GX 301-2	41.5	0.83	B1.5 Ia	43	75	30	290
X Per	250	2.0	B0 Ve	15	0.05	0.06	140
RX J0146.9+6121	330	2.1	B1 Ve	10	0.05	0.11	120

This finding suggests that the radial velocity of stellar wind ejected by massive stars in HMXBs within the orbital plane is unlikely to be smaller than a few percent of the orbital velocity of the neutron star itself. However, this rather simple estimation should be taken into account as a necessary condition in the modeling of outflowing disks surrounding the massive early-type stars.

Finally, the above method allows us to evaluate also the density of the wind by combining Equation (3) with Equation (2) and solving it for $\rho_{\rm w}$. The minimum possible value of the neutron star relative velocity can be estimated by its orbital velocity which in our case can be approximated by the keplerian velocity: $v_{\rm rel} \geq v_{\rm k}^{(\rm ns)}(a)$, where

$$v_{\rm k}^{(\rm ns)}(a) = \left(\frac{GM_2}{a}\right)^{1/2} \simeq 365\,{\rm km\,s^{-1}} \times \left(\frac{M_2}{15\,M_{\odot}}\right)^{1/2} \left(\frac{a}{0.1\,{\rm AU}}\right)^{-1/2}, \qquad (12)$$

and M_2 is the mass of the optical component of the system. Thus we obtain $\rho_{\rm w} \geq \rho_0$, where

$$\rho_0 = \frac{L_{\rm x} R_{\rm ns}}{4\pi (GM_{\rm ns})^3} \left(\frac{GM_2}{a}\right)^{3/2} \simeq 6 \times 10^{-16}\,{\rm g\,cm^{-3}}\, L_{36} R_6 m^{-3} \left(\frac{M_2}{15\,M_{\odot}}\right)^{3/2} \left(\frac{a}{0.1\,{\rm AU}}\right)^{-3/2}. \qquad (13)$$

4. Wind Velocity Estimation

The results of the relative velocity evaluation for the neutron stars in the HMXBs, using the methods described above and employing the Expression (7) for the most thoroughly studied persistent X-ray pulsars in the HMXBs are presented in the last column of Table 1. It also provides the values of the key parameters of these objects used in our calculations (see [13–15], and references therein), namely, the orbital period and size of the system, the spectroscopic mass, spectral class, and mass loss rate of the optical (massive) component and the maximum luminosity of the X-ray source.

5. Discussion

The estimates we obtained for the upper limit to the relative velocity between the neutron star and stellar wind of its companion indicate that the wind speed in the orbital plane of the system is lower than the typical terminal wind velocity of O-type stars by a factor of 2–4 and is comparable with the expected wind velocity for B-type supergiants. The estimated velocity of the wind ejected in the orbital plane of two Be/X-ray pulsars is smaller than the wind velocity measured through observations of the UV lines in the spectra of massive stars by a factor of a few.

This result supports the hypothesis about a multi-component structure of the stellar wind of massive stars. It should be noted that the moderate wind velocity in the orbital plane of the system turns out to be inherent not only to the systems with Be stars, for which this result is rather expected, but also to the systems with optical components, which do not show the Be phenomenon and/or are the stars of a significantly earlier spectral class.

The obtained values of relative velocity in the systems with short orbital periods (compact systems) are somewhat higher than in the long-period binaries (wide pairs). Moreover, there is a noticeable tendency towards a decrease in the upper limit to the relative velocity as the system size increases. This may indicate that the velocity of the wind flowing out in the orbital plane of the system changes with the distance from the massive component insignificantly.

Finally, the obtained lower limit to the radial velocity of the stellar wind, $v_{\rm f} \simeq 2$–$12\,{\rm km\,s^{-1}}$, is comparable to the sound speed in the gas heated to a few thousand Kelvin and is unlikely to be smaller than a few percent of the orbital velocity of the neutron star itself. This finding challenges scenarios in which the mass outflow from a Be star is treated in terms of a hydrodynamical cool moderately viscous disk. Incorporation of the magnetic field of the stellar wind into the model may help to increase the efficiency of the mass and angular momentum transfer out from the star and to explain a relatively high value of the lower limit to the radial velocity of the wind in the orbital plane, $v_{\rm f}$.

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