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ON THE RARITY OF X-RAY BINARIES WITH WOLF-RAYET DONORS

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ABSTRACT

The paucity of High mass X-Ray binaries (HMXB) consisting of a neutron star (NS) accretor and Wolf-Rayet (WR) donor has long been at odds with expectations from population synthesis studies indicating that these systems should survive as the evolved offspring of the observed HMXB population. This tension is particularly troubling in light of recent observations uncovering a preponderance of HMXBs containing loosely bound Be donors which would be expected to naturally evolve into WR-HMXBs. Reconciling the unexpectedly large population of Be-HMXBs with the lack of observed WR-HMXB sources thus serves to isolate the dynamics of CE physics from other binary evolution parameters. Here, we find that binary mergers during CE events must be common in order to resolve tension between these observed populations. Furthermore, future observations which better constrain the background population of loosely bound O/B-NS binaries are likely to place significant constraints on the efficiency of CE removal.

1. INTRODUCTION

As a star in a binary system evolves off of the main sequence (MS) and radially expands, it can overflow its Roche lobe and begin transferring mass onto its companion. If this transfer proceeds on a timescale shorter than the timescale in which the accretor can achieve thermal equilibrium, a common envelope (CE) develops and the stars begin to orbit through a combined atmosphere. Energy is then transferred from the binary orbit into the CE through frictional forces and torques which unbind the CE gases (Iben & Livio 1993; Taam & Sandquist 2000). This process has long been discussed as the dominant mechanism for forming tight binaries from widely separated systems and is thought to produce many closely interacting binaries such as cataclysmic variables (Paczynski 1976) and low mass X-Ray binaries (Eggleton & Verbunt 1986; Bailyn & Grindlay 1987).

Unfortunately the hydrodynamic and long-term interactions during the CE phase are not well understood, making it difficult to accurately determine the efficiency of energy transfer from the binary into the removal of the CE. While advancements in computational hydrodynamics have elucidated several trends near the onset of the CE phase (Sandquist et al. 2000; Taam & Ricker 2006; Ricker & Taam 2008), an approximation must be employed in situations where a population of binaries is to be considered. To this end, Webbink (1984) incorporated the myriad uncertainties in CE evolution into a single parameter α_{CE}, which governs the efficiency of transferring gravitational energy into the complete removal of the CE. Within this framework, a relation between the initial and final orbital separations can be written as:

$$\alpha_{CE}\,(\frac{GM_cM_a}{a_f} - \frac{G(M_e+M_c)M_a}{a_i}) = E_{bind} \quad (1)$$

where G is the gravitational constant, a_i and a_f are the initial and final orbital separations, M_c, M_e and M_a are the masses of the donor core, donor envelope, and accretor respectively, and E_{bind} is the energy necessary to unbind the CE. The value of E_{bind} is not trivially calculable, as it includes not only the (negative) gravitational binding energy, but also terms relating to the (positive) thermal energy of the plasma gas, the ionization of H and He and the disassociation of H_2 (Han et al. 1994, 1995). The uncertainties in the binding energy of the CE have traditionally been summarized into a parameter λ, often set as a constant between 0.5 and unity (Hurley et al. 2002; de Kool et al. 1987; Belczynski et al. 2008a). However, the value of λ is known to vary considerably depending on the evolutionary state of the donor star (Dewi & Tauris 2000; Loveridge et al. 2010; Xu & Li 2010b,a; Ivanova 2011). In this work, we follow the analytical prescriptions developed by Loveridge et al. (2010), which have shown high accuracy in the range of masses considered here.

One long-standing expectation from these models of binary evolution concerns the resilient population of HMXBs consisting of neutron stars (NS) accreting from the winds of Wolf-Rayet (WR) donor. However, numerous observations have uncovered only one such system, Cyg X-3 (van Kerkwijk et al. 1992). Ten years after, Van Bever & Vanbeveren (2000) noted that the lack of WR-HMXBs is consistent with the lack of observed WR stars in the solar neighborhood. Only recently, observations demonstrating a significant population of WR stars in star-forming regions places the lack of observed WR-HMXBs at odds with theoretical models.

The sparseness of WR-HMXBs is particularly puzzling in light of recent observations uncovering an unexpectedly large population of HMXBs with Be-type donors. At least 81 such systems are currently observed, with 69 reported by both Raguzova & Popov (2005), Belczynski & Ziolkowski (2009), and numerous reference therein, as well as 12 additional systems recently discovered by INTEGRAL (Kaur et al. 2008; Rodriguez et al. 2009,

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TABLE 1

Name	Spectroscopy	$M_{\rm don}(M_\odot)$	$P_{\rm orb}$ (d)	e
γ-Cas	B0.5 IVe	13.8	203.59	0.26
0115+634	B0.2 Ve	14.9	24.3	0.34
0236+610	B0.5 Ve	13.8	26.5	0.55
0331+530	O8-9 Ve	23.0	34.3	0.3
0352+309	O9.5 IIIe-B0 Ve	16.7	250	0.11
0535+262	B0 IIIe	15.6	111	0.47
0834-430	B0-2 III-Ve	12.0	105.8	0.12
J1008-57	O9e-B1e	15.6	247.5	0.66
1417-624	B1 Ve	12.0	42.1	0.446
J1946+274	B0-1 IV-Ve	13.8	169.2	0.33
J1948+32	B0 Ve	15.6	40.4	0.03
2030+375	B0e	15.6	46.03	0.41
J2103.5+4545	B0 Ve	15.6	12.67	0.40

Table 1: List and parameters of the 13 galactic Be-HMXBs with complete binary orbital information. Data obtained from Raguzova & Popov (2005) and Belczynski & Ziolkowski (2009), and numerous references therein. The donor mass, orbital period and eccentricity are denoted by $M_{\rm don}$, $P_{\rm orb}$, and e, respectively. Each donor mass is derived from the spectral classification using Table VIII of Habets & Heintze (1981).

2010; Corbet & Krimm 2009). Of these systems, 13 have known orbital period, eccentricity, and spectral data, and are summarized in Table 1.

Since each Be-HMXB contains a NS accretor along with a massive (O8-B2) donor in a wide orbital period ($P_{orb} > 30$ days), these systems are expected progenitors of a bright WR-HMXB population. Specifically, as both the orbital separation of these systems is smaller than the supergiant radius of the donor star, and the mass ratio between the Be donor and NS is large, Be-HMXBs inevitably evolve into a CE. If the binary survives the CE event, the resultant system would contain a WR-NS binary in a relatively tight orbit. Due to the high mass loss rates of WR stars (de Jager et al. 1988), we would expect to observe this system as a bright WR-HMXB.

In this *paper*, we investigate whether the discrepancy between Be-HMXBs and WR-HMXB observations can be used to place constraints on the dynamics of the CE event. For this purpose, we use the currently observed sample of Be-HMXBs and find that CE-driven mergers must be common in the later evolution of these systems in order to explain the lack of observed WR-HMXBs. To investigate which limits can be placed upon α_{CE} in a more general context, we additionally simulate a grid of widely separated O/B-NS binaries, and determine the survival probability of WR-HMXB systems as a function of α_{CE}. We then normalize the number of simulated systems using the observed population of Be-HMXBs.

The outline of the paper is as follows: in Section 2 we describe the modeling codes developed to calculate the orbital parameters of binary systems directly before and after the CE phase. In Section 3 we investigate the necessity of CE mergers to explain the lack of observed WR-HMXB systems. In Section 4 we populate a parameter space with possible WR-HMXB progenitors and investigate the constraints that can be placed on the CE efficiency α_{CE} as a function of the initial parameter space of WR-HMXB progenitors. Finally, in Section 5 we discuss the impact of our results on population synthesis parameters.

2. SIMULATION AND MODELING CODES

In this work, we develop an orbital evolution code capable of quickly evolving binaries from the creation of the NS through the onset of the CE created from the donor envelope, yielding both the stellar parameters of the donor star (e.g. core and envelope masses and the envelope binding energy) as well as the binary orbital parameters at the time of CE formation. In order to accurately determine these properties, our orbital evolution code accounts for the evolution of the orbital separation and eccentricity, as well as the spin frequency of the stellar (secondary) component due to effects such as tidal forces, stellar wind mass loss, gravitational radiation, and accretion events onto the NS. Throughout the simulation the NS is considered as a 1.4 $M_\odot$ point mass and the relevant ordinary differential equations are integrated. The input stellar evolution models are calculated with an up-to-date version of the stellar evolution code STARS (Eggleton 1971, 1973; Eggleton & Kiseleva-Eggleton 2002; Pols et al. 1995).

In order to calculate the effect of tides on the donor's spin and orbital properties, tidal evolution is calculated in the standard weak-friction approximation (Zahn 1977, 1989), following the formalism of Hut (1981). Specifically, we integrate numerically the set of differential equations as presented in Belczynski et al. (2008a). The evolution of the orbital separation and eccentricity driven by stellar wind are calculated following Hurley et al. (2002), while the time evolution of the rotational frequency follows Hurley et al. (2000). For the latter we assume that all the mass is lost uniformly at the surface of the star. The evolution of the orbital separation and eccentricity due to gravitational radiation is calculated following Junker & Schaefer (1992). The accretion efficiency is calculated according to Bondi & Hoyle (1944) following Belczynski et al. (2008a). We calculate the accretion efficiency at present, and consider it constant throughout the evolution. For each time step during the orbital evolution we calculate the Roche-lobe radius of the star at periastron (Sepinsky et al. 2007), and extract the relevant system parameters at the onset of Roche-lobe overflow (RLO).

In this study we halt the binary evolution code at the onset of the CE phase, recording the orbital period,

donor mass and envelope binding energy of the binary. We employ direct calculations of the envelope binding energy, following the analytical prescriptions of Loveridge et al. (2010) and determine the survivability of the resultant WR-NS system as a function of the CE efficiency. Furthermore, in order to determine whether a surviving WR-NS would be observable in X-Ray wavelengths, we calculate the luminosity of any surviving systems using the calculations for WR-HMXB wind accretion discussed in Hurley et al. (2000) and Belczynski et al. (2008b).

A critical assumption in this modeling effort is that negligible binary interactions have occurred prior to the formation of the NS. This is unlikely to be the case in scenarios where a CE develops during the evolution of the primary NS progenitor. However, the orbital period of systems moving through a CE phase is known to be substantially shorter than that of the Be-HMXB population (Nebot Gómez-Morán et al. 2011). Thus, our model can be accurately applied in situations where loosely bound MS-NS systems are observed. Another uncertainty in this binary modeling concerns the evolutionary stage at which the Be-HMXB is observed, which affects how long the simulation should persist before the Be donor evolves off of the MS. In order to constrain the error introduced by this uncertainty we test three scenarios where current Be-HMXBs are assumed to be observed at zero-age main sequence (ZAMS), terminal-age main sequence (TAMS), and an intermediate case in the middle of the main sequence lifespan (MAMS). This effectively brackets the uncertainty stemming from the evolutionary state of the observed Be-HMXB population.

In addition to investigating the production of WR-HMXBs from the currently observed population of Be-HMXBs, we expand on this procedure through the creation of a grid containing systems with parameters similar to the observed Be-HMXB population. Specifically, we assume a secondary mass in the range 10-30$M_\odot$ with a resolution of 1$M_\odot$ and a probability distribution following Salpeter (1955). We assume an initial orbital period in the range 10-200d with a resolution of 1 day, and a density distribution which is flat in the logarithm of orbital period, which we use as a tracer for the orbital separation (Abt 1983). In an alternative model we also investigate systems with orbital periods extending out to 1000d, to determine the impact of this cutoff on our results. Finally, we employ a thermal eccentricity distribution following Heggie (1975). From this grid, the probability of a given progenitor surviving to become a visible WR-HMXBs can be computed for an arbitrarily large population of likely progenitor systems. The normalization of the survivable probability to stellar environments can be ascertained through normalization against the observed population of Be-HMXBs as described in Section 4.

3. RESULTS FOR THE OBSERVED BE-HMXBS

In Figure 1, we illustrate the dynamics of our orbital evolution code by providing the detailed evolutionary history for a single simulation of 0236+610 (Table 1). Specifically, we plot the evolution in time of the orbital separation, eccentricity, stellar radius, Roche-lobe radius, spin and orbital frequencies until the onset of RLO, when our calculation is halted. In this simulation we assume that the system is currently observed at

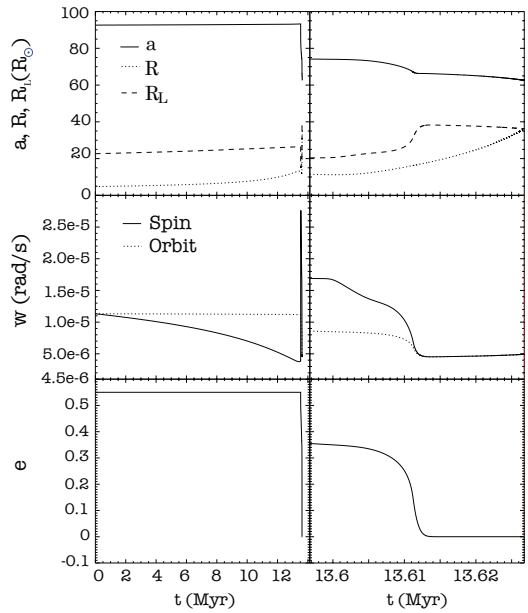

FIG. 1.— Evolution of the orbital parameters for a binary with the properties of 0236+610. *Top*: orbital separation (a), radius (R), and Roche-lobe radius (R_L); *middle*: spin and orbital angular frequency (w); *bottom*: orbital eccentricity (e). The left panel shows the overall evolution, while the right panel shows a zoom-in at RLO. For the first $\simeq$ 13 Myr, stellar wind mass-loss drives the evolution of the orbital separation, while the expansion of the star during its MS lifetime causes a decrease of the spin angular velocity. The evolution of the orbital eccentricity is driven by tides, which are too weak to affect it significantly. Towards the end of the MS the development of a convective envelope greatly increases the efficiency of tides. This mechanism controls the remaining orbital evolution leading to a decrease in the orbital separation and eccentricity, and driving the system into spin-orbit synchronism.

ZAMS. In addition to the current evolutionary phase of the observed Be stars, another uncertainty entering our calculation of E_{bind} is the definition of the core-envelope boundaries. As a rough definition of the stellar core, we define the boundary to occur at the radius where the mass fraction of H drops below a critical value $X_{\rm min}$. Here we set $X_{\rm min}$=0.01 and will investigate the effect of changing both these parameters in what follows.

From this detailed analysis it is evident that the evolution of the each parameter is dominated by only the last 0.1% of its total lifetime, when the star develops a convective envelope which strongly enhance the tidal evolution. This suggests that simulations beginning at ZAMS, MAMS or TAMS will produce nearly identical results at the onset of the CE.

The currently observed population of Be-HMXBs includes only 13 systems with sufficient observational constraints to allow for a detailed modeling of their orbital evolution (listed in Table 1). Therefore, it is important to first determine which factors, other than CE dynamics, could prevent the observation of WR-HMXBs. Taking a small aside, we test two likely factors, the relative lifetime of a bright WR-HMXB phase compared to the Be-HMXB phase, and the expected X-Ray luminosity of the WR-HMXB population.

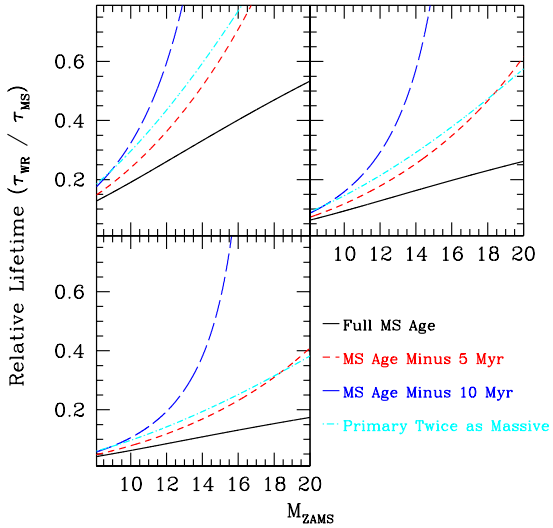

FIG. 2.— Relative timescale of a 2 $M_\odot$ (top left), 3 $M_\odot$ (top right) and 4 $M_\odot$ (bottom left) He-rich star compared to the MS lifetime of O and B stars with various initial masses. To translate these results into a comparison of WR-HMXB lifetimes and Be-HMXB lifetimes, we make four different assumptions regarding the fraction of the MS lifetime during which the star is a Be-HMXB: it's entire lifetime (black solid), beginning at 5 Myr (red dashed), beginning at 10 Myr (blue long dashed), at the SN age of a primary star which is twice as massive as M_{ZAMS} (cyan dot-dashed). The mass range of 2-4 $M_\odot$ for our WR population is set by the range of He core masses found in our models at the time of CE formation.

3.1. *Alternative Explanations for the lack of WR-HMXBs*

One possible explanation for the lack of observed WR-HMXBs concerns the relative duration of WR-HMXB and Be-HMXB phases. If the WR phase is only a small fraction of the Be-HMXB lifetime, we would be unlikely to observe a large population of these systems regardless of the CE dynamics. In order to investigate this effect, we follow the calculations of Hurley et al. (2000) where the lifetimes of the MS and He-MS phases (τ_{MS} and τ_{WR} respectively) are given by:

$$\tau_{MS} = \frac{1594 + 2707M_0^4 + 146.6M_0^{5.5} + M_0^7}{0.04142M_0^2 + 0.3426M_0^7} Myr \quad (2)$$

$$\tau_{WR} = \frac{0.4129 + 18.81M_{WR}^4 + 1.853M_{WR}^6}{M_{WR}^{6.5}} Myr \quad (3)$$

where M_0 is the ZAMS mass and M_{WR} is the mass of the Helium main sequence star. We note that the direct comparison of these lifetimes sets an extremely conservative lower bound on the population of expected WR-HMXBs, as it assumes that the Be-HMXB is X-Ray bright for the entire MS lifetime of the donor star. This assumption is unrealistic, as it includes the portion of the MS lifetime which occurs prior to the evolution of the primary star into a NS. In Figure 2, we plot the fractional lifetime for a WR star of 2$M_\odot$, 3$M_\odot$, and 4$M_\odot$ as a function of the ZAMS mass under four assumptions for the fraction of the total MS lifetime our observed systems spend as a Be-HMXB. First, we assume that the system exists as a Be-HMXB for it's entire MS lifetime (solid black). Secondly, we subtract 5 Myr from the MS lifetime to account for the formation of an NS from

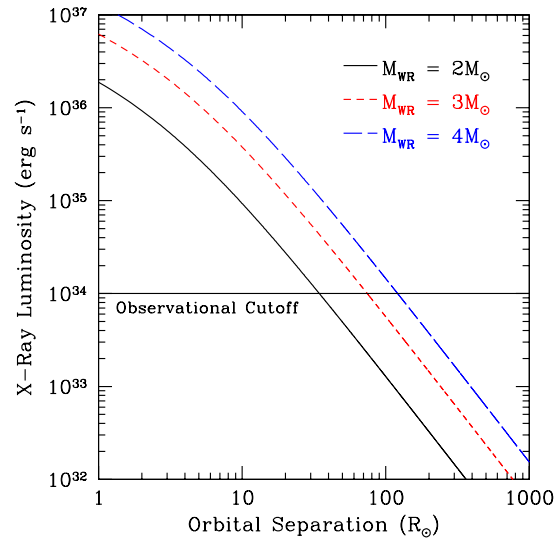

FIG. 3.— X-Ray Luminosity in the *Chandra* band for a WR-NS HMXB as a function of the orbital separation, using the WR wind prescriptions of Hurley et al. (2000) and the X-Ray luminosity prescriptions of Belczynski et al. (2008b)

the most massive progenitors (see e.g. Muno et al. 2006) (red dashed). Third, we subtract 10 Myr from the NS lifetime to account for the average lifetime of NS progenitors (Heger et al. 2003). Lastly, we follow the model of McSwain & Gies (2005), who propose that the early evolution of Be-HMXBs is governed by stable mass transfer from the NS progenitor onto the Be progenitor. This sets an upper limit for the ZAMS mass of the NS progenitor at twice the initial Be star mass. Thus we can conservatively calculate the lifetime of the Be-HMXB phase as the MS lifetime of the Be star minus the MS lifetime of a star twice as massive. We note that all these scenarios are fairly conservative, due to the possibility that NSs in Be-HMXBs are formed via Electron-Capture supernovae (Nomoto 1984) which sets much stronger constraints on the lifetime of the Be-HMXB phase (Linden et al. 2009). We note that a range of 2-4 $M_\odot$ for the mass of the Helium core at the time of CE formation is strongly suggested by the results of our modeling code, as well as by previous models of WR formation.

Even considering the most massive WR stars (with the shortest lifetime), as well as the most conservative calculation of the Be-HMXB lifetime, we expect a fractional lifetime (τ_{WR}/τ_{Be}) of between 5-10% for Be stars between 10-15 $M\odot$. Thus the population of 81 currently observed Be-HMXBs predicts a population of at least 4 WR-HMXBs, which is at odds with the observation of only one such system at the 2σ level. A significantly larger population exceeding 15 WR-HMXBs is expected from more reasonable calculations of the luminous Be-HMXB lifetime and the WR stellar mass. Thus, we may reject the hypothesis that the lack of observed WR-HMXBs stems from their short lifespan.

A second explanation for the lack of observed WR-HMXBs concerns their assumed X-Ray luminosities. If mass lost from the WR star is not efficiently transferred onto the NS, the systems may simply fall below the luminosity threshold of present observations. While this appears unlikely, due both to the high mass loss rates observed in individual WR stars, as well as the extremely

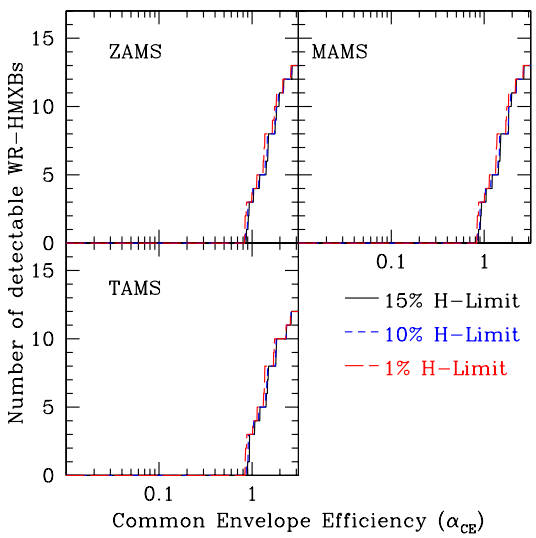

FIG. 4.— Number of surviving and observable ($L_x > 10^{34}$ erg s^{-1}) WR-HMXBs as a function of the CE parameter α_{CE} employing the orbital characteristics at RLO determined via our stellar evolution code for the 13 known Be-HMXBs.

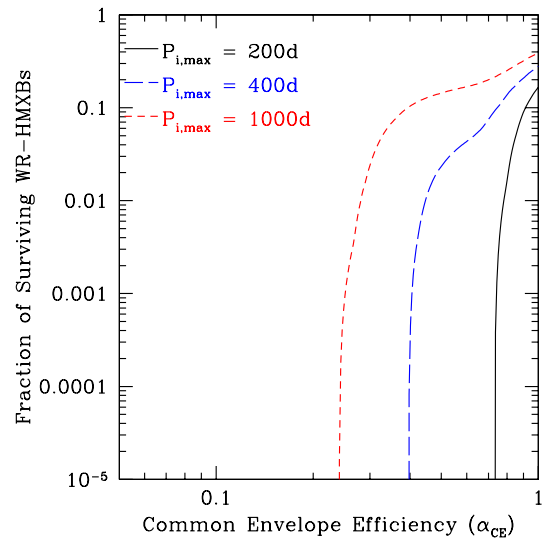

FIG. 5.— Fraction of surviving and visibly detected WR-HMXBs from a parameter space of initially widely separated O/B-NS binaries defined in the text with a maximum initial orbital separation between the compact object and MS star of 200 days (solid black), 400 days (blue long-dash) and 1000 days (red short-dash).

high X-Ray luminosity of Cyg X-3, we check this assumption explicitly by following the WR wind and X-Ray luminosity prescriptions of Hurley et al. (2000) and Belczynski et al. (2008b) respectively. In Figure 3 we show the luminosity of WR-HMXBs for WR stars of $2M_\odot$, $3M_\odot$, an $4M_\odot$ as a function of the orbital separation. We find that for all WR masses, these systems exceed a luminosity of 10^{34} erg s^{-1} out to orbital radii of more than 35 $R_\odot$. Since CE evolution typically creates much tighter orbits (Nebot Gómez-Morán et al. 2011), we conclude that WR-HMXBs which survive CE evolution should be easily visible in surveys of the Milky Way, LMC and SMC, where the population of visible Be-HMXBs has been observed.

3.2. *CE and the Observed Be-HMXB population*

Since the WR-HMXB population has both a sufficiently long lifespan and high luminosity to indicate the existence of numerous observable systems, another mechanism must halt the formation of these binaries. Since their progenitors are known to exist during the Be-HMXB phase, CEs stand as the only dynamical interaction which may eliminate WR-HMXBs progenitors. Thus, it is possible to set constraints on the CE efficiency α_{CE} by demanding that enough of these systems are disrupted during a CE to bring the respective populations into agreement. Using the 13 Be-HMXBs with known orbital parameters as a template for the larger population of 81 systems, we employ our orbital evolution code to determine the orbital and stellar parameters of the observed Be-HMXBs at the onset of the CE.

In Figure 4, we show the number of surviving WR-HMXBs as a function of the CE efficiency α_{CE} under the assumption that detectable Be-HMXBs were observed at the ZAMS, MAMS and TAMS, and with $X_{\rm min}$ set to 15%, 10%, and 1%. We find nearly identical results in all scenarios, indicating that for $\alpha_{CE} \lesssim 1$, mergers occur in all 13 of the observed Be-HMXB systems, regardless of their previous evolutionary history. Since one WR-HMXB is in fact observed, and the lifetime of WR-HMXBs may be smaller than that of Be-HMXBs, only the theoretically established constraint that the CE efficiency must fall below unity (due to conservation of energy) can be confirmed through this analysis. We note this does indicate that current models are not missing any significant energy sources available to remove the CE, as the survivability of the CE phase approaches 100% for $\alpha_{CE} > 1.2$.

4. A COMPLETE PARAMETER SPACE

In the previous sections we've shown that CE-driven mergers are necessary to explain the discrepancy between Be-HMXB and WR-HMXB observations. However, the observed Be-HMXbs exist only as a subset for the potential class of WR-HMXB progenitors. In addition to these luminous systems, we would expect a much larger population of widely separated binaries containing an O/B star and a NS. This underlying population remains undetected because either the donor star does not carry enhanced winds stemming from the Be phenomenon, or the system is too widely separated for stellar material to be effectively accreted onto the NS. In any case, the binary dynamics of this underlying population are identical to the visible population, and evolution through a CE phase may similarly result in bright WR-HMXBs.

In order to model the evolution of these systems, we create a grid of binaries containing a NS and O/B donor following the parameters described in Section 2. In Figure 5, we show the fraction of binaries which survives the CE yielding bright WR-HMXBs. We assume maximum initial orbital periods of 200d (black solid), 400d (blue dashed), and 1000d (red dotted), following a distribution which is flat in the logarithm of the orbital period. We find that a potentially sizable fraction of WR-HMXBs are created for larger values of α_{CE}, although the bounds depend strongly on the maximum assumed orbital period of the underlying O/B-NS population. We note the observation of two Be-HMXBs with orbital periods above 200d allows us to set this as an observed lower limit on

our simulated population (see Table 1). We note that we do not expect a similar variation in our results if we were to vary the minimum orbital period in our sample grid (currently set at 10d). These relatively tightly bound systems are unlikely to survive a CE, and their inclusion in our models will not greatly affect the calculated number of WR-HMXBs.

In order to apply these results to the expected number of observed WR-HMXBs, we must normalize the number of systems in our grid against the expected number of loosely bound O/B-NS binaries. We note that the number of WR-HMXBs expected from our simulated population of O/B-NS systems can be expressed as:

$$N_{WR-HMXBs} = f_s(\frac{N_{Be}}{N_B})^{-1}(\frac{\tau_{WR}}{\tau_{Be}})N_O \qquad (4)$$

where f_s is the survival probability of a given system from our simulation grid (shown in Figure 5), N_{Be}/N_B provides the fraction of B-type donors which have observed Be properties, $\tau_{WR}/\tau_{Be-HMXB}$ describes the relative lifetime of the WR-HMXB and Be-HMXB phases (shown in Figure 2), and N_O is the observed number of Be-HMXB systems ($N_O = 81$ throughout this paper).

The fraction of B-type stars which show emission-line (Be) spectra have been observed to vary between 2%-7% (McSwain & Gies 2005), although we note some sources have shown Be-fractions as high as 8.5% (McSwain et al. 2008). While this ratio may be substantially higher in binary systems if the spin-up of the Be population is due to binary interactions, this line of reasoning is disputed by Oudmaijer & Parr (2010), who find a similar binary fraction for both B and Be stars. In this work, we assume a Be-fraction of 7%, and a fractional lifetime for the WR-HMXB population (τ_{WR}/τ_{Be}) of 20%, taking a central value from Figure 2, under the assumption that the primary progenitor was not more than twice as massive as the Be-star. From these values, we would anticipate a population of 230f_s visible WR-HMXBs.

Thus, we constrain f_s by comparing this expected population of WR-HMXBs to the observation of only a single system. Noting that a prediction exceeding four WR-HMXBs would create a 2σ discrepancy with observation, we thus constrain the survivability of the CE phase to less than 2%. Comparison with Figure 5 thus constrains the CE efficiency to $\alpha_{CE} < 0.8$, $\alpha_{CE} < 0.5$, and $\alpha_{CE} < 0.3$ if the maximum orbital period is 200d, 400d, and 1000d, respectively.

We note that the above calculation is conservative in several ways. First, we have assumed that all systems containing a Be star and NS are visibly bright X-Ray sources. Secondly, we have assumed that the observed population of Be-HMXBs can be translated to a population of O/B-NS with an orbital period which is logarithmically flat starting at 10d. We note that the observed Be-HMXB population is instead biased towards systems with orbital periods around 100d. While the lack of observed loosely bound systems may be due to luminosity cutoffs or simply to limited to observational time, the low period population is likely complete. This implies that the survival fraction of O/B-NS systems resembling the Be-HMXBs may be substantially higher. However, less conservative estimations are unlikely to significantly alter the constraint imposed on α_{CE}, as Figure 5 shows that the survivability of the CE phase plunges for smaller values of α_{CE}, implying that uncertainties in the estimation of the population of O/B-NS binaries has only a negligible effect on the number of expected WR-HMXBs.

5. DISCUSSION AND CONCLUSIONS

Theoretical models predict the production of WR-HMXBs through the CE evolution of widely separated binary systems containing a NS and a massive donor. However, recent observations show a discrepancy between the large population of observed Be-HMXBs and the lack of observed WR-HMXB systems. We show that this population is currently in tension with the lack of observed WR-HMXB systems. We find that theoretical models predict the WR-HMXB population to be sufficiently long-lived and luminous to be detected as the evolved offspring of the observed Be-HMXB population. Noting that a CE phase acts as the only dynamical mechanism which may disrupt the production of WR-HMXBs, we set constraints on the CE efficiency parameter α_{CE}. Using the binary parameters of the observed Be-HMXB population, we are only able to set a limit than α_{CE} falls below unity, echoing theoretical constraints due to conservation of energy. However, simulating a larger grid of O/B-NS binaries with characteristics similar to the observed Be-HMXB population constrains α_{CE} to be <0.8 for a population of O/B-NS binaries with maximum orbital period of 200d, and possibly as low as α_{CE} <0.3 if the O/B-NS population instead extends to orbital periods of 1000d.

We note that the stringency of our constraints are limited primarily by the low number of observed Be-HMXBs, and especially by the limited number of observed Be-HMXBs with known orbital period and eccentricity information. We expect that observational detections of both new B-star NS binaries and determinations of the binary parameters of known Be-HMXBs will greatly reduce these measurement errors and provide a more accurate understanding of CE evolution in massive binaries.

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