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On the possibility of disk-fed formation in supergiant high-mass X-ray binaries

Ali Taani[1], Shigeyuki Karino[2], Liming Song[3], Mashhoor Al-Wardat[4], Awni Khasawneh[5] and Mohammad K. Mardini[6,7]

[1] Physics Department, Faculty of Science, Al-Balqa Applied University, 19117 Salt, Jordan; *ali.taani@bau.edu.jo*
[2] Faculty of Science and Engineering, Kyushu Sangyo University, 2-3-1 Matsukadai, Higashi-ku, Fukuoka 813-8503, Japan
[3] Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[4] Department of Physics, Al al-Bayt University, Mafraq 25113, Jordan
[5] Royal Jordanian Geographic Center, Amman 11941, Jordan
[6] Key Lab of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
[7] University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract We consider the existence of a neutron star magnetic field by the detected cyclotron lines. We collected data on nine sources of high-mass X-ray binaries with supergiant companions as a test case for our model, to demonstrate their distribution and evolution. The wind velocity, spin period and magnetic field strength are studied under different mass loss rates. In our model, correlations between mass-loss rate and wind velocity are found and can be tested in further observations. We examine the parameter space where wind accretion is allowed, avoiding the barrier of rotating magnetic fields, with robust data on the magnetic field of neutron stars. Our model shows that most sources (six of nine systems) can be fed by the wind with relatively slow velocity, and this result is consistent with previous predictions. In a few sources, our model cannot fit the standard wind accretion scenario. In these peculiar cases, other scenarios (disk formation, partial Roche lobe overflow) should be considered. This would provide information about the evolutionary tracks of various types of binaries, and thus exhibit a clear dichotomy behavior in wind-fed X-ray binary systems.

Key words: binaries: X-rays — stars: neutron — stars: fundamental parameters — accretion disks — formation — magnetic fields

1 INTRODUCTION

High mass X-ray binaries (HMXBs), with inferred magnetic fields on the surface of the compact companion of $B \sim 10^{12}$ G, are composed of two subclasses: Be X-ray binaries ($\sim \%$ 80) in the Galaxy (e.g. van den Heuvel 2004; Liu et al. 2006; Taani 2016), with orbital periods ranging from ∼15 days to several years, and with relatively low mass companions ($\sim$ 8 to 20 $M_\odot$). In contrast, the second group of HMXBs is the supergiant (SG) sources. They consist of OB SG mass donors ($\sim$ 18 to over 40 $M_\odot$) and a compact object accreting from the strong stellar wind with short orbital periods ($\leq$ 11 days) like Cen X-1 and Vela X-1. This group only has about a dozen known members (see e.g. Bhattacharya & van den Heuvel 1991; Reig et al. 2001; Taani et al. 2012b,a; Walter et al. 2015; Taani et al. 2017; Dai et al. 2017).

The cyclotron lines are detected as absorption lines in high-energy spectra (see Truemper et al. 1978, for full details and references) of magnetized accreting neutron stars (NSs). They form in the presence of a strong magnetic field due to resonant scattering processes with electrons (Voges et al. 1982; Wilson et al. 2008) and can provide the only direct estimate of magnetic field strength for an accreting NS. The presence of a cyclotron feature has been reported for the SG-HMXBs listed in our sample at $\geq$ 17 keV (see Table 1). There are also factors that represent several uncertainties in the value of the NS magnetic field derived from these lines due to unknowns in the geometry and emission mechanisms of the system (see, e.g., Reig et al. 2001; Mushtukov et al. 2015; Walter et al. 2015). Nishimura (2003) demonstrated that variations in the strength of a magnetic field affect the profile of the cyclotron line. It is noteworthy to mention here that most observed cyclotron lines detected above 10 keV (e.g. Makishima et al. 1990; Cusumano et al. 1998; Coburn et al. 2002) are interpreted as electron features, with inferred magnetic fields $B \sim 10^{12}$ G. However, the NS magnetic field of HMXB may decay a little by accreting matter (see, e.g. Zhang & Kojima 2006 and references therein).

As the mass-loss rate through stellar winds may have an influence on the stellar evolution and modify the stellar spectrum (Krtička et al. 2016), many observational methods can be used to derive wind mass-loss rate. This will also allow the phenomenology of the X-ray sources and their optical counterpart to be distinguished in a natural way (Wei et al. 2010; Shakura et al. 2012; Saladino et al. 2018; Taani et al. 2018), such as the shape of X-ray emission lines in cool wind (Macfarlane et al. 1991; Feldmeier et al. 2003), the strength of ultraviolet P Cygni lines (Lamers et al. 1999), Hα emission line (Puls et al. 2006) and near-infrared emission lines (Najarro et al. 2011).

Several disk-fed models have been proposed to explain the disk accretion mechanism, including a circumstellar disk (see i.e. Wang 1995; Dai & Li 2006; Kluźniak & Rappaport 2007; Shakura et al. 2012; Taani et al. 2018). For a recent review of stellar wind models, we refer to Krtička et al. (2016) and Krtička & Kubát (2017). One of the most accepted models about properties of the stellar wind is the quasi-spherical accretion of captured matter from the stellar wind of the star (Shakura et al. 2012; Postnov et al. 2017). In this work, we concentrate more on the study and interpretation of the evolution of the wind accretion velocity, spin period, magnetic field and mass-loss rate for nine HMXBs with SG companions. In addition, we study the disk-fed NS formation through the relations between mass-loss rate and wind velocity. The article is organized as follows: Section 2 deals with consideration of our model. Section 3 discusses accretion regimes. The obtained results on $\dot{m}_{\rm w}$, v_∞, $B_{\rm field}$ and $P_{\rm spin}$ for several SG-HMXB listed in our sample are discussed in Section 4 and conclusions are summarized in Section 5.

2 THE WIND MODEL

In order to build an evolutionary framework for HMXBs, it is essential to map the mass-loss processes during the various evolutionary stages. According to equation (2) in Karino & Miller 2016 (KM16), we apply the equilibrium period equation (the magnetospheric radius is equal to the NS corotation radius, $r_{\rm m}$=$r_{\rm co}$), where disk accretion is assumed (Bhattacharya & van den Heuvel 1991). It is determined by the long term averaged mass accretion rate (Tong 2015), thus it is convenient for the wind accretion calculation. The magnetic field strength of the NS can be estimated by

$$B_{\rm NS} = 2.184 \times 10^{12}{\rm G} \times \zeta^{1/2} \times \left(\frac{\dot{M}}{10^{18}{\rm g\,s^{-1}}}\right)^{1/2} \left(\frac{P_{\rm s}}{1{\rm s}}\right)^{7/6} , \quad (1)$$

where we assume that the mass of the NS is $1.4\,M_\odot$ and radius of the NS is 10 km; for wind accretion ($\zeta \approx 1$) or disk accretion ($\zeta \approx 0.1$).

Since mass-loss rate is one of the key parameters that determines the influence of the stellar wind on stellar evolution and on the circumstellar medium (Krtička & Kubát 2017), we assume Bondi-Hoyle-Littleton accretion (Bondi & Hoyle 1944) with a smooth wind to estimate the mass accretion rate onto the NS as

$$\dot{M}_{\rm acc} = \rho_{\rm w} R_{\rm acc}^2 v_{\rm rel} , \quad (2)$$

where $\rho_{\rm w}$ is the density of the wind during the steady state of spherical wind. $v_{\rm rel}$ is the relative velocity of the wind

$$v_{\rm rel} = \left(v_{\rm orb}^2 + v_{\rm w}^2\right)^{1/2} , \quad (3)$$

where $v_{\rm orb}$ and $v_{\rm w}$ denote the orbital velocity and the wind velocity, respectively. Note that the stellar wind velocity ($v_{\rm w}$) is usually larger (typically $100 - 1000\,{\rm km\,s^{-1}}$) than the orbital velocity $v_{\rm orb}$ for typical wind-fed systems with $P_{\rm orb} \approx 10\,{\rm d}$ (Shakura et al. 2012). Hence, in these systems, we could neglect $v_{\rm orb}$ from the calculation. $R_{\rm acc}$ is the accretion radius (Bondi radius) defined by

$$R_{\rm acc} = \frac{2GM_{\rm NS}}{v_{\rm rel}^2} . \quad (4)$$

We adopt the standard Castor et al. (1975) formula for wind velocity $v_{\rm w}$, which assumes a stationary, homogeneous and spherically symmetric outflow

$$v_{\rm w} = v_\infty \left(1 - \frac{R_{\rm d}}{a}\right)^\beta . \quad (5)$$

In this study, we assume β, which is a free input parameter, to be $\beta = 1$ (Puls et al. 2006). $R_{\rm d}$ is the radius of the donor. v_∞ denotes the terminal velocity of the wind. The density of the wind in the stellar atmosphere can be derived from the continuity equation

$$\dot{M}_{\rm w} = 4\pi a^2 \rho_{\rm w} v_{\rm w} . \quad (6)$$

Here $\dot{M}_{\rm w}$ is the mass loss rate from the donor and a denotes the orbital radius of the system. (Here we assume a circular orbit.) By combining Equations (2)–(6), we obtain

$$\dot{M}_{\rm acc} = \left(\frac{GM_{\rm NS}}{a}\right)^2 \frac{\dot{M}_{\rm w}}{\pi v_{\rm rel}^3 v_{\rm w}} \,. \tag{7}$$

The mass accretion rate can be derived from the X-ray luminosity as follows

$$L_{\rm X} \simeq \frac{GM_{\rm NS}\dot{M}_{\rm acc}}{R_{\rm NS}} \,. \tag{8}$$

Hence, $\dot{M}_{\rm acc}$ could be known from observed luminosities. Adopting formulae by Vink et al. (2001), we can estimate $\dot{M}_{\rm w}$ from the parameters of donors; most SG-type donors in our sample show $\dot{M}_{\rm w} \sim 10^{-7} - 10^{-6}\, M_\odot\,{\rm yr}^{-1}$.

Assuming that the NS has typical parameters ($M_{\rm NS} = 1.4\, M_\odot$ and $R_{\rm NS} = 10\,{\rm km}$), the orbital parameters and wind parameters can be obtained from the donor mass and radius. Adopting the donor parameters given by previous studies such as Coley et al. (2015), Falanga et al. (2015), Rawls et al. (2011) and Reig et al. (2016), we can obtain the possible parameter range of the unknown wind parameters (terminal velocity v_∞ of the wind and mass loss rate $\dot{M}_{\rm w}$ of the donor) with robust values of the B-field obtained from cyclotron lines (see Table 1).

3 ACCRETION REGIME

Stella et al. (1986) and Bozzo et al. (2008) considered three typical radii: accretion radius ($r_{\rm a}$), magnetic radius ($r_{\rm m}$) and corotation radius ($r_{\rm co}$), and divided the parameter space into five accretion regimes based on their magnitude relation. That is, the parameter space can be categorized into (A) supersonic inhibition regime ($r_{\rm m} > r_{\rm a}, r_{\rm co}$), (B) subsonic inhibition regime ($r_{\rm co} > r_{\rm m} > r_{\rm a}$), (C) supersonic propeller regime ($r_{\rm a} > r_{\rm m} > r_{\rm co}$), (D) subsonic propeller regime ($r_{\rm co}, r_{\rm a} > r_{\rm m}$, $\dot{M} < \dot{M}_{\rm c}$), where $\dot{M}_{\rm c}$ denotes the critical limit where radiative cooling starts working (see Bozzo et al. 2008), and (E) direct accretion regime. These radii, in turn, depend on: $\dot{M}_{\rm w}$, v_∞, $B_{\rm NS}$ and $P_{\rm spin}$. Among these parameters, now we have robust data on $P_{\rm spin}$ given by light curve analysis and $B_{\rm NS}$ provided by cyclotron-feature observation. We apply the above segmentation in magnetic field-wind velocity space intended for several SG-HMXBs. Although the possible effect of angular momentum loss during the propeller regime still has to be extensively discussed (see, e.g., Pringle & Rees 1972; Wang & Robertson 1985; Shakura et al. 2012; Dai et al. 2016), in this study we only concentrate our attention on the direct accretion regime.

A graphical illustration of the accretion regime is displayed in Figure 1: the different accretion regimes (A) to (E) are divided by dashed lines. The shaded region indicates the direct accretion regime; only HMXBs in this regime can be observed as bright X-ray sources. The horizontal solid lines represent wind velocity corresponding to $v_{\rm inf} = 1500\,{\rm km\,s^{-1}}$ (upper line) and $700\,{\rm km\,s^{-1}}$ (lower line). (From recent observations, it is suggested that the wind velocity in persistent SG HMXBs is relatively slow; for example, in Vela X-1, $v_\infty = 700\,{\rm km\,s^{-1}}$), while the wind velocity in SG fast X-ray transient (SFXT) systems seems as fast as $v_\infty = 1500\,{\rm km\,s^{-1}}$.) Tentatively, we fix the mass loss rate of the donor as $\dot{M}_{\rm w} = 5 \times 10^{-7}\, M_\odot\,{\rm yr}^{-1}$, so as to yield typical results.

The vertical line is the magnetic field strength which is derived by observed cyclotron lines. In case that the cross-section of the vertical line and the horizontal band between two horizontal lines appears in the shaded region, the system can be considered a *normal* wind-fed HMXB, which can be understood only with the previous model. Actually, most of our sample shows good agreement with the standard scenario. However, in some systems, we need to reconsider our models in order to explain the fact that such crossing points come out of the direct accretion regime.

Figure 1 depicts the results of our sample. Six of nine sources (4U1907, 4U1538, J16493, 2S0114, J16393 and J18027) are found to be in good agreement with the standard wind-fed scenario as described above. A note should be made concerning Vela X-1, because this source can satisfy our constraint if the mass-loss rate reaches $\dot{M} = 5 \times 10^{-7}\, M_\odot\,{\rm yr}^{-1}$. If this value is larger, however, this system cannot satisfy the above condition when v_∞ is large. Assuming that the mass-loss rate is reasonably high ($\dot{M} \sim 10^{-6}\, M_\odot\,{\rm yr}^{-1}$), the wind velocity would be limited below $1000\,{\rm km\,s^{-1}}$. This result is consistent with a recent result given by Giménez-García et al. (2016). On the other hand, two systems (LMC X-4 and OAO 1657) cannot satisfy the wind-fed condition. That is, the reasonable band-region of v_∞ cannot cross the observed $B_{\rm field}$ in the direct accretion regime (shaded area in Fig. 1).

Since LMC X-4 is one of the tightest X-ray binaries with an SG donor, it has been argued that the Roche lobe of the donor is filled in this system. If this is true, in this system the accreting matter is transferred via a Roche lobe overflow scenario passing the L1 point, and the wind-fed scenario cannot be applied. In a recent study, however, it is suggested that the donor in LMC X-4 is much smaller than its Roche radius (Falanga et al. 2015). Another possibility is that our assumption on the mass-loss rate ($\dot{M} = 5 \times 10^{-7}\, M_\odot\,{\rm yr}^{-1}$) is not valid. To check this validity, we vary the mass-loss rate and try the computations again. In Figure 2, the same expressions are shown

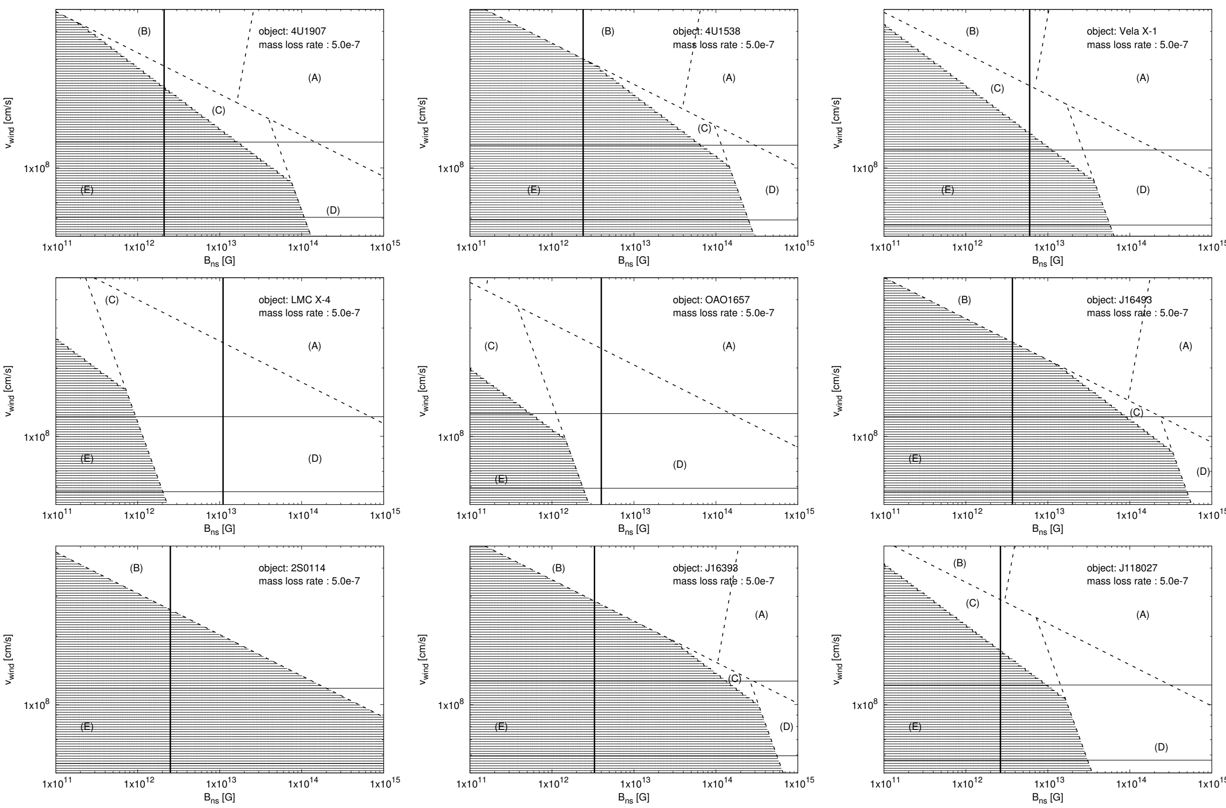

Fig. 1 The accretion regime in the wind velocity-mass loss rate space for different systems. The *shaded region* labeled as (E) indicates the direct accretion regime where an HMXB can be observed as a bright X-ray source. The two *horizontal lines* represent high $(1500\,\mathrm{km\,s^{-1}})$ and low $(700\,\mathrm{km\,s^{-1}})$ terminal velocity: v_∞. The *vertical line* shows the derived magnetic field from cyclotron lines. If the region is being bounded by the vertical line with two *horizontal lines* (in the *shaded region*), the system can be understood with the standard wind-fed scenario of SG-HMXB. In our sample set, only two systems (LMC X-4 and OAO 1657) cannot be explained with the standard model.

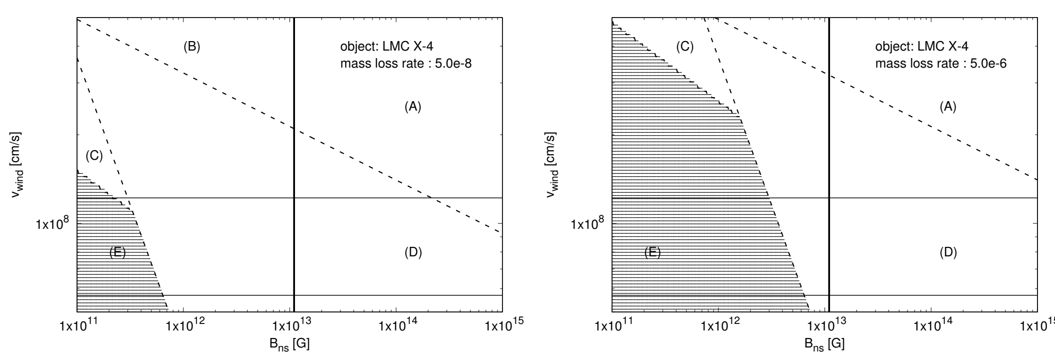

Fig. 2 The same as Fig. 1, but for LMC X-4 in the cases of high and low mass-loss rate: $5 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ (*left panel*) and $5 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$ (*right panel*).

for LMC X-4 in the cases of high and low mass-loss rate: $5 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ (left panel) and $5 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$ (right panel), respectively. When the mass-loss rate is quite large and the wind velocity is slow, the wind-fed condition could be satisfied. However, the donor of LMC X-4 is not highly evolved if its Roche lobe is not filled, and it is questionable if such a donor can emit such a dense and slow wind. Hence, in this system, the intermediate state between Roche lobe overflow and wind-fed accretion (Nagae et al. 2004) may be realized.

OAO 1657 also cannot be explained by a standard wind-fed scenario in Figure 1. For this source, we try to

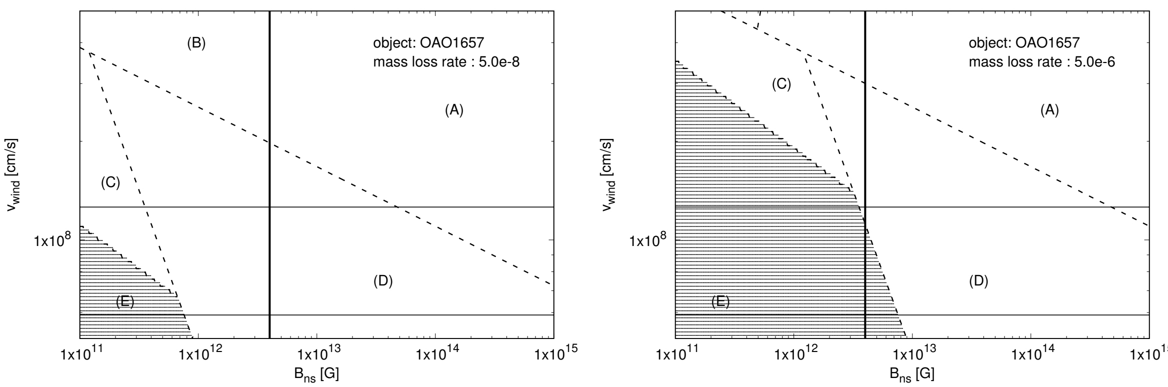

Fig. 3 The same as Fig. 2, but for OAO 1657 in the cases of high and low mass-loss rate.

compute the different mass-loss rate and show the results in Figure 3. From this figure, we can see that if the mass-loss rate is extremely high (and wind velocity is preferably slow), the system can satisfy the wind-fed condition. In this system, the donor may be a Wolf-Rayet (WR) star and may emit a very dense wind. Therefore, such a dense and slow wind may be possible in this system. However, if the donor is a WR star, its evolutionary process becomes another puzzle (Mason et al. 2012). In this source, further studies both with theory and observations are required.

4 DISCUSSION

Our method based on the equations gives a relationship of $v_{\rm w}$ as a function of $B_{\rm NS}$. We plotted figures (Figs. 1–3) for all our sample. We have considered two extreme cases of wind velocity in these figures ($1500\,{\rm km\,s^{-1}}$ for fast wind and $700\,{\rm km\,s^{-1}}$ for slow wind). The lower sequence is realistic for persistent wind-fed HMXBs and the upper bound is typical for SFXTs (Giménez-García et al. 2016). The direct accretion region is also plotted in the same figures, which qualitatively explain their different X-ray behavior. From these figures (especially Figs. 2 and 3), it has been shown that a smaller $\dot{M}_{\rm w}$ could be rejected.

Another important parameter of HMXBs which we have not examined in this study is the variation of spin. The numerical calculations carried out by many authors suggest that there is no significant influence of angular momentum transfer onto the NS from the wind of SG sources (Ruffert 1999; Fryxell & Taam 1988; Matsuda et al. 1992; Anzer & Boerner 1995; Reig et al. 2001; Ikhsanov & Mereghetti 2015). Even with slow wind velocity, the flow structure seems to be insufficient to exert a spin-up torque onto the NS. Since the transfer of angular momentum during the accretion phase is inefficient, there could be a small deviation from the instantaneous spin periods at the early stage of the accretion phase (Dai et al. 2016).

We should note here that if the accretion rate is too small, e.g. $\dot{M} \geq 10^{8-10}\,M_\odot\,{\rm yr^{-1}}$, the shock-crossing time would become too long and the angular momentum could be diffused when the shock passes (see Shakura et al. 2012). If enough angular momentum is transferred around the NS, an accretion disk may be formed outside the magnetic radius under certain conditions. However, at the higher accretion rate, the disk could not be a standard disk and expands, making a torus. In our preliminary analysis, the mass loss rate from the donor should be between 10^{-7} and $10^{-5}\,M_\odot\,{\rm yr^{-1}}$ to form an accretion disk. This range seems to be reasonable from a standard mass loss theory of SG stars. Therefore, the magnetic field is responsible for formation of an accretion column since it forces the particles to hit the NS surface at its magnetic poles. In principle, more complex magnetic fields than a dipole field are possible. It is noteworthy to mention here that a relatively high X-ray luminosity such as J16493 makes these sources the prime candidates for being disk-fed systems (see Reig et al. 2001; Falanga et al. 2015), whereas rather dim systems are all thought to be wind-fed systems (Shakura & Postnov 2017).

It may be interesting to investigate the relation of wind velocity as a function of spin period. These parameters greatly affect the model of wind-fed binary systems and can be constrained during binary evolution. It is clear that sudden changes in the wind density as well as the mass loss rate may lead to switching from one accretion regime to the other. It should be noted that the eccentricity of the orbit ($e \leq 0.25$) would lead also to additional variations in the orbital separation (and consequently in $v_{\rm w}$), which reinforce the intrinsic variability of the stellar wind and its capability to lead to transitions across regimes (Shenar 2017).

It is convenient to separate the evolution of the sources based on their accretion regimes as well as the stellar parameters. The unusual properties (slow rotator, low X-

Table 1 Parameters of HMXBs with SG Companions Identified with Their Cyclotron Lines

Object	$P_{\rm spin}$ (s)	$P_{\rm orbit}$ (d)	e	distance (kpc)	$E_{\rm cyc}$ (keV)	$M_{\rm NS}$ ($M_\odot$)	$M_{\rm comp.}$ ($M_\odot$)	Reference
4U 1907+09	439	8.37	0.28	5	18.8±0.4	1.4	27	[1], [2], [3]
4U 1538−52	529	3.73	0.18	4.5	$21.4^{+0.9}_{-2.4}$	1.06	16.4	[2], [4], [5], [6]
Vela X–1	283	8.96	0.09	1.4	$54^{+0.5}_{-1.1}$	1.86	23.8	[7], [8], [9], [10], [11]
Cen X–3	4.8	2.09	0.01	5.7	$30.4^{+0.3}_{-0.4}$	1.5	20	[2], [8], [11], [12]
LMC X–4	13.5	1.4	0.06	50	100±2.1	1.25	14.5	[8], [13]
OAO 1657–415	37.7	10.4	0.1	7.1	36	1.42	41	[14], [15], [16]
J16493–4348	1069	6.78	0.25	10.7	33±4	–†	–	[17], [18], [19], [20]
2S 0114+65	9700	11.6	0.16	7.2	22	1.7	16	[21], [22]
J18027–201	140	4.6	0.2	12.4	23	1.6	21.8	[23], [24]

† The X-ray mass function is $6.5 \pm 1.1\,M_\odot$ (see Thompson et al. 2006, for full details).

References: [1] Cusumano et al. (1998); [2] Coburn et al. (2002); [3] Rivers et al. (2010); [4] Clark et al. (1990); [5] Robba et al. (2001); [6] Rodes-Roca et al. (2009); [7] Kretschmar et al. (2005); [8] Makishima et al. (1990); [9] Kreykenbohm et al. (2002); [10] Schanne et al. (2007); [11] Walter et al. (2015); [12] Santangelo (1998); [13] La Barbera et al. (2001); [14] Orlandini et al. (1999); [15] Denis et al. (2010); [16] Pottschmidt et al. (2012); [17] Bodaghee et al. (2006); [18] Nespoli et al. (2010); [19] D'Aì et al. (2011); [20] Bodaghee et al. (2016); [21] Bonning & Falanga (2005); [22] den Hartog et al. (2006); [23] Mason et al. (2012); [24] Lutovinov et al. (2017).

ray luminosity and a super-orbital periodicity of 30.7 days, Farrell et al. 2006) exhibited by 1A 0114+650 would be worth investigating with regards to the origin of the X-ray behavior. It suggests that this source evolves on the time scale of several years (Wang 2010), or it was born as a magnetar with $B \sim 10^{14}$ G (Sanjurjo-Ferrrín et al. 2017; Tong & Wang 2018). However, the propeller effect can spin down the NS to $5{\times}10^3$ s (Reig et al. 2001) keeping the same values as above but taking the magnetic field to 10^{14} G, two orders of magnitude higher. On the other hand, a note should be made concerning systems with slow wind (such as OAO 1657-415). This source is considered a suitable candidate to be a wind-fed system for most of the time among the known HMXBs, and it is undergoing an episode of enhanced accretion from a temporary disk (Falanga et al. 2015). Since this binary system has a wide range for Roche-lobe overflow to occur, this may provide clear evidence that winds in HMXBs possess sufficient angular momentum to form accretion disks (see, e.g., Chakrabarty et al. 1993; Bildsten et al. 1997). In contrast, in tight systems (such as LMC X-4), the donor does not fill its Roche lobe (see Falanga et al. 2015). As explained before, this would imply the possibility that even in wind-fed systems, in a certain situation, enough angular momentum could be transferred via stellar wind and accreted matter may form an accretion disk.

5 CONCLUSIONS

We have performed parameter search computations to study the physical parameters of wind terminal velocity, mass loss rate and then the magnetic field of HMXBs with SG companions. These quantities are important aspects of their evolution due to the interaction between components of the binary system. We also studied the accretion regimes modeled by Bozzo et al. (2008) and prospects corresponding to the mass loss rate. Depending on their theory, this will allow us to plot the $v_{\rm wind}$-$B_{\rm field}$ diagram of several sources at different mass-loss rates, where the different accretion regimes occupy a different space of parameters. This would help us to study their evolutionary scenario.

We demonstrate that six of nine systems show good agreement with the standard wind-fed scenario. They are 4U1907, 4U1538, J16493, 2S0114, J16393 and J18027. Additionally, Vela X-1 satisfies our constraint in the $v_{\rm wind} - B_{\rm field}$ plane with $\dot{M} \leq 5 \times 10^{-7}\,M_\odot\ {\rm yr}^{-1}$. We assume that the mass-loss rate is reasonably high ($\dot{M} \sim 10^{-6}\,M_\odot\,{\rm yr}^{-1}$). As a result, the wind velocity would be limited below $1000\,{\rm km\,s}^{-1}$. This result is consistent with the recent result given by Giménez-García et al. (2016). On the other hand, two systems (LMC X-4 and OAO 1657) cannot satisfy the wind-fed condition, since the reasonable band-region of v_∞ cannot cross the observed $B_{\rm field}$ in the direct accretion regime.

Our study shows that only when the system enters the inner edge of the accretion regime can it emit bright X-rays and can be observed as an SG-HMXB, characterized by the zone of cross-section of the magnetic field in the figures (vertical line) with the wind velocity given by equations (two horizontal lines).

As has been correctly pointed out, several sources show variations in wind velocity in the range of about 500 – $2300\,{\rm km\,s}^{-1}$. These variations can be understood during the rotation phase at different parts, and also due to a change in structure of the magnetic field through to accretion dynamics, e.g. a change in accretion rate, as is seen for sources like Vela X-1, J118027 and OAO 1657.

The mass loss proceeds via spherical wind and the terminal velocity can be obtained in a well-defined way for a number of wind-fed sources, where the donor is an SG-type. According to our model, a sufficient amount of angular momentum can be transferred via stellar wind and accreted matter to form an accretion disk. This would make it happen in tight systems such as in J18027–201, J16393–4643 and 4U 1538–52, or in systems with slow wind compared to the relative orbital velocity of the system, such as OAO 1657-415 and 2S 0114+65. As a result, more interaction between the accreted matter and stars occurs, which may turn the binary into a good HMXB candidate via wind fed accretion around NS. One can relate the changes in accretion rates with the formation of a temporary accretion disk.

Furthermore, we have found that the range between 10^{-7} and $10^{-5}\,M_\odot$ yr^{-1} represents the critical value of the disk to be formed in wind-fed X-ray binary systems. This range seems to be reasonable from a standard mass loss theory of SG systems. As a result, if the wind mass-loss rate decreased, this would lead to the disruption of the disk and disappearance of the X-ray emission, which supports the reliability of current mass-loss rate predictions.

Finally, however, our model explains several important aspects of the behavior of disk-fed accreting X-ray binaries from low-level stellar wind accretion. In a few sources, the wind-accretion scenario cannot be applied. Thus, other scenarios (i.e. disk formation, partial Roche lobe overflow or quasi Roche lobe) should be considered for further evolution of such binaries.

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References

Anzer, U., & Boerner, G. 1995, A&A, 299, 62
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1
Bildsten, L., Chakrabarty, D., Chiu, J., et al. 1997, ApJS, 113, 367
Bodaghee, A., Tomsick, J. A., Fornasini, F. M., et al. 2016, ApJ, 823, 146
Bodaghee, A., Walter, R., Zurita Heras, J. A & et al. 2006, A&A, 447, 1027B
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Bonning, E. W., & Falanga, M. 2005, A&A, 436, L31
Bozzo, E., Falanga, M., & Stella, L. 2008, ApJ, 683, 1031
Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, ApJ, 195, 157
Chakrabarty, D., Grunsfeld, J. M., Prince, T. A., et al. 1993, ApJ, 403, L33
Clark, G. W., Woo, J. W., Nagase, F., Makishima, K., & Sakao, T. 1990, ApJ, 353, 274
Coburn, W., Heindl, W. A., Rothschild, R. E., et al. 2002, ApJ, 580, 394
Coley, J. B., Corbet, R. H. D., & Krimm, H. A. 2015, ApJ, 808, 140
Cusumano, G., di Salvo, T., Burderi, L., et al. 1998, A&A, 338, L79
D'Aì, A., Cusumano, G., La Parola, V., et al. 2011, A&A, 532, A73
Dai, H.-L., & Li, X.-D. 2006, A&A, 451, 581
Dai, H.-L., Liu, X.-W., & Li, X.-D. 2016, MNRAS, 457, 3889
Dai, Z., Szkody, P., Taani, A., Garnavich, P. M., & Kennedy, M. 2017, A&A, 606, A45
den Hartog, P. R., Hermsen, W., Kuiper, L., et al. 2006, A&A, 451, 587
Denis, M., Bulik, T., & Marcinkowski, R. 2010, Acta Astronomica, 60, 75
Falanga, M., Bozzo, E., Lutovinov, A., et al. 2015, A&A, 577, A130
Farrell, S. A., Sood, R. K., & O'Neill, P. M. 2006, MNRAS, 367, 1457
Feldmeier, A., Oskinova, L., & Hamann, W.-R. 2003, A&A, 403, 217
Fryxell, B. A., & Taam, R. E. 1988, ApJ, 335, 862
Giménez-García, A., Shenar, T., Torrejón, J. M., et al. 2016, A&A, 591, A26
Ikhsanov, N. R., & Mereghetti, S. 2015, MNRAS, 454, 3760
Karino, S., & Miller, J. C. 2016, MNRAS, 462, 3476
Kluźniak, W., & Rappaport, S. 2007, ApJ, 671, 1990
Kretschmar, P., Kreykenbohm, I., Pottschmidt, K., et al. 2005, The Astronomer's Telegram, 601
Kreykenbohm, I., Coburn, W., Wilms, J., et al. 2002, A&A, 395, 129
Krtička, J., & Kubát, J. 2017, A&A, 606, A31
Krtička, J., Kubát, J., & Krtičková, I. 2016, A&A, 593, A101
La Barbera, A., Burderi, L., Di Salvo, T., Iaria, R., & Robba, N. R. 2001, ApJ, 553, 375

Lamers, H. J. G. L. M., Haser, S., de Koter, A., & Leitherer, C. 1999, ApJ, 516, 872

Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2006, A&A, 455, 1165

Lutovinov, A. A., Tsygankov, S. S., Postnov, K. A., et al. 2017, MNRAS, 466, 593

Macfarlane, J. J., Cassinelli, J. P., Welsh, B. Y., et al. 1991, ApJ, 380, 564

Makishima, K., Mihara, T., Ishida, M., et al. 1990, ApJ, 365, L59

Mason, A. B., Clark, J. S., Norton, A. J., et al. 2012, MNRAS, 422, 199

Matsuda, T., Ishii, T., Sekino, N., et al. 1992, MNRAS, 255, 183

Mushtukov, A. A., Tsygankov, S. S., Serber, A. V., Suleimanov, V. F., & Poutanen, J. 2015, MNRAS, 454, 2714

Nagae, T., Oka, K., Matsuda, T., et al. 2004, A&A, 419, 335

Najarro, F., Hanson, M. M., & Puls, J. 2011, A&A, 535, A32

Nespoli, E., Fabregat, J., & Mennickent, R. E. 2010, A&A, 516, A106

Nishimura, O. 2003, PASJ, 55, 849

Orlandini, M., dal Fiume, D., del Sordo, S., et al. 1999, A&A, 349, L9

Postnov, K., Oskinova, L., & Torrejón, J. M. 2017, arXiv:1701.00336

Pottschmidt, K., Suchy, S., Rivers, E., et al. 2012, in American Institute of Physics Conference Series, Vol. 1427, American Institute of Physics Conference Series, ed. R. Petre, K. Mitsuda, & L. Angelini, 60

Pringle, J. E., & Rees, M. J. 1972, A&A, 21, 1

Puls, J., Markova, N., Scuderi, S., et al. 2006, A&A, 454, 625

Rawls, M. L., Orosz, J. A., McClintock, J. E., et al. 2011, ApJ, 730, 25

Reig, P., Negueruela, I., Buckley, D. A. H., et al. 2001, A&A, 367, 266

Reig, P., Nersesian, A., Zezas, A., Gkouvelis, L., & Coe, M. J. 2016, A&A, 590, A122

Rivers, E., Markowitz, A., Pottschmidt, K., et al. 2010, ApJ, 709, 179

Robba, N. R., Burderi, L., Di Salvo, T., Iaria, R., & Cusumano, G. 2001, ApJ, 562, 950

Rodes-Roca, J. J., Torrejón, J. M., Kreykenbohm, I., et al. 2009, A&A, 508, 395

Ruffert, M. 1999, A&A, 346, 861

Saladino, M. I., Pols, O. R., van der Helm, E., Pelupessy, I., & Portegies Zwart, S. 2018, arXiv:1805.03208

Sanjurjo-Ferrrín, G., Torrejón, J. M., Postnov, K., et al. 2017, A&A, 606, A145

Santangelo, A., del Sordo, S., Segreto, A., et al. 1998, ApJ, 340, 55

Schanne, S., Götz, D., Gérard, L., et al. 2007, in ESA Special Publication, Vol. 622, The Obscured Universe. Proceedings of the VI INTEGRAL Workshop, 479

Shakura, N., & Postnov, K. 2017, arXiv:1702.03393

Shakura, N., Postnov, K., Kochetkova, A., & Hjalmarsdotter, L. 2012, MNRAS, 420, 216

Shenar, T. 2017, Comprehensive Analyses of Massive Binaries and Implications on Stellar Evolution, PhD thesis, Universität Potsdam

Stella, L., White, N. E., & Rosner, R. 1986, ApJ, 308, 669

Taani, A. 2016, RAA (Research in Astronomy and Astrophysics), 16, 101

Taani, A., Karino, S., Song, L., Zhang, C., & Chaty, S. 2018, arXiv:1808.05345

Taani, A., & Khasawaneh, A. 2017, Journal of Physics: Conference Series, 869, 012090

Taani, A., Zhang, C., Al-Wardat, M., & Zhao, Y. 2012a, Ap&SS, 340, 147

Taani, A., Zhang, C. M., Al-Wardat, M., & Zhao, Y. H. 2012b, Astronomische Nachrichten, 333, 53

Thompson, T. W. J., Tomsick, J. A., Rothschild, R. E., in't Zand, J. J. M., & Walter, R. 2006, ApJ, 649, 373

Tong, H. 2015, RAA (Research in Astronomy and Astrophysics), 15, 517

Tong, H., & Wang, W. 2018, arXiv:1806.05784

Truemper, J., Pietsch, W., Reppin, C., et al. 1978, ApJ, 219, L105

van den Heuvel, E. P. J. 2004, Science, 303, 1143

Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574

Voges, W., Pietsch, W., Reppin, C., et al. 1982, ApJ, 263, 803

Walter, R., Lutovinov, A. A., Bozzo, E., & Tsygankov, S. S. 2015, A&A Rev., 23, 2

Wang, W., 2010, A&A, 520, A22

Wang, Y.-M. 1995, ApJ, 449, L153

Wang, Y.-M., & Robertson, J. A. 1985, A&A, 151, 361

Wei, Y. C., Taani, A., Pan, Y. Y., et al. 2010, Chinese Physics Letters, 27, 119801

Wilson, C. A., Finger, M. H., & Camero-Arranz, A. 2008, ApJ, 678, 1263

Zhang, C. M., & Kojima, Y. 2006, MNRAS, 366, 137