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Forming short-period Wolf–Rayet X-ray binaries and double black holes through stable mass transfer

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ABSTRACT

We show that black hole high-mass X-ray binaries (HMXBs) with O- or B-type donor stars and relatively short orbital periods, of order one week to several months may survive spiral-in, to then form Wolf–Rayet (WR) X-ray binaries with orbital periods of order a day to a few days; while in systems where the compact star is a neutron star, HMXBs with these orbital periods never survive spiral-in. We therefore predict that WR X-ray binaries can only harbour black holes. The reason why black hole HMXBs with these orbital periods may survive spiral-in is: the combination of a radiative envelope of the donor star and a high mass of the compact star. In this case, when the donor begins to overflow its Roche lobe, the systems are able to spiral in slowly with stable Roche lobe overflow, as is shown by the system SS433. In this case, the transferred mass is ejected from the vicinity of the compact star (so-called isotropic re-emission mass-loss mode, or SS433-like mass-loss), leading to gradual spiral-in. If the mass ratio of donor and black hole is $\gtrsim$3.5, these systems will go into common-envelope evolution and are less likely to survive. If they survive, they produce WR X-ray binaries with orbital periods of a few hours to one day. Several of the well-known WR+O binaries in our Galaxy and the Magellanic Clouds, with orbital periods in the range between a week and several months, are expected to evolve into close WR–black hole binaries, which may later produce close double black holes. The galactic formation rate of double black holes resulting from such systems is still uncertain, as it depends on several poorly known factors in this evolutionary picture. It might possibly be as high as $\sim 10^{-5}$ yr^{-1}.

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

1 INTRODUCTION

Wolf–Rayet (WR) stars are hot and luminous evolved stars characterized by spectra with strong emission lines of He, C and/or N and O, produced by a dense high-velocity stellar wind. Their wind mass-loss rates are typically of order 10^{-5} M$_\odot$ yr^{-1}. Except for the most luminous WN stars, WR stars do not contain hydrogen; they are helium stars, as was first pointed out by Paczyński (1967, for recent reviews of WR star properties see Crowther 2007; Sander, Hamann & Todt 2012; McClelland & Eldridge 2016). WR X-ray binaries are composed of a helium star and a compact star, which can be a neutron star or a black hole (BH). Their existence was predicted by Tutukov & Yungelson (1973) and van den Heuvel & De Loore (1973), as the outcome of the later evolution of high-mass X-ray binaries (HMXBs), when the evolved massive O- or B-type donor stars in these systems started to overflow their Roche lobes (the classical definition of a HMXB is: an X-ray binary in which the mass-donor star is an O- or early B-type star, while in a WR X-ray binary the donor is a massive helium star; we follow here this nomenclature). Van den Heuvel and de Loore pointed out that the outcome of this later evolution of an HMXB is expected to be a very close binary, consisting of a helium star (the helium core of the original HMXB donor star) and a compact star. They suggested that the peculiar 4.8 h orbital period X-ray binary Cygnus X-3 (Cyg X-3) is such a WR X-ray binary. This was confirmed 19 yr later (van Kerkwijk et al. 1992): the companion of Cyg X-3 is a WR star of type WN5. When the 1973 prediction of the existence of WR X-ray binaries was made, it was thought that all HMXBs would produce such systems. Since the WR phase lasts some 400 000 yr (Rosslowe & Crowther 2015), which is longer than the duration of the HMXB phase (e.g. van den Heuvel 1994), one would expect that WR X-ray binaries would be more abundant in the Galaxy than over the 200 known HMXBs. However, apart from Cyg X-3, no other WR X-ray system has been found in the Galaxy, and the problem of the 'missing WR X-ray binaries' (van Beveren et al. 1982; Lommen et al. 2005) has been with us for over 40 yr. In recent years, six more WR X-ray binaries have been discovered in other galaxies

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(Esposito et al. 2015); with the exception of one, all of these have short orbital periods, between 0.2 and 1.5 d; one system has a period of about 8 d. Two possible factors that may lead to the reduction of the predicted numbers of WR X-ray binaries in the Galaxy are:

(1) when the existence of WR X-ray binaries was predicted it was thought that all helium stars with masses $\gtrsim$3–4 M$_\odot$ would be observable as WR stars. However, more recent estimates of masses of WR stars, either in binary systems or from their absolute luminosities have shown that, in order to show the typical WR spectral characteristics produced by a dense high-velocity stellar wind outflow, the helium stars must have a mass $\gtrsim$10($\pm$2) M$_\odot$ (Crowther 2007; Sander et al. 2012). This implies that the hydrogen-rich progenitor of the WR star most probably must have had a mass $\gtrsim$30($\pm$5) M$_\odot$, and in any case $\gtrsim$20 M$_\odot$.

Or

(2) only very few HMXBs survive the spiral-in during the Roche lobe overflow phase that follows the HMXB phase [we use here the expression ‘spiral-in’ for a drastic decrease of the orbital period by any kind of mechanism, not only by common-envelope (CE) evolution].

Here we will argue that the latter factor is the key reason for the scarcity of WR X-ray binaries, and that HMXBs in which the compact star is a neutron star hardly ever survive spiral-in (only very wide neutron star systems with donor masses below about 20 M$_\odot$ may survive, see Section 3).

We show that, on the other hand, if the compact star is a BH, with a mass $\gtrsim$5–10 M$_\odot$, the systems may survive spiral-in, and become close binaries consisting of a WR star and a BH. For this reason, one expects in general that in WR X-ray binaries the compact star is a BH.

Our ideas about which systems may survive spiral-in and produce WR X-ray binaries were triggered by the realization that the peculiar X-ray binary SS433 has avoided going into CE evolution, and that the donor star in this system is transferring mass to the compact star by stable Roche lobe overflow (RLOF; King & Begelman 1999; King, Taam & Begelman 2000). By analysing the properties of this system we realized that it is the high mass of the compact star in this system [4.3($\pm$0.8) M$_\odot$] in combination with the relatively low mass of its donor star [12.3($\pm$3.3) M$_\odot$] (Hillwig & Gies 2008), which allowed it to avoid CE evolution and enables it to gently spiral in without ever coalescing with its donor. As we consider SS433 to be a ‘keystone’ for understanding the formation of the WR X-ray binaries, we give in Section 2 a brief overview of its properties and evolutionary state. The avoidance of its going into CE evolution is – as we will argue – a consequence of the donor star having a radiative envelope (King et al. 2000), in combination with the donor star and accretor having a mass ratio less than 3.5. In Section 3, we then examine for which donor masses, mass ratios and orbital periods HMXBs will, when they start Roche lobe overflow, avoid going into CE evolution and may survive as WR X-ray binaries with short orbital periods. We also examine under which conditions they may still survive after having gone into CE evolution. In this section, some examples are given on how a number of well-known observed WR+O binaries with relatively short orbital periods are expected to evolve in the future, and are expected to produce WR X-ray binaries and, as a final evolutionary state, close double BHs. This model for producing double BHs is different from the ones proposed by Belczynski et al. (2016), Marchant et al. (2016) and de Mink & Mandel (2016). In Section 4, we attempt to estimate the birth rate of WR X-ray binaries in the Galaxy on the basis of our model, and find it to be still higher than observed and discuss possible ways to minimise this discrepancy. In Section 5, we discuss the results and estimate the possible birth rate of double BHs based on our model.

2 SS433 – A KEYSTONE FOR UNDERSTANDING WHICH HMXBs GO INTO STABLE ROCHE LOBE OVERFLOW

2.1 The evolutionary state and future evolution of SS433

The SS433 system consists of a Roche lobe filling a A4-7I supergiant donor star with an estimated mass of 12.3($\pm$3.3) M$_\odot$ and a luminosity of about 3800 L$_\odot$, plus a compact star with a mass of 4.3($\pm$0.8) M$_\odot$, in a 13.1 d period binary (Hillwig & Gies 2008). The compact star is surrounded by an extended and luminous accretion disc, about an order of magnitude brighter than its A-supergiant companion. This disc ejects the famous precessing relativistic jets with a velocity of 0.265c, in which neutral hydrogen is ejected at a rate of some 10^{-6} M$_\odot$ yr^{-1}, while in a strong disc wind with a velocity of about 1500 km s^{-1} of order some 10^{-4} M$_\odot$ yr^{-1} is ejected, as is seen in the form of the ‘stationary’ H α line and broad absorption lines (Fabrika 2004). The total mass-loss from the disc is basically all the matter that the A-supergiant donor is transferring to the compact object by Roche lobe overflow on its thermal time-scale of $\sim 10^5$ yr (see also Begelman, King & Pringle 2006).

The observed radiative accretion luminosity of the compact star with its disc does not exceed the Eddington luminosity $L_{\rm Edd} \simeq 6 \times 10^{38}$ erg s^{-1} of the compact star (which corresponds to a real accretion rate on to the compact star of order only a few times 10^{-8} M$_\odot$ yr^{-1}), although when seen along the jets the UV luminosity might be as large as perhaps 10^{40} erg s^{-1} (Fabrika 2004), which would correspond to an accretion rate of order 10^{-7} M$_\odot$ yr^{-1}. This mass-loss has been going on for thousands of years, as can be seen from the large radio nebula W50 that surrounds the system and has been produced by the precessing jets and the strong disc wind. Even though this mass transfer has been going on for thousands of years, the system has not entered into a CE state.

The reason why SS433 has not gone into a CE phase is, as argued by King & Begelman (1999) and King et al. (2000), the fact that the A-supergiant star has a radiative envelope. If one takes away mass from a star with a radiative envelope, this envelope responds by shrinking on a dynamical time-scale, followed by a re-expansion on the thermal time-scale of the envelope. As a result, this star can keep its radius close to that of its Roche lobe and will transfer matter to its companion on the thermal time-scale of its envelope, without going into a CE phase. There is, however, an extra condition for keeping the Roche lobe overflow stable, which was not mentioned in the above references, namely: the thermal time-scale mass transfer from a radiative donor envelope may itself become unstable, if the mass ratio of donor and companion star is larger than a value in the range 3–4 (e.g. Tout et al. 1997; Tauris, van den Heuvel & Savonije 2000; Hurley, Pols & Tout 2000).

For the sake of argument, we will assume here this limiting mass ratio to be 3.5. For mass ratios larger than about 3.5, the shrinking of the system due to the mass transfer goes so fast that the shrinking of the donor star cannot keep in pace with it, and the system will enter a CE phase. SS433 has indeed a mass ratio below 3.5 and therefore avoided going into a CE phase. Apart from systems with a donor with a radiative envelope and mass ratio larger than 3.5, also for systems in which the donor has a convective envelope, the formation of a CE is unavoidable. The reaction of a convective envelope to mass-loss is expansion on a dynamical (pulsational) time-scale, and thus the envelope becomes violently unstable, which leads to runaway mass transfer and the formation of a CE.

2.2 Why systems like SS433 are so rare: the fate of HMXBs with a 'standard' neutron star companion

One may wonder what is so special about SS433 and why we do not see more SS433-like systems. We propose that the answer is the very unusual combination for an HMXB of a rather low donor mass (presently $\sim$12.3 $\mathrm{M_\odot}$ and initially $\sim$14 to $\sim$15 $\mathrm{M_\odot}$) plus a quite massive compact star ($\sim$4.3 $\mathrm{M_\odot}$). A 14–15 $\mathrm{M_\odot}$ initial donor mass and an orbital period of $\sim$13.1 d are typical for a Be/X-ray binary, the most common type of HMXBs, containing a B-emission (Be) line star. There are some 200 Be/X-ray binaries known in our Galaxy and the Magellanic Clouds.

Raguzova & Popov (2005) list 160 in our Galaxy and the two Magellanic Clouds and Reig (2011) lists 141 in our Galaxy plus the Small Magellanic Cloud alone. Since these papers appeared, *Swift*, *INTEGRAL* and other satellites have discovered several tens more, bringing the total presently known number to about 200.

In all but one of the known Be/X-ray binaries, the compact stars are neutron stars which have a typical mass of about 1.4 $\mathrm{M_\odot}$. Only one Be/X-ray binary is known to harbour probably a BH companion, with a mass of 3.6–6.9 $\mathrm{M_\odot}$ (Casares et al. 2014). If the companion of a 14 $\mathrm{M_\odot}$ Be star is a 1.4 $\mathrm{M_\odot}$ neutron star, the mass ratio is 10, and the formation of a CE is unavoidable, and the two stars will merge (unless the orbital period is longer than 1–2 yr, which is the case for only a small fraction of the Be/X-ray binaries, see Section 3).

Only if the compact star has a mass $\sim$4 $\mathrm{M_\odot}$ or larger, and the donor has a radiative envelope, the system will spiral in slowly and survive the SS433-like mass-transfer process. Therefore, out of the $\sim$200 Be/X-ray binaries, only the one system with (an alleged) BH companion will in the future evolve like SS433 and survive, all the others will have merged after transferring only a small amount of mass (or, the small fraction of systems with orbital periods longer than about 1 to 2 yr, will have produced a very close Helium star plus neutron star system, after a short-lasting CE phase). So, the birth rate of SS433-like systems is at most about 0.5 per cent of the birth rate of Be/X-ray binaries (for the formation and future evolution of the possible Be/BH binary in a model, see Grudzinska et al. 2015).

The simple reason why SS433 can stably survive this type of spiral-in process for $\sim10^4$ to perhaps $\sim10^5$ yr is because of its unique combination – for a Be/X-ray binary progenitor – of a quite massive compact star and a relatively moderate-mass donor star.

The $\sim$4.3 $\mathrm{M_\odot}$ compact object in SS433 must be a low-mass BH, because causality allows neutron stars to have masses not larger than about 3 $\mathrm{M_\odot}$ (Nauenberg & Chapline 1973; Kalogera & Baym 1996).

3 CONDITIONS FOR SURVIVAL OF ROCHE LOBE OVERFLOW IN HMXBs AS A FUNCTION OF DONOR MASS, COMPACT STAR MASS AND ORBITAL PERIOD

3.1 Evolution of the orbit during SS433-like mass transfer

As shown by King et al. (2000) and Begelman et al. (2006), in the case of Roche lobe overflow from donor stars with a radiative envelope, a further condition for avoiding the formation of a CE is that the spherization radius R_{sp} of the accreting compact object remains smaller than its Roche lobe, where R_{sp} is given by (Shakura & Sunyaev 1973)

$$R_{\mathrm{sp}} = -\frac{27}{4}\frac{\dot{M}_{\mathrm{donor}}}{\dot{M}_{\mathrm{Edd}}} R_{\mathrm{s}}, \tag{1}$$

where R_{s} is the Schwarzschild radius of the compact object. In the case of SS433, $-\dot{M}_{\mathrm{donor}}/\dot{M}_{\mathrm{Edd}}$ is of order 10^4 and $R_{\mathrm{s}} \simeq 9$ km, so $R_{\mathrm{sp}} \sim 6 \times 10^5$ km $\simeq 0.9\,\mathrm{R_\odot}$, which is deep inside the Roche lobe of the compact star, and a CE will be avoided. In all HMXBs with orbital periods upwards of one day the same will hold. So in all cases of HMXB systems with a donor with a radiative envelope and mass ratio less than about 3.5, one expects the system to go into normal Roche lobe overflow evolution similar to that of SS433. The 'SS433-mode' of mass transfer is what we have in the past called 'isotropic re-emission' (e.g. Massevitch & Yungelson 1975; Bhattacharya & van den Heuvel 1991; van den Heuvel 1994; Soberman, Phinney & van den Heuvel 1997; Tauris & van den Heuvel 2006).

With the SS433 mode of mass transfer, followed by mass-loss from the disc, which has the specific orbital angular momentum of the compact object, it is simple to calculate how the orbit of the system will change. In case that a fraction β of the transferred matter is ejected from the compact star and its disc with the specific orbital angular momentum of this star, and a fraction $(1 - \beta)$ is accreted by this star, the orbital angular momentum loss leads to a change of the orbital radius as given by (e.g. see Tauris 1996; Soberman et al. 1997; Tauris & van den Heuvel 2006)

$$a/a_o = \frac{q_0+1}{q+1}\left(\frac{q_0}{q}\right)^2\left[\frac{(1-\beta)q_0+1}{(1-\beta)q+1}\right]^{-3-2/(1-\beta)}, \tag{2}$$

where q is the mass ratio of donor and compact star, and subscript zero indicates the initial situation at the onset of Roche lobe overflow.

For the case in which $\beta = 1$, as is in fact the case in SS433, as the accreted amount is 10^{-4}–10^{-3} times the transferred amount, this equation in the limit of β approaching unity simplifies to

$$a/a_0 = \left(\frac{q_0+1}{q+1}\right)\left(\frac{q_0}{q}\right)^2 \mathrm{e}^{-2(q_0-q)}. \tag{3}$$

Using Kepler's third law, the corresponding equation for the change of the orbital period is

$$P/P_0 = \left(\frac{q_0+1}{q+1}\right)^2\left(\frac{q_0}{q}\right)^3 \mathrm{e}^{-3(q_0-q)}. \tag{4}$$

In the case of SS433, assuming the initial mass of the A-supergiant donor to have been $\sim$14–15 $\mathrm{M_\odot}$, the mass of its helium core is about 3.5 $\mathrm{M_\odot}$. This means that at the end of the Roche lobe overflow phase $q = 0.81$, while at present $q_0 = 2.86$. Inserting these values into equation (4), one finds that at the end of the Roche lobe overflow the orbital period of the system will be $P \simeq 5.60$ d. So, SS433 will, with these assumed component masses, finish as a detached binary consisting of a 3.5 $\mathrm{M_\odot}$ helium star and a 4.3 $\mathrm{M_\odot}$ compact star. The entire process will take place on the thermal time-scale of the envelope of the 12.3 $\mathrm{M_\odot}$ A-supergiant which is between $\sim10^4$ and $\sim10^5$ yr.

The helium star in the resulting system may during helium shell burning go through a second mass-transfer phase and finally explode as a supernova, likely leaving a neutron star. If the system remains bound in response to the natal kick of the neutron star, a close eccentric binary will result, consisting of the present $\sim$4.3 $\mathrm{M_\odot}$ compact star plus a neutron star.

3.2 Upper limiting orbital period for having a radiative envelope

In order to determine the limiting orbital period for having a radiative envelope, we notice that for an effective temperature $T_{\rm eff} >$ 8100 K (spectral type earlier than ∼A7), stars have a deep radiative envelope (e.g. see Clayton 1968). If the luminosity of a donor star of a given mass M is known, its radius R can be found from the relation $L = 4\pi\sigma R^2 T_{\rm eff}^4$, where σ is the Stefan–Boltzmann constant. If the mass $M_{\rm c}$ of the compact companion of the star is known, and we set the stellar radius R equal to the radius $R_{\rm L1}$ of the Roche lobe of the donor, then the equation for the Roche lobe given by Eggleton (1983):

$$R_{\rm L1} = \frac{0.49\,a}{0.6 + q^{-2/3}\ln\left(1 + q^{1/3}\right)}, \qquad (5)$$

allows one to calculate the orbital radius a of the binary in which the donor fills its Roche lobe, as the mass ratio $q = M_{\rm donor}/M_{\rm c}$ is known. Using Kepler's third law, one also calculates the corresponding orbital period P.

To calculate the maximum orbital periods up to which donor stars still have a radiative envelope, we used the luminosities of post-main-sequence evolutionary tracks, for solar metallicity, of rotating stars with masses up to 50 $\mathrm{M}_{\odot}$ given by Ekström et al. (2012), and the limiting effective temperature of $T_{\rm eff} \sim 8100$ K. Post-main-sequence stars originating from stars more massive than about 50 $\mathrm{M}_{\odot}$ have very strong stellar wind mass-loss, or become luminous blue variables, stars that experience strong eruptive mass-loss episodes. Because of their strong mass-loss they lose most of their hydrogen-rich envelope and always stay at effective temperatures above 8100 K. Therefore these post-main-sequence stars are expected to have radiative envelopes, so for them we used as maximum radius just their maximum post-main-sequence stellar radius. We made these calculations for compact companions with masses of 1.5 $\mathrm{M}_{\odot}$, 5 $\mathrm{M}_{\odot}$, 10 $\mathrm{M}_{\odot}$ and 15 $\mathrm{M}_{\odot}$. Figs 1 and 2 give these upper limiting orbital periods as a function of donor mass for initial donors with masses between 9 $\mathrm{M}_{\odot}$ and 85 $\mathrm{M}_{\odot}$. (In the mass range between 40 $\mathrm{M}_{\odot}$ and 60 $\mathrm{M}_{\odot}$ there are no tracks by Ekström et al. (2012) available. It is known from evolutionary calculations with similar assumed wind mass-loss rates that for masses above 50 $\mathrm{M}_{\odot}$ the stars at the end of hydrogen burning have lost most of their H-rich envelopes and their radii drop rapidly as a function of mass. We have, for the sake of argument, assumed that in the mass range between 40 and 50 $\mathrm{M}_{\odot}$ the orbital periods at $T_{\rm eff} = 8100$ K are constant and after that they linearly decrease towards the orbital period of the 60 $\mathrm{M}_{\odot}$ star.)

The figures show that for donor masses up to about 50 $\mathrm{M}_{\odot}$ these upper limiting orbital periods range from about 50 to 400 d, and beyond 50 $\mathrm{M}_{\odot}$ they go down rapidly. Below these limiting curves, the donor stars in HMXBs will transfer mass to their compact companions according to the SS433-type of mass transfer, and the systems will not go into CE evolution provided the mass ratio of donor and compact star is less than about 3.5. The regions where this SS433-like evolution will occur are indicated in Fig. 2 by the blue-coloured parts of the diagrams (notice that for calculating the curves of the limiting orbital periods, as well as the limiting donor masses for mass ratio 3.5, we used the real post-main-sequence masses of the stars, which are considerably reduced with respect to the initial masses, due to stellar wind mass-loss on the main sequence). To the right of these blue regions and below the radiative boundary periods, systems will go into CE evolution with a donor with a radiative envelope. Above the radiative boundary periods they will go into CE evolution with a convective envelope (or if the period is too large they will not experience mass transfer at all).

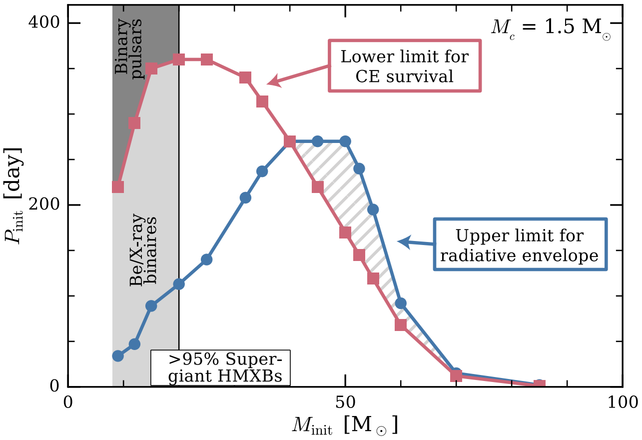

Figure 1. Upper limiting orbital periods for having a donor star with a radiative envelope (blue line, circles, as explained in Section 3.2), together with the formal lower limiting orbital periods for surviving CE evolution (red line, squares, as explained in Section 3.3). This diagram shows the case of a 1.5 $\mathrm{M}_{\odot}$ neutron star companion (see Fig. 2 for more massive companions). In all cases considered here the mass ratio between donor and accretor is so large ($q > q_{\rm limit} = 3.5$) that Roche lobe overflow is expected to be unstable and lead to CE evolution, irrespective of whether the donor has a radiative envelope. Only systems with periods larger than the limiting period for CE survival (above the red curve) are expected to survive spiral-in and avoid coalescence. A small region of the parameter space allows for radiative donors that may survive CE inspiral (grey hashed region), but this is limited to donors with masses above 40 $\mathrm{M}_{\odot}$. The typical orbital periods and donor masses of the observed supergiant HMXBs and the Be-HMXBs are indicated. Over 95 per cent of the NS–supergiant HMXBs do not survive SS433-like spiral-in, and only the Be-HMXBs with very long orbital periods survive CE evolution and can be progenitors of binary pulsars.

The next question is: which systems with donor stars in this radiative-envelope regime, will survive as binaries after the onset of mass transfer by Roche lobe overflow? It turns out that none of the systems with a 1.5 $\mathrm{M}_{\odot}$ compact star (neutron star) will, as was already mentioned above. Because of their mass ratios of far above the mass ratio upper limit of 3.5, they go into CE evolution and for initial donor masses below 40 $\mathrm{M}_{\odot}$ they all merge. This can be seen from the lower-limit curve for survival of CE evolution (the red curve) in Fig. 1 (the way this curve was calculated is explained in the next section). Although for donor masses larger than 40 $\mathrm{M}_{\odot}$ according to the figure, systems might survive CE evolution (grey hashed region), such massive donors with neutron star companions may not be very likely, for stellar evolution reasons. In Fig. 1, we have also indicated the ranges of orbital periods and masses of the bulk of the known supergiant HMXBs with neutron star companions and of the Be X-ray binaries with neutron star companions. One observes that the vast majority of the known supergiant HMXBs with neutron stars does not survive spiral-in.

It can be seen from this figure that among the known types of HMXBs only the Be X-ray binaries with a neutron star companion and orbital periods ranging from larger than 220 d with a 9 $\mathrm{M}_{\odot}$ donor to larger than 370 d with a 20 $\mathrm{M}_{\odot}$ donor (the dark region of the diagram) will survive spiral-in and can later form double neutron stars, after explosion of the helium star. This is a well-known result (e.g. see Portegies Zwart & Spreeuw 1996; Taam 1996; Dewi, Podsiadlowski & Pols 2005).

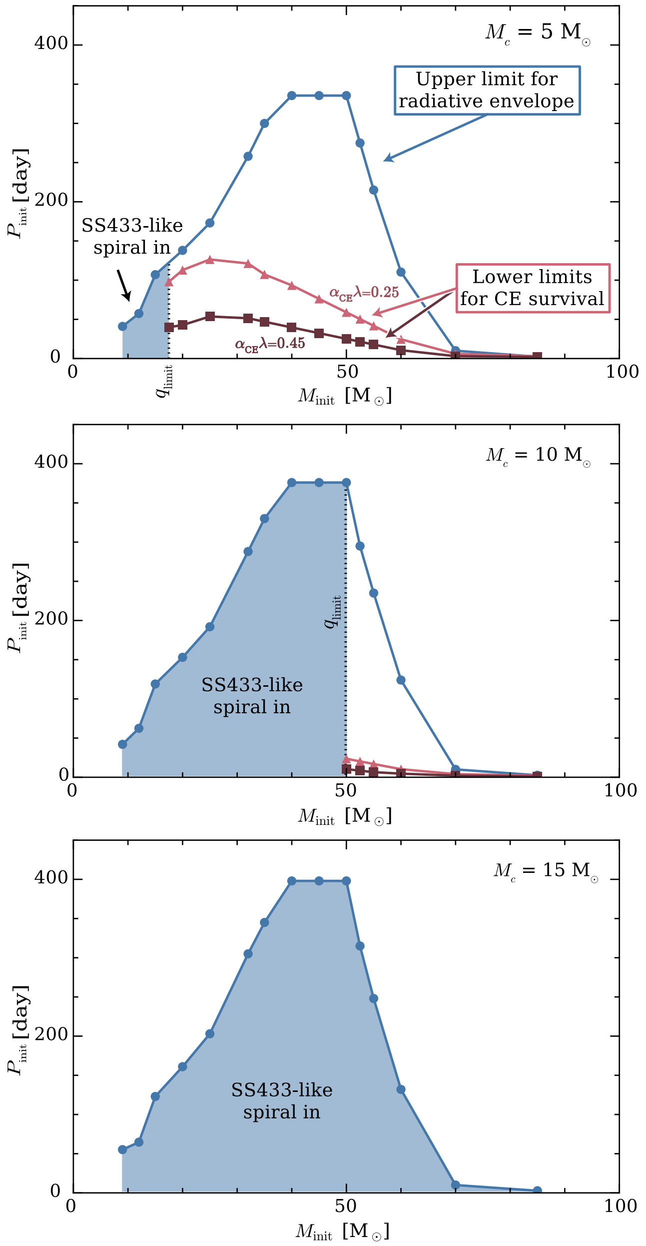

Figure 2. The blue shaded region indicates systems that are expected to undergo stable mass transfer from a radiative donor and survive a 'SS433-like spiral-in'. Top, middle and bottom panels show the range for a BH companion with a mass $M_c = 5$, 10 and 15 $M_\odot$, respectively (compare with Fig. 1, where we showed the case of an $M_c = 1.5\,M_\odot$ neutron star companion). The region is bounded by the condition that the mass ratio between the donor and the compact object is not too extreme, i.e. smaller than $q_{\rm limit} = 3.5$ (vertical dotted grey line). Systems in the part to the right of the blue region will go into CE evolution. The upper-limiting period for mass transfer from a donor with a radiative envelope (blue line with circles, see Section 3.2) and the lower-limiting orbital-period curves for the survival of CE evolution as WR X-ray binaries are shown for two values of the CE parameters (red and dark lines, see Section 3.3).

While none of the systems in the radiative-donor regime with a 1.5 $M_\odot$ neutron star survives the mass transfer, the systems with a 5 $M_\odot$, 10 $M_\odot$ and 15 $M_\odot$ compact companion star (BH), in the blue-coloured parts of Fig. 2, do survive SS433-like mass transfer and can produce helium-star binaries with relatively short orbital periods: WR/X-ray binaries.

It should be kept in mind that for the case with a 5 $M_\odot$, 10 $M_\odot$ and 15 $M_\odot$ compact star, the donors which we consider, overflow their Roche lobes after leaving the main sequence, which means that they evolve according to case B of close binary evolution (Kippenhahn & Weigert 1990). The lower limit for the orbital period for this case is about one week.

An example of a system that will survive SS433-like evolution is Cygnus X-1 (Cyg X-1), which has a 5.6 d orbital period, a 14.8 ± 1.0 $M_\odot$ BH and a 19.2 ± 1.9 $M_\odot$ donor, which according to its luminosity must have started out as a 30 $M_\odot$ star (Orosz et al. 2011). After SS433-like mass transfer the donor in Cyg X-1 will leave a helium star of about 10 $M_\odot$, which might either leave a neutron star or a low-mass BH, with an orbital period of about 9 d, depending on the direction and magnitude of the birth kick of the compact object. So Cyg X-1 will not terminate as a close system.

3.3 Lower limiting orbital periods for surviving CE evolution

Systems with orbital periods above the upper-limit line for radiative envelope in Figs 1 and 2 will have convective envelopes and will, when their donor stars overflow their Roche lobes, go into CE evolution and spiral-in, as described e.g. by Tutukov & Yungelson (1993), Portegies Zwart & Verbunt (1996), Lipunov, Postnov & Prokhorov (1997) and later papers and recently by Belczynski et al. (2016) and Eldridge & Stanway (2016).

The same holds for systems with donors in the radiative region and mass ratios larger than about 3.5. We use here the formalism for the orbital change in the case of CE evolution as given by Webbink (1984) and de Kool (1990), which yields a ratio of the final and initial orbital radii $a_{\rm f}$ and $a_{\rm i}$, respectively, given by

$$a_{\rm f}/a_{\rm i} = \frac{M_{\rm core}\, M_{\rm c}/M_{\rm donor}}{M_{\rm c} + 2M_{\rm env}/(\alpha_{\rm CE}\,\lambda\, r_{\rm L})}, \tag{6}$$

where $M_{\rm core}$ is the mass of the helium core of the donor, $M_{\rm env} \equiv M_{\rm donor} - M_{\rm core}$ is the mass of the hydrogen-rich envelope of the donor at the moment when Roche lobe overflow begins, $\alpha_{\rm CE}$ is the so-called efficiency factor of CE evolution which indicates the efficiency with which the release of orbital gravitational binding energy that occurs during spiral-in of the compact star towards the core of the donor is converted into kinetic energy required to eject the common envelope, λ is a parameter that depends on the stellar mass density distribution and $r_{\rm L}$ is the ratio of the Roche lobe radius $R_{\rm L}$ and the orbital radius $a_{\rm i}$ at the onset of CE evolution.

The value of $r_{\rm L}$ is typically of order 0.5. There are many factors that influence the precise value of the product $\alpha_{\rm CE}\lambda$, such as energy sources like recombination energy and accretion energy release (e.g. see the discussions in Taam & Sandquist (2000); Tauris & van den Heuvel (2006); Portegies Zwart 2013, and in Ivanova et al. 2013; Kruckow et al. 2016). We assume here two values of the CE efficiency: $\alpha_{\rm CE} = 0.5$ and $\alpha_{\rm CE} = 0.9$ (e.g. Taam 1996), $r_{\rm L} = 0.5$, and – while we know this is an oversimplification – for our calculations we assume $\lambda = 0.5$.

To calculate the outcome of CE evolution for stars in the mass range 10–85 $M_\odot$ we used the rotating evolutionary models for solar metallicity of Ekström et al. (2012). These models were calculated with stellar wind mass-loss, such that at the end of core-hydrogen burning, when the stars leave the main sequence, their masses are lower than their initial values, and the mass of the helium core is known. Using for $M_{\rm donor}$ then these reduced post-main-sequence masses, and the corresponding $M_{\rm core}$ values, one can calculate, for

Table 1. Anticipated future evolution of seven well-observed WR+O binaries. The orbital periods, spectral types and masses of the components were taken from the catalogue by van der Hucht (2001). The WR stars and O-stars in these systems are sufficiently massive to leave BH remnants. The ways how the masses of these BHs (bold-print numbers) were calculated are explained in the text. It is assumed for the top six systems that the resulting O+BH systems will spiral in following the SS433-recipe. In the three first systems, the mass ratio of O-donor and BH is very close to 3.5, such that it is not fully certain that the mass transfer will be stable (see text). To indicate this uncertainty, a colon was placed after the short orbital periods of the resulting WR-XRBs. Assuming the SS433-type mass transfer indeed to be stable, the masses of the double BHs, with their orbital periods, indicated in the last columns, will result. The very last column lists the GW-merger times of these systems (no times are given if the merger time is longer than the age of the Universe). In case the SS433-like mass transfer would not be stable, the WR/X-ray systems indicated with colons will go into CE evolution; in that case none of these systems will survive. The bottom line gives the anticipated evolution WR 11 (Gamma-2 Velorum), which will in the second phase of mass transfer goes into CE evolution and produce a very short-period WR/X binary and double BH.

Name	Spectrum	Observed		HMXB at RLOF	WR X-ray binary		Double black hole		
		P (d)	Masses ($\mathrm{M}_\odot$)	Masses ($\mathrm{M}_\odot$)	Masses ($\mathrm{M}_\odot$)	P (d)	Masses ($\mathrm{M}_\odot$)	P (d)	$t(merge)$ (Gyr)
WR 127	WN3 + O9.5V	9.555	17 + 36	**9.6** + 33	**9.6** + 13.6	1.54:	**9.6** + **7.0**	1.71	6.91
WR 21	WN5 + O4-6	8.255	19 + 37	**10.2** + 34	**10.2** + 14.1	1.64:	**10.2** + **7.9**	1.77	6.50
WR 62a	WN5 + O5.5	9.145	22 + 40.5	**10.8** + 37	**10.8** + 16.1	1.45:	**10.8** + **8.8**	1.61	4.40
WR 42	WC7 + O7V	7.886	14 + 23	**10.4** + 22	**10.4** + 8.0	13.75	**10.4** + **4.5**	14.71	–
WR 47	WN6 + O5V	6.2393	51 + 60	**18.1** + 46	**18.1** + 25.8	7.96	**18.1** + **10.4**	8.59	–
WR 79	WC7 + O5-8	8.89	11 + 29	**9.0** + 27.4	**9.0** + 10.1	2.44	**9.0** + **5.4**	2.64	–
WR 11 (CE)	WC8 + O7.5III	78.53	9.0 + 30	**7.8** + 28.5	**7.8** + 10.5	0.90	**7.8** + **5.6**	0.98	2.24

given values of M_c and of the combination $\alpha_\mathrm{CE}\lambda r_\mathrm{L}$, what the values of the ratio $a_\mathrm{f}/a_\mathrm{i}$ will be.

Given the mass M_core of the helium core one knows the radius of this helium star (for these we used the interpolation formula from Onno Pols given in Tauris & van den Heuvel 2006). Together with the mass M_c of the compact star this radius gives the minimum final orbital radius a_f for systems that survive CE evolution, as the helium star is not allowed to be larger than its Roche lobe radius in the final system. If a_f would be smaller than this minimum value, the system does not survive and merges.

Using the above-given values of $\alpha_\mathrm{CE}\lambda$ and r_L, and the values of $a_\mathrm{f}/a_\mathrm{i}$ calculated according to the above-given recipe for each initial donor mass and M_c, one can then calculate the lower limits to the initial orbital radii a_i required for the systems to survive CE evolution. These a_i values also give one the minimum initial orbital periods for surviving CE evolution, as a function of initial donor mass and M_c.

In Fig. 1, the lower limiting period curve for survival of CE evolution for $\alpha_\mathrm{CE} = 0.5$ is indicated for systems with a neutron star companion with $M_\mathrm{c} = 1.5\,\mathrm{M}_\odot$. For the case of $M_\mathrm{c} = 5\,\mathrm{M}_\odot$, $10\,\mathrm{M}_\odot$ and $15\,\mathrm{M}_\odot$, the calculated lower limiting period curves for CE evolution with the above-given values of $\alpha_\mathrm{CE}\lambda = 0.25$ and 0.45 are given in Fig. 2 (the latter value was derived from orbits of post-CE binaries by Portegies Zwart & Verbunt 1996). Systems above these curves in the parts of the panels in Fig. 2, to the right of the blue-coloured regions are expected to survive CE evolution as WR/X-ray binaries with short orbital periods.

3.4 Examples of the future evolution of some well-known WR+O spectroscopic binaries: formation of close WR X-ray binaries and of double black holes

Table 1 shows as an example how we expect seven well-known observed massive WR+O spectroscopic binaries with well-determined masses and orbital periods to evolve in the future. The masses and orbital periods of these systems were taken from the catalogue of van der Hucht (2001), to which we refer for the original references for these systems. We have calculated the future evolution of these systems semi-empirically, as follows. We adopted the Conti scenario (Conti 1976) for the evolution of WR stars. According to this model, WR stars begin as WN stars and then evolve with strong wind mass-loss into WC/WO stars, that finally undergo core collapse (Crowther 2007, for an alternative point of view, see Sander et al. 2012; McClelland & Eldridge 2016).

To calculate the evolution of the observed WR+O binaries in Table 1, we made the following assumptions.

(i) On the basis of evolution calculations, such as by the Geneva group, we assumed, adopting the Conti scenario, the WR stars spend 70 per cent of their helium-burning lifetime as a WN star and 30 per cent as a WC star.

(ii) We assumed an observed WN star to be half-way its WN lifetime, that is at 35 per cent of its helium star lifetime. Similarly, we assumed the observed WC stars to be at 85 per cent of their helium star lifetime, so they still have 15 per cent of this lifetime to go.

(iii) We assumed their wind mass-loss rates over their entire lifetime to correspond to the stars of their presently observed WR type. For these rates we used wind mass-loss rates 1.4 times lower than assumed by Schaller et al. (1992), for the following reasons: Schaller et al. found for their adopted wind mass-loss rates for solar metallicity that even stars up to $120\,\mathrm{M}_\odot$ finished with a mass of only $8\,\mathrm{M}_\odot$. It is evident that this cannot be correct, since the Population I X-ray binary Cyg X-1 is a $14.8\,\mathrm{M}_\odot$ BH (Orosz et al. 2011; Ziolkowski 2012). Assuming some 90 per cent of the final WC star (basically a CO core) to become the BH (e.g. Heger 2012), the final mass of the WR progenitor of Cyg X-1 must have been $16.4\,\mathrm{M}_\odot$. The formation of a BH with the mass of Cyg X-1 is possible only if the real wind mass-loss rates at solar metallicity are about 1.4 times lower than the ones used by Schaller et al. In that case, the progenitor of Cyg X-1 was a star of about $80\,\mathrm{M}_\odot$ with solar metallicity.

(iv) Also for the O-stars we used wind loss rates of 1.4 times lower than the ones used by Schaller et al. (1992).

(v) As the total lifetime of the WR stars (massive helium stars) we used 400 000 yr (Rosslowe & Crowther 2015).

The results of these calculations are listed in Table 1. Columns 2, 3 and 4 list the observed parameters of the systems. Column 5 lists the masses of the components after the WR star has terminated its evolution and has become a BH, and subsequently the companion has evolved for 3 million yr to leave the main sequence and start Roche lobe overflow (RLOF). We calculated the masses in column 5 by taking into account the wind mass-loss of both stars, and by assuming that at the end of the life of the Wolf–Rayet star as a WC-type star, 90 per cent of the mass of the WC star disappeared into the BH (cf. Heger 2012; Sukhbold et al. 2016), meaning that just only the gravitational binding energy of the helium star is lost. As there is no mass lost, we have assumed that the BHs did not receive a natal kick. [We realize that our implicit assumption in these calculations that stars with initial masses larger than about 25 $M_\odot$ always leave BHs may not be fully realistic, since Sukhbold et al. (2016) (and also Ertl et al. and Muller in 2015, in papers referred to in this paper) find from their calculations that, quite arbitrarily, sometimes even very massive stars may still leave a neutron star as a remnant. Since the precise reasons why this happens is not fully understood, we have chosen not to take this into account here].

A possible indication that WR stars tend to leave BHs is that, so far, no WR stars have been detected as progenitors of Type Ib,c supernovae (Smartt 2015).

We calculated how the orbits changed due to the wind mass-loss and the core-collapse gravitational mass-loss, and assumed that after this the orbits tidally synchronized again. We then assumed the O-type companions of the BHs still live another 3 million yr as core-hydrogen burning stars, losing mass by stellar wind in this period. For the top six systems in the table, we subsequently calculated the spiral-in of the resulting HMXB consisting of the O-star and the BH using the SS433-type of spiral-in. This resulted in the WR+BH systems with masses and orbital periods listed in columns 6 and 7, respectively. For the seventh system, the mass ratio of O-star and BH is larger than 3.5 and we assumed this system to pass through CE evolution.

One notices that several of the top-six WR X-ray binaries have orbital periods of order 1–2 d, and that their compact stars are BHs. After taking account of the wind mass-loss of the WR stars in the WR X-ray systems during their further evolution and, again assuming that 90 per cent of the mass of the final WC star disappears into the BH, one obtains masses and orbital periods of the double BH binaries resulting from these systems listed in columns 8 and 9, respectively. (We assumed that the wind mass-loss did not increase the orbital period of the WR X-ray binary, as the gravitational torque exerted by the BH on the outflowing thick wind will cause loss of orbital angular momentum, which is expected to compensate the increase of orbital period due to the mass-loss; if the latter torques would not occur, the final orbital periods will be about 1.8 times larger.)

One observes from this table that some well-known WR+O spectroscopic binaries with orbital periods of order one week can produce close WR+BH X-ray binaries, and subsequently produce close double BH binaries, which merge within a Hubble time.

Since the first three systems in Table 1 have a mass ratio of donor and BH before spiral-in mass transfer very close to the 3.5 limit, it is not completely sure whether the mass transfer from the radiative envelope will not become unstable. To mark this uncertainty, we have a put a colon after the post-spiral-in orbital periods in Table 1. For the 4th to 6th systems in Table 1, the mass ratio before spiral-in is below 3.5 and the transfer is expected to certainly be stable. The 4th and 5th systems however do not leave close WR X-ray binaries, and also not close double BHs. They leave WR X-ray binaries resembling the one observed system with an orbital period of about 8 d, mentioned in the introduction. (In the VIIth catalogue of WR stars (van der Hucht 2001) there are three more systems (WR30, 113 and 141) that will evolve similarly and leave wide WR X-ray binaries and wide double BHs.)

In the case of the first three systems in Table 1, if their mass transfer becomes unstable, a CE will form and the outcome of the evolution must be calculated using equation (6). It turns out that with the above assumed value of $\alpha_{\rm CE}\,\lambda = 0.25$–$0.45$, none of these three systems survive the CE evolution, as in each case the Roche lobe radius of the post-CE helium star is smaller than the radius of this star.

One sees that the orbital periods of WR XRBs produced by stable Roche lobe overflow are considerably larger than the one produced by CE evolution in the system of WR11.

4 THE GALACTIC FORMATION RATE OF WR X-RAY BINARIES

4.1 Predicted galactic numbers of WR X-ray binaries, compared to observations: still too few observed systems

Rosslowe & Crowther (2015) estimate the number of WR stars in the Galaxy to be 1200(±200). WR X-ray binaries have in our model come from WR plus O-type binaries similar to the systems in Table 1. In these systems, the WR star and the O-star have comparable luminosities, meaning that they are double-lined spectroscopic binaries (abbreviated as SB2), which started out as O-type binaries with components with roughly similar masses. van der Hucht (2001) found 13 of the 61 WR stars within 3 kpc from the sun to be SB2s, so about 20 per cent, which would imply 240 SB2 WR-systems in the Galaxy. We particularly selected the seven systems in Table 1, plus the three other systems mentioned in the foregoing section, for their masses and orbital periods such that they could potentially produce WR X-ray binaries. They therefore are not a representative sample of the SB2 WR+O binaries in van der Hucht's VIIth catalogue of WR stars, in which there are in total 31 SB2 systems. Assuming these 10 systems to be representative for one-third of all WR SB2 systems in the Galaxy, then 80 such systems may be expected to evolve similarly to the 10 systems mentioned in the last section, and produce similar WR/X-ray binaries. As in WR+O binaries and in WR X-ray binaries, the WR stars are expected to live equally long, one would then expect, in a steady state of star formation, that there are also 80 WR X-ray binaries in the Galaxy. However, we know only one such system in the Galaxy: Cyg X-3, which has an orbital period of 0.2 d. This system, at some 8–10 kpc distance, is in absolute terms one of the brightest X-ray sources in the Galaxy; although only our side of the Galaxy has been well surveyed for X-ray sources, it is unlikely that there are more than three similar systems in the entire Galaxy. The large absolute X-ray luminosity of Cyg X-3 may be due to its short orbital period, which implies that the compact star is moving in the low-velocity part of its stellar wind. As the accretion rate scales with the minus fourth power of the wind velocity times the minus second power of the orbital radius, in systems with orbital periods of 1 d or more, like in Table 1, the compact stars are in the high-velocity part of the wind, and are at some three times larger orbital radius, such that their X-ray luminosities will be at least some three orders of magnitude lower than that of Cyg X-3, i.e. below $\sim 10^{35}$ erg s^{-1}. Since however we know none of such systems among the well-surveyed part of our Galaxy, up to some 6 kpc distance, which is one-fifth of the area of the galactic disc, the number in the entire galaxy is unlikely to be larger than about five. So, the total number of observable WR X-ray binaries in the Galaxy is unlikely to be larger than eight, which is at most only

10 per cent of the above expected number. In the following section, we discuss possible ways out of this conundrum.

4.2 Conceivable explanations for the large difference between expected and observed numbers of galactic BH WR X-ray binaries

To calculate the parameters of the WR X-ray binaries in Table 1, a number of assumptions about the evolution of the WR+O binary predecessors were made, as described in Section 3.4. We now critically examine the effects of changing a number of the underlying assumptions.

(i) The assumption that for $q < 3.5$ the systems evolve with stable Roche lobe overflow. If the real q-limit would be lower, e.g. $q < 3$, the six uppermost O+BH systems in Table 1 will all go into CE evolution and will not survive. Also the three systems WR30, 113 and 141 mentioned in Section 3.4 will not survive. Only the system WR 11 with its large orbital period will, going through CE evolution, survive. This could reduce the expected number of WR X-ray binaries by a factor of 10. It would then imply that there are some eight WR X systems in the Galaxy with orbital periods like that of the descendent of WR 11: about 1 d.

(ii) The assumption that the BH formed from a WC star has 90 per cent of the final mass of this star. Nelemans, Tauris & van den Heuvel (1999) argue that only 0.65 of the final mass of a helium star ends up in the BH. We repeated the calculations of the evolution of the systems in Table 1 with this assumption. The first three systems in Table 1, as well as WR 79 will now go into CE evolution and coalesce, while WR 42 and 47 go through 'isotropic re-emission' and terminate with periods of about 4 d; WR 30, 113 and 141 evolve in a similar way and produce systems with still longer periods. The only system that in this case still survives as a short-period WR X-ray binary is WR 11, which terminates with an orbital period of 2.13 h if $\alpha_{\rm CE} = 0.50$ and 4.98 h if $\alpha_{\rm CE} = 0.90$.

(iii) Our assumption that the core collapses of the massive stars always leave BHs. As mentioned in Section 3.4, the results of the core-collapse calculations of massive stars by Sukhbold et al. (2016) show that, while sometimes even stars in the mass range 15–20 $M_{\odot}$ may leave a BH, also in very massive stars the core collapse may, in a number of cases, still lead to the formation of a neutron star. If this is indeed the case, and would, for example, occur in half of the cases of the core collapses involved in the systems in Table 1, it would reduce the resulting number of WR X-ray binaries produced by these systems by a factor of 2 – if half of the systems produced a neutron star in the first core collapse in the system, these systems would merge on Roche lobe overflow. And the produced number of double BHs would be reduced by a factor of 4, as also in the second supernova half of the collapses would produce a neutron star.

5 DISCUSSION – POSSIBLE GALACTIC FORMATION RATE OF DOUBLE BLACK HOLES ORIGINATING FROM WR X-RAY BINARIES

From the discussion in the last section, it appears that lowering the fraction of the final WR-star mass that goes to form the BH does not solve the problem of the lack of Galactic WR X-ray binaries. On the other hand, we found that a more promising way to explain the low observed incidence of WR X-ray binaries is a lower q-limit than $q = 3.5$ for stable mass transfer by Roche lobe overflow. The latter limiting value was derived for binary systems with components less massive than 12 solar masses. It is therefore crucial to make more detailed binary evolution calculations for more massive BH HMXBs, in order to more precisely estimate this q-limit for massive systems (see also Pavlovskii et al. 2017).

Also, it is important to calculate this limit for different values of the metallicity, as this type of evolution is expected to have been important also in the early universe. Further, we saw that if a sizeable fraction of the core-collapses of massive stars would still leave a neutron star instead of a BH, this could further reduce the produced number of WR X-ray binaries by a factor of 2. This would then result in only four such systems in the Galaxy at any time.

Finally, assuming that the solution of the low incidence of WR X-ray binaries in the Galaxy is indeed a lower q-limit than 3.5, and combining this with half of the massive star core collapses producing neutron stars, one can make an estimate of the Galactic formation and the merger rate of close double BHs resulting from WR X-ray binaries. As mentioned above, the produced double BH systems then resemble the systems resulting from WR11, which have orbital periods of around 1 d. Such systems will merge on a time-scale of order $\sim 10^9$ yr by the loss of gravitational radiation. As we expect half of the estimated four close WR X-ray binaries to form a close double BH in 400 000 yr (the WR lifetime), the galactic merger rate of close double BHs produced by this process is $\simeq 0.5 \times 10^{-5}$ yr^{-1}. The rate based on the system of Cyg X-3 alone – assuming its WR star to be massive enough to leave a BH – is of similar order as its WR lifetime is again of order 400 000 yr (see also Esposito et al. 2015 and references therein). Although the uncertainties on these estimated rates are expected to be at least an order of magnitude (each way), they nevertheless are interesting. The rates are an order of magnitude lower than the estimated galactic double-neutron-star merger rate (Kalogera et al. 2004).

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