

Evidence from high-mass X-ray binaries that Galactic WR components of WR+O binaries end their life with a supernova explosion

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ABSTRACT

Context. Theoretical population number studies of binaries with at least one black hole (BH) component obviously depend on whether or not BHs receive a (natal) kick during their formation.

Aims. Several observational facts seem to indicate that BHs do indeed receive a kick during their formation. In the present paper, we discuss additional evidence of this.

Methods. The progenitors of wind-fed high-mass X-ray binaries (HMXB) with a BH component (BH HMXB) are WR+OB binaries where the Wolf-Rayet (WR) star will finally collapse and form the BH. Starting from the observed population of WR+OB binaries in the solar neighborhood, we predict the population of wind-fed BH HMXBs as a function of the BH-natal kick.

Results. The simulations reveal that when WR stars collapse into a BH with a zero or low kick, we should expect 100 or more wind-fed BH HMXBs in the solar neighborhood, whereas only one is observed (Cyg X-1). We consider this as evidence that either WR components in binaries end their life as a neutron star or that they collapse into BHs, both accompanied by a supernova explosion imparting significant (natal) kicks.

Key words. binaries: close – stars: evolution – stars: massive – X-rays: binaries – stars: Wolf-Rayet – stars: black holes

1. Introduction

The detection by LIGO/Virgo of gravitational waves (GW) resulting from merging binary neutron stars (BNS), merging binary black holes (BBH), and merging mixed binary systems (BNSBH) opened a new window to explore the Universe. One of the striking results (striking at least as far as the evolution of massive binaries is concerned) is that the LIGO/Virgo data support the existence of BHs with a mass up to (and even larger than) $40 M_{\odot}$. We note that these high masses were predicted in the recent past (De Donder & Vanbeveren, 2003, 2004; Belczynski et al., 2010) by evolutionary simulations of massive binaries during which core helium burning (= the Wolf-Rayet [WR] phase) the effect of stellar wind mass loss was calculated using a formalism obtained with a WR-atmosphere code that includes clumping and with a metallicity dependency as predicted by the radiatively driven wind theory (e.g., Hamann & Koesterke, 1998, 2000; see also the Appendix).

The LIGO-discovery of the first massive BBH merger (GW150914) was announced in 2015. We note that before 2015, binary population number (BPN) simulations of double compact star binaries predicted GW150914-like events (e.g., Voss & Tauris (2003), Dominik et al. (2012, 2013), Mennekens & Vanbeveren (2014)). Since 2015, the number of such BPN simulations has increased significantly.

One of the main uncertainties in the BPN prediction of BBH and BNSBH mergers is whether BH formation is accompanied by a supernova (SN) explosion and whether this SN explosion produces a BH kick that is large enough to affect overall BBH

and BNSBH formation. This is the main scope of the present paper.

The proper motion of pulsars has been intensively studied since the early 1990s (e.g., Lyne & Lorimer, 1994; Hansen & Phinney, 1997; Arzoumanian et al., 2002; Pfahl et al., 2002; Hobbs et al., 2005) and this resulted in the now generally accepted conclusion that neutron stars (NSs) may receive kicks at birth (natal kicks - NKs) with an average in the range of 200-500 km/s, when they are formed in core-collapse SNe. Possible exceptions are NSs born in a prompt (fast) electron-capture SN where the resulting kick is expected to be small (Nomoto, 1984, 1987; Podsiadlowski et al., 2004).

Arguments favoring or disfavoring BH kicks based on direct physical principles are inconclusive (Ozel et al., 2010; Farr et al., 2011; Belczynski et al., 2012). Individual binaries containing a BH companion have been investigated by many authors (e.g., Brandt et al., 1995; Nelemans et al., 1999; Remillard et al., 2000; Gualandris et al., 2005; Willems et al., 2005; Dhawan et al., 2007; Fragos et al., 2009; Wong et al., 2010, 2012, 2014). A common conclusion is that the BHs in these binaries must have either been formed without, or with rather modest, NKs.

Repetto et al. (2012) (see also Repetto et al., 2017) considered the observed distribution of distances above the Galactic plane of low-mass X-ray binaries containing a BH component and compared this with binary population synthesis simulations by adopting different initial NK-distributions. They conclude that a distribution similar to that of neutron stars (e.g., Hanson & Phinney, 1997) seems to be preferred. For a critical discussion of the Repetto et al. results, see Belczynski et al. (2016).

Woosley (2019) present detailed evolutionary computations of massive galactic helium stars that have lost all of their hydrogen at the beginning of core helium burning (e.g., remnants after Roche-lobe overflow (RLOF) if these stars were binary components equal to He-zero age main sequence (He-ZAMS) stars). To account for mass loss by Wolf-Rayet-like stellar winds, the author used the prescription of Yoon (2017) (see Appendix). An important conclusion resulting from these computations is that most of the hydrogen free helium stars with He-ZAMS mass between $9 M_{\odot}$ and $60 M_{\odot}$, which correspond to end-core-helium burning mass between $7 M_{\odot}$ and $30 M_{\odot}$ and to progenitor H-ZAMS mass between $30 M_{\odot}$ and $120 M_{\odot}$, make BHs. It is unclear whether some of them might explode and for those that explode whether the explosion is symmetric or asymmetric.

To further study the latter, the following may be a possibility. The 9-60 M_{\odot} He-ZAMS mass range is also the mass range of the WR stars in the known galactic WR+O binaries. If the WR star collapses into a BH, a BH+O binary is formed, which may become a wind-fed high-mass X-ray binary (a BH HMXB like Cyg X-1). In the present paper, we consider the following: There are about 70 WR+OB binaries, probable WR+OB binaries in the solar neighborhood¹ (van der Hucht, 2001), and only one high-mass BH+OB X-ray binary. We explore whether this is compatible with the assumption that the WR stars collapse into a BH and that the collapse does not disrupt the binary. Section 2 describes the methodology. In Sections 3 and 4, we demonstrate that the aforementioned assumption is incorrect. Section 5 then deals with an alternative.

2. Method

We consider the population of observed WR+O binaries in the solar neighborhood and selected those where we have a reasonable estimate of the masses of both components. Using our evolutionary computations of hydrogen deficient post-RLOF massive core helium burning stars² and given the mass of the WR star, we calculated the expected mass of the WR star at the end of core helium burning. In order to do this, we assumed that in case the WR star is of the nitrogen sequence (a WN star) (of the carbon sequence, a WC star, respectively) the star is at the beginning of the core helium burning phase (beginning of the WC phase defined as the moment during core helium burning where due to stellar wind mass loss 3-alpha burning products appear at the surface, respectively). It is important to mention that this assumption does not significantly affect the overall conclusions of the present paper. If the final WR star collapses into a BH without a SN explosion (i.e., the mass of the BH is equal to the final WR mass) a BH+O binary is formed, which may evolve into a (wind-fed) BH HMXB. Given the mass-spectral type-luminosity class of the O-type companion, we simulated its further evolution by interpolating in the Geneva tracks described in Ekstrom et al. (2012). We note that these evolutionary computations hold for massive stars that rotate at rates which are similar to the rotation rates of O-type components in WR+O binaries (Shara et al., 2017). We now proceed as follows. A massive binary system consisting of an OB star and a BH may become a HMXB when part of the stellar wind matter that is lost by the OB star is grav-

itationally trapped by the BH. Losses of gravitational energy of this material at the time of accretion by the BH then produce the X-ray radiation.

To obtain X-rays, however, the presence of an accretion disk is required in the case of a BH (Shapiro & Lightman, 1976; Iben et al., 1995). A Keplerian disk is formed when the specific angular momentum of the accreted matter exceeds that of the largest possible stable orbit around the BH, corresponding to a radius R_K in which R_K is approximately three times the Schwarzschild radius. This condition is satisfied when

$$\frac{R}{A} \geq \left(1 - \frac{R}{A}\right)^{\frac{8}{7}} \left(\frac{R_K}{R}\right)^{\frac{1}{7}} \left(\frac{M}{M_{BH}}\right)^{\frac{3}{7}} \quad (1)$$

or equivalently

$$\frac{R}{A} \geq \frac{a}{1+a} \quad (2)$$

with $a = \left(\frac{R_K}{A}\right)^{\frac{1}{8}} \left(\frac{M}{M_{BH}}\right)^{\frac{3}{8}}$, where R and M are the radius and the mass of the optical component, respectively, A is the semimajor axis of the binary, and M_{BH} is the mass of the BH. When the optical OB companion of a BH does not fill its Roche lobe, the latter accretes material by capturing a fraction of the stellar wind gas of the former. To estimate the X-ray luminosity in these wind-fed systems, we used the model of Davidson & Ostriker (1973), which involves accretion of matter according to Bondi & Hoyle (1944).

We identified the X-ray luminosity L_X with the gravitational energy release of the accreted matter

$$L_X = G \frac{M_{BH} \dot{M}_{accr}}{R_K}, \quad (3)$$

where G is the gravitational constant and \dot{M}_{accr} is the amount of matter accreted from the stellar wind by the BH in a unit of time, given by

$$\dot{M}_{accr} = \varepsilon \left(\frac{M_{BH}}{M}\right)^2 \frac{\delta^2}{(1+\delta)^{3/2}} \dot{M} \quad (4)$$

with $\delta = \frac{R}{2A} \left(\frac{v_{esc}}{v_{wind}}\right)^2$. Here, v_{esc} and v_{wind} are the escape velocity of the OB-star and wind velocity at the location of the BH, respectively. The stellar wind mass loss rate of the OB-type star, \dot{M} was calculated using the formalism proposed by Vink et al. (2000), which corresponds to the mass loss rate formalism used in the Geneva evolutionary code.

As shown by Groenewegen & Lamers (1989), v_{wind} can be described by a β -law $v_{wind} = v_{\infty} \left(1 - \frac{R}{A}\right)^{\beta}$, where v_{∞} is the wind velocity at infinity and β is between 0.7 and 1.5. Our results were computed with $\beta = 1$ but the L_X values differ by no more than a factor of two when other values of β were used and this difference is small enough not to affect our basic conclusions. The ratio $\frac{v_{esc}}{v_{\infty}}$ was also taken from the formalism proposed by Vink et al. (2000).

The factor ε in Equation (4) accounts for a self-limiting effect on the X-ray luminosity due to its radiation pressure. Eddington (1926) estimated it as

$$\varepsilon = \left(1 - \frac{L_X}{L_{Edd}}\right)^2 \quad (5)$$

¹ Here, 3-4 kpc from the Sun is defined as the solar neighborhood.

² We used the Brussels stellar evolutionary code as it was described in Vanbeveren et al. (1998c). One of the main uncertainties that significantly affects the core helium burning evolution of massive stars and binary components is the stellar wind mass loss rate formalism used in the code. The latter is discussed in the Appendix.

with $L_{Edd} = \frac{4\pi c G M_{BH}}{\sigma_e} = \frac{65335 L_{\odot} M_{BH}}{1+X M_{\odot}}$, where X represents the hydrogen abundance in the accreted material, c is the speed of light, and σ_e is the electron scattering coefficient. The mass accretion rate \dot{M}_{Edd} producing L_{Edd} through its gravitational energy release satisfies

$$L_{Edd} = G \frac{M_{BH}}{R_K} \dot{M}_{Edd}. \quad (6)$$

Then, when solving for L_X , one obtains

$$L_X = \frac{\alpha}{(1 + \sqrt{1 + \alpha})^2} L_{Edd} \quad (7)$$

with $\alpha = 4 \frac{\delta^2}{(1+\delta)^{3/2}} \left(\frac{M_{BH}}{M}\right)^2 \frac{\dot{M}}{\dot{M}_{Edd}}$.

To illustrate our method, it is helpful to consider a fictitious but typical WR+O binary: a WN+O6V system with masses $19 + 32 M_{\odot}$ and with an orbital period of 2, 4, 10, and 15 days. The pre-RLOF progenitor of the WN star has a ZAMS mass of $40 M_{\odot}$, which implies that the WN star is ~ 5.5 Myr old (see Vanbeveren et al., 1998b, c). At the end of core helium burning (~ 0.5 Myr later), the WR star is a WC-type star with mass = $11 M_{\odot}$, whereas the orbital period has increased due to the spherical wind and reaches values of 2.8, 5.6, 14.1, and 21.1 days, respectively. According to the spectral type and luminosity class of the O-type companion, the star is on the Geneva $32 M_{\odot}$ evolutionary track somewhere between 0 and 2 Myr. This means that due to mass accretion during the previous RLOF, the O star is rejuvenated and looks like a $32 M_{\odot}$ star that is at most 2 Myr old, even though the lifetime of the binary is 5.5 Myr. We began our simulations by starting from the 2 Myr point on the $32 M_{\odot}$ evolutionary track and we computed the temporal evolution of the X-ray luminosity using the formalism described above and assuming that the $11 M_{\odot}$ WC star collapses into a $11 M_{\odot}$ BH without a SN explosion and thus without a natal kick. The results are shown in Figure 1³. First, it is important to note that all of our wind-fed systems have $L_X > 10^{35}$ erg/sec, which means that they would have been detected by present (and previous) all-sky-monitors if the sources were located within 3-4 kpc from the Sun (prof. Wijnands, prof. van der Klis, private communication). We note that high-mass X-ray binaries with X-ray luminosities similar to the ones of the BH-systems predicted here (around 10^{35} erg/s or larger) are concentrated close to the Galactic plane, and they are seen throughout our Galaxy. So, extinction is not expected to play a role in their detectability. In particular, the hard part of their X-ray spectrum (above 10 keV), which tends to dominate in the case of BHs, is not expected to suffer any interstellar extinction. The results can be interpreted as follows: The average core helium burning lifetime of the WR+O binary is 400000 ± 100000 yrs. Figure 1a, which reveals that the X-ray lifetime of the wind-fed system is 4-5 Myr, then illustrates that for every WR+O binary within 3-4 kpc from the Sun with masses $19+32 M_{\odot}$ and with a period of two days, we expect to observe $4-5 \text{ Myr}/300000-400000 \text{ yr} = 10-17$ BH+OB HMXBs. When we repeated this for the same WR+O binary but with an orbital period of ten days, it follows from Figure 1d that we expect 1 BH+OB HMXB at most. It is important to note that for

³ The final rise of the X-ray luminosity is due to the fact that the $32 M_{\odot}$ star enters the hydrogen shell burning phase, thus implying a rapid increase in the radius and the stellar wind mass loss rate (the Vink-rates) of the star. Due to the fact that this phase is very short, it does not affect our population number results. The simulations stop when the star fills its Roche lobe.

a WR+O period of 15 days, we essentially expect no wind-fed HMXBs. By considering the observed WR+O binary population within 3-4 kpc from the Sun and by performing the previous exercise for all of them, we can get an indication of how many BH+OB HMXBs are expected within 3-4 kpc if it is assumed that the WR stars in all of the WR+O binaries collapse into BHs without a SN explosion. This is discussed in the next section.

3. The WR+O binary population in the solar neighborhood

Using the WR catalogs of van der Hucht (2001, 2006) and of Crowther (2017), Table 1 collects the double-lined spectroscopic WR binaries in the solar neighborhood for which reasonable estimates of the minimum masses of both components are known. The procedure as outlined by Vanbeveren et al. (2018) allows one to propose most probable masses of both components. In summary, applying the mass-spectral type and luminosity class relation proposed by Vanbeveren et al. (1998c) for the O-type component yields the mass-range estimates of Table 1⁴. We note that very similar results are obtained when the calibration of stellar parameters of Galactic O stars of Martins et al. (2005) is used. The combination of the observed mass functions and the inclination angle ranges (we used the values given in the catalogues listed above when available) explains the adopted masses in Table 1. Using the method outlined at the beginning of the previous section then allows one to propose the masses of the WR components and the system periods at the end of core helium burning. The following two remarks are appropriate. First, the minimum mass of the WR components is $\sim 9 M_{\odot}$, corresponding to an initial hydrogen ZAMS mass of $\sim 25-30 M_{\odot}$. Second, in accounting for the study of Woosley (2019), it cannot be excluded that most of the WR components end their life as a BH.

4. The expected BH+O wind-fed HMXB population in the solar neighborhood

We calculated the expected BH+O wind-fed HMXB population in the solar neighborhood starting from the WR+O sample of Table 1 and assuming that at the end of core helium burning the WR star collapses into a BH without a SN explosion. The further evolution of the O component, and thus the further evolution of the BH+O binary, is interpolated from the Geneva tracks. The onset of X-ray radiation and the evolution of the X-ray luminosity was then computed using the method from Section 2. Table 1 lists the lifetime where the system is visible as a wind-fed HMXB with $L_X > 10^{35}$ erg/s. As outlined in Section 2, division by the average WR lifetime = 400000 yrs gives an indication of how many wind-fed BH+O HMXBs are expected for the WR+O binary considered. The table illustrates the conclusion that if the WR components in the 17 systems collapse into a BH without a SN explosion, we expect 44 wind-fed BH+O HMXBs in the solar neighborhood. If the 17 systems are representative for the whole population of WR binaries in the solar neighborhood (~ 80 according to the WR catalogs of van der Hucht, 2001, 2006 and of Crowther, 2017), the number of expected wind-fed BH+O HMXBs is even more than 200. Since only one system is observed (Cyg X-1), the discrepancy is enormous.

⁴ In case the luminosity class is not known assuming class V applies to the minimum mass and assuming class I applies to the maximum mass.

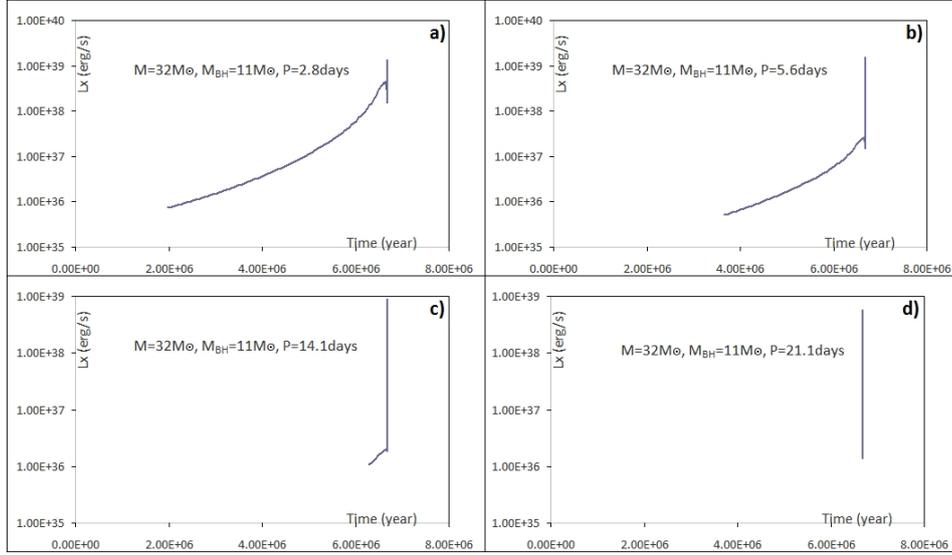


Fig. 1. Temporal evolution of the X-ray luminosity (as a function of O-star apparent, rejuvenated age; also see the text) of an O+BH binary with orbital parameters indicated in the figure.

5. Two possible solutions

5.1. Most WR stars end their life as a NS

Binary interaction (RLOF or the common envelope process) removes the hydrogen rich envelope of the mass loser on a very short timescale: the thermal timescale in the case of a RLOF and the dynamical timescale in the case of the common envelope process. At the end of RLOF, most of the mass losers are hydrogen depleted stars at the beginning of core helium burning, that is, in the case of massive binaries, the hydrogen depleted WR phase always starts at the beginning of core helium burning. Together with the effects of WR-like stellar wind mass loss, this has a significant effect on the evolution of the convective helium burning core, in general, and on the evolution of the compactness of the core (the compactness parameter as introduced by O'Connor & Ott, 2011) in particular. Detailed calculations of the variation of the compactness parameter in massive helium burning stars have been presented by Sukhbold et al. (2016) and Ebinger et al. (2019) (see also references therein). Although these computations hold for massive single stars, we think that they illustrate that it cannot be excluded that many of the WR stars in our Galactic WR+O binaries end their life as a NS. Since these NSs are expected to be accompanied by an asymmetric SN explosion, many of the WR+O binaries may be disrupted and it is clear that this would (at least partly) solve our problem.

5.2. During their formation, BHs receive a kick

The large number of expected wind-fed BH+O HMXBs discussed in the previous section obviously critically depends on the assumption that the collapse of the WR stars into a BH is not accompanied by a SN explosion. The discrepancy with observations may therefore be indicative that BH formation is accompanied by a SN explosion and that the BH receives a (natal) kick. If the natal kick is large enough to disrupt the binary, obviously no wind-fed HMXB is expected. However, the binary does not need to be disrupted in order to reduce the number of expected wind-fed HMXBs drastically. The simulations shown in Figure 1 (Section 2) illustrate that very few wind-fed HMXBs are expected from BH+O binaries with a period > 15 days (see also

the evolutionary models of the WR+O binaries in Table 1). So, a natal kick velocity distribution that assures that most of the BH+O binaries resulting from the WR+O sample have a period larger than 15 days significantly reduces the expected number of wind-fed HMXBs, and it explains the fact that only one (Cyg X-1) is observed. To get an idea as to the order of magnitude of the kick velocities that are capable of doing this, we used the formularium given below.

We define

$$m = \sqrt{\frac{M_1 + M_2}{M_{BH} + M_2}}, \quad (8)$$

$$v_{rel} = \frac{\|v_{kick}\|}{v_{orb}}, \quad (9)$$

$$v_{orb} = \sqrt{G \frac{M_1 + M_2}{A}}, \quad (10)$$

where M_1 and M_2 are the masses of both components before the collapse and A is the distance between both components before the collapse. Additionally, v_{rel} thus represents the magnitude of the kick velocity relative to the orbital velocity. If P is the binary period before the SN explosion, P_{PS} is the binary period after the SN explosion, and θ and ϕ are the angles that describe the direction of the kick velocity v_{kick} with respect to the orbital velocity v_{orb} before the collapse and SN explosion of M_1 . Then, following Brandt & Podsiadlowski (1995) (see also Vanbeveren et al., 1998c)

$$c = \left(\frac{P \sqrt{m}}{P_{PS}} \right)^3 = 2 - m(1 + 2v_{rel} \cos \theta \cos \phi + v_{rel}^2) \quad (11)$$

and after some straightforward calculus

$$v_{rel} = -\cos \theta \cos \phi + \sqrt{-1 + (\cos \theta \cos \phi)^2 + \frac{2-c}{m}}. \quad (12)$$

For the WR+O binaries listed in Table 1, we calculated the v_{kick} value needed to obtain a BH+O binary with a period of 15 days (we also give the value to disrupt the binary). For most of

the WR+O binaries, m is close to one at the end of the core helium burning phase of the WR component. We intend to give indicative results and therefore we simplified the previous formulae by replacing m with one. It is important to note that in this case, an asymmetrical SN explosion (and a resulting substantial kick) is still possible due to the neutrino momentum flux (see e.g., Brandt & Podsiadlowski 1995). Results for this case $m = 1$ are given in Table 2 for $\cos \theta \cos \phi = 1$ (corresponding to a minimum kick, $v_{kick,min}$, that is needed to obtain the desired result) and $\cos \theta \cos \phi = 0$ (since $\cos \theta \cos \phi$ ranges between -1 and +1, the v_{kick} corresponding to $\cos \theta \cos \phi = 0$ can be considered as an average value, $\langle v_{kick} \rangle$). Similarly, a maximum value $v_{kick,max}$ can be calculated for $\cos \theta \cos \phi = -1$. The $\langle v_{kick} \rangle$ values of Table 2 allow us to conclude that the paucity of observed BH+O wind-fed HMXBs in the solar neighborhood can at least partly be explained when the collapse of WR stars into a BH is accompanied by an asymmetric SN explosion, resulting in a moderate kick imparted to the BH. We also notice that the $\langle v_{kick} \rangle$ values that are needed to disrupt most of the WR+O binaries during the collapse of the WR star into a BH are very similar to the average value of the kick velocity distribution of NSs. This means that when BHs are formed with kicks similar to those of NS (as suggested by Repetto et al., 2012, 2017), then most of the WR+O binaries are disrupted when the WR star collapses into a BH.

6. Final remarks

We end the paper with the following remarks.

1. Both solutions discussed in the previous section would explain, in a straightforward manner, the fact that the solar neighborhood only contains 1 WR+BH binary (Cyg X-3).
2. The number of merging BBH expected from isolated binary evolution would obviously be significantly reduced.
3. A kick may lead to an eccentric system and one may wonder if one could get a periodically wind-fed system even when the binary period is 15 days or larger. However investigating the effects of eccentricity and of circularization is beyond the scope of the present paper since it does not affect the main conclusion, that is, the population of high-mass X-ray binaries in general; those with a BH component, in particular, seem to indicate that many Galactic WR stars in WR+O binaries end their life with an asymmetrical SN explosion.

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Appendix A: The mass loss rate formalism during the core helium burning phase of hydrogen depleted massive stars

To calculate the evolution of hydrogen depleted massive stars (singles and binaries), since 1998, we (the Brussels team) have used (Vanbeveren et al., 1998a, b, c) a mass loss rate formalism during core helium burning that is based on the clumping corrected mass loss rates of WR stars that were available at that time (Hamann & Koesterke, 1998) but also on the WN/WC number ratio of WR-binaries (a mass loss rate that is too high predicts a WN/WC number ratio that is too small and vice versa). We proposed

$$\log_{10} \dot{M}[M_{\odot}/\text{yr}] = \log_{10} L[L_{\odot}] - 10. \quad (\text{A.1})$$

Recently, the mass loss rates of Galactic WN and of Galactic WC stars and WR stars of the oxygen sequence (WO stars) were reconsidered accounting for the impact of revised distances from Gaia DR2 (Hamann et al., 2019; Sander et al., 2019). In Figure A.1(a), we compare our linear relation with the linear regression lines of Hamann et al. and of Sander et al. The figure illustrates the statement that the core helium burning evolutionary results predicted with our mass loss rate formalism should be more than satisfactory, in general, for the scope of the present

Table 1. For the selected observed WR+O binaries, the mass-range of the O star based on its spectral type and luminosity class, the adopted WR and O masses based on all available data, the estimated mass of the WR star at the end of core helium burning, the present observed period and the estimated period at the end of the core helium burning phase of the WR star, the time (in Myr) where the resulting wind-fed BH+O is observable as a X-ray binary, and finally the number of expected wind-fed BH high-mass X-ray binaries. Masses are in M_{\odot} and periods are in days.

system	spectral type	O-star mass est.	adopted mass (WR)	adopted mass (O)	mass at end CHeB (WR)	present period	period at end CHeB	L_X time (Myr)	L_X time (Myr)/0.4
WR21	WN5+O4-5	37-60	>19	>37	>10	8.3	11.8	0.3	0.8
WR30	WC6+O6-8	24-50	16	34	14	18.8	20.4	0.0	0.0
WR31	WN4+O8V	24-34	>11	>24	>7	4.8	6.1	2.5	6.3
WR35a	WN6+O8.5V	19-33	18	19	10	41.9	68.2	0.0	0.0
WR42	WC7+O7V	27-37	16	27	14	7.9	8.7	1.8	4.5
WR47	WN6+O5V	37-70	>40	>47	>20	6.2	10.5	0.6	1.5
WR79	WC7+O5-8	24-60	>10	>24	>7	8.9	10.7	1.1	2.8
WR97	WN5+O7	>30	>17	>30	>9	12.6	18.3	0.0	0.0
WR113	WC8+O8-9IV	20-30	>11	>22	>8	29.7	35.9	0.0	0.0
WR11	WC8+O7.5III-V	25-47	10	31	8	78.5	86.8	0.0	0.0
WR127	WN3+O8.5V	17-24	>9	>20	>6	9.5	11.8	0.8	2.0
WR139	WN5+O6III-V	28-59	9	28	6	4.2	5.0	3.0	7.5
WR151	WN4+O5V	28-56	20	28	10	2.1	3.4	5.7	14.3
WR133	WN5+O9I	34-66	17	34	9	112.4	158.1	0.0	0.0
WR141	WN5+O5III-V	26-59	36	26	18	21.7	43.1	0.0	0.0
WR155	WN6+O9II-Ib	30-44	24	30	12	1.6	2.6	1.5	3.8
WR9	WC5+O7	>30	9	32	8	14.3	15.0	0.1	0.3

Table 2. For the WR+O binaries listed in Table 1, we calculated the v_{kick} needed to obtain a BH+O binary with a period of 15 days (we also give the value to disrupt the binary). The meaning of $v_{kick,min}$, $< v_{kick} >$, and $v_{kick,max}$ is explained in the text. Velocities in km/s.

system	spectral type	$v_{kick,min}$ $P = 15d$	$v_{kick,min}$ disrupted	$< v_{kick} >$ $P = 15d$	$< v_{kick} >$ disrupted	$v_{kick,max}$ $P = 15d$	$v_{kick,max}$ disrupted
WR21	WN5+O4-5	24	140	130	338	701	817
WR30	WC6+O6-8	-	117	-	284	-	685
WR31	WN4+O8V	75	152	246	367	809	886
WR35a	WN6+O8.5V	-	66	-	160	-	387
WR42	WC7+O7V	51	148	197	358	767	864
WR47	WN6+O5V	95	196	315	472	1039	1140
WR79	WC7+O5-8	45	134	175	324	692	781
WR97	WN5+O7	-	114	-	275	-	664
WR113	WC8+O8-9IV	-	83	-	201	-	485
WR11	WC8+O7.5III-V	-	68	-	164	-	395
WR127	WN3+O8.5V	20	115	107	278	576	671
WR139	WN5+O6III-V	94	167	292	405	903	977
WR151	WN4+O5V	132	198	378	478	1087	1153
WR133	WN5+O9I	-	57	-	138	-	334
WR141	WN5+O5III-V	-	89	-	215	-	519
WR155	WN6+O9II-Ib	162	224	448	540	1242	1303
WR9	WC5+O7	-	123	-	296	-	715

paper in particular. The latter is strengthened by Figure A.1(b) where we compare our formalism with the formalism for WC and WO stars proposed by Tramper et al. (2016). And finally Figure A.1(c) compares the Potsdam formalism for early type WN stars (WNE stars) with the one advocated by Yoon (2017, $f_{WR} = 1$). As can be noticed, the latter may significantly underestimate the true WNE-rates.

The relation between the initial mass of a massive primary in an interacting binary and its mass at the end of core helium burning (just prior to the formation of a NS or a BH) critically depends on the adopted stellar wind mass loss rate formalism during core helium burning. The relation computed with our mass loss rate formalism was presented for the first time by De Donder & Vanbeveren (2003, 2004) and it is shown once more in Figure A.2. The figure illustrates that when the mass of the BH in Cyg X-1 is confirmed to be $15 M_{\odot}$, then the initial mass of the BH-progenitor should be at least $60 M_{\odot}$. Moreover, massive BHs, such as those predicted by the LIGO/Virgo data, are

no surprise in low metallicity regions. We would like to end this appendix with a word of caution. Number synthesis simulations that aim to predict the populations of double compact star binaries (NS+NS, NS+BH, BH+BH) rely on the evolution during core helium burning and thus on the WR-type stellar wind mass loss rate formalism. In Figure A.1(d), we compare our formalism with the one used by the Warsaw team (Belczynski et al., 2010). The difference is quite significant and may explain, at least partly, why some of the results of Warsaw differ from those of Brussels.

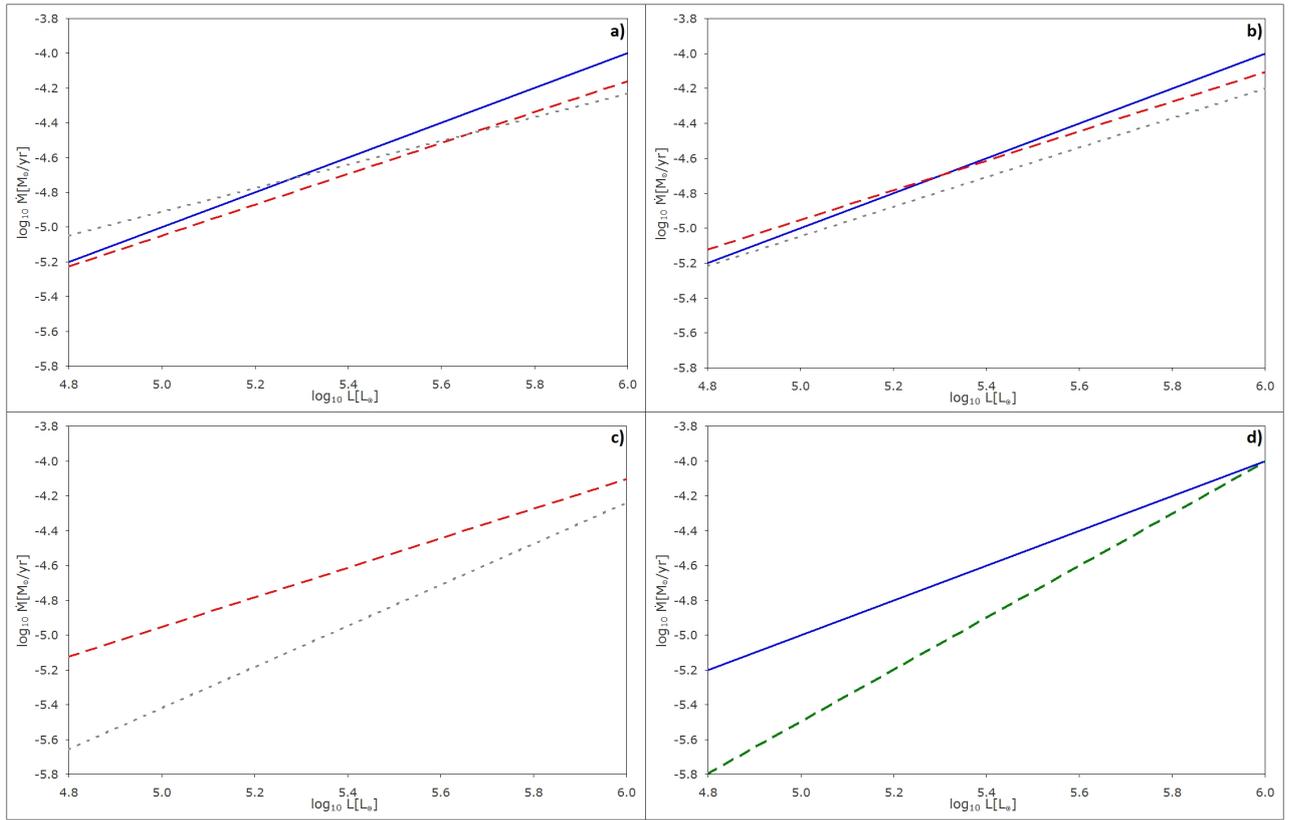


Fig. A.1. Stellar wind mass loss rate as a function of luminosity of hydrogen depleted massive stars. **(a)** Solid blue line: Brussels. Dashed red line: WNE Potsdam. Dotted gray line: WC Potsdam. **(b)** Solid blue line: Brussels. Dashed red line: Tramper WC $Y = 0.98$. Dotted gray line: Tramper WC $Y = 0.6$. **(c)** Dashed red line: Potsdam. Dotted gray line: Yoon $f_{WR} = 1$. **(d)** Solid blue line: Brussels. Dashed green line: Warsaw.

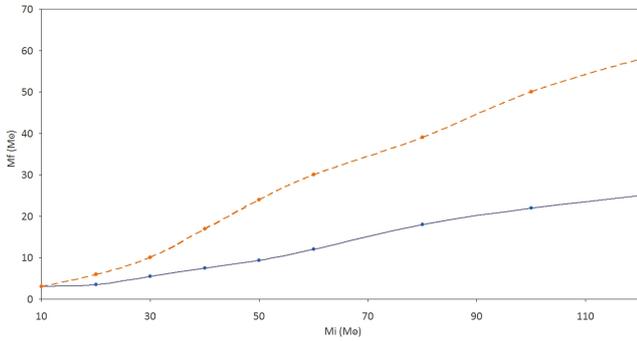


Fig. A.2. Relation between the initial mass of a massive primary in an interacting binary and its mass at the end of core helium burning (just prior to the formation of a NS or a BH). Solid blue line: Solar. Dashed red line: SMC. Masses in M_{\odot} .