**Wolf-Rayet Stars**
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# The missing Wolf-Rayet X-ray binary systems

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We investigate the rarity of the Wolf-Rayet X-ray binaries (WRXRBs) in contrast to their predecessors, the high mass X-ray binaries (HMXRBs). Recent studies suggest that common envelope (CE) mergers during the evolution of a HMXRBs may be responsible (Linden et al. 2012). We conduct a binary population synthesis to generate a population of HMXRBs mimicking the Galactic sample and vary the efficiency parameter during the CE phase to match the current WRXRB to HMXRB ratio. We find that ∼50% of systems must merge to match observational constraints.

## 1 Introduction

Current Wolf-Rayet (WR) evolution theories agree that WR stars originate from O-type main sequence stars. Thus, we expect a commonplace O+O binary system to evolve into an O+cc, a high mass x-ray binary, and eventually to a WR+cc system. Yet, while the number of known O + cc is significant, the number of detected WR+cc systems is much lower than predicted. In fact, while there are a total of 114 confirmed HMXRBs (Liu et al. 2006) in our Galaxy, there is only a single confirmed WR+cc binary: Cyg X-3 (Tutukov et al. 2013).

To explain this discrepancy, the evolution of an HMXRB to a WRXRB is presumably halted by a CE merger. The goal is to produce a sufficient number of massive OB binaries to obtain 114 HMXRBs and adjust the efficiency parameter such that the merger rate of the HMXRBs is compatible with the observed number of WRXRBs.

## 2 Computational method

### 2.1 Initial binary population

Assuming zero eccentricity, the synthetic binaries can be synthesized with the aid of three probability distribution functions (PDFs): 1) the Salpeter initial mass function to determine the mass of the primary, $m_1$ 2) empirical mass ratio to determine the mass of the secondary, $m_2$ 3) Öpiks law to determine the orbital period, $P$. Respectively, the PDFs are:

$$\begin{aligned} f(m_1) &\propto m_1^{-2.35} \\ f(q) &\propto 1 \\ f(P) &\propto 1/P \end{aligned} \tag{1}$$

where $q = m_2/m_1$. The masses will range from 8 $M_\odot$, the minimum threshold for massive stars to undergo a supernova explosion, to 100 $M_\odot$, the maximum capacity in the binary evolution code (see section 2.2), and the period from 2 to 3000 days. Any system with a period less than 2 days is expected to merge and binary interaction is insignificant above 3000 days.

### 2.2 Binary Evolution

The generated binaries are evolved with a binary evolution code from Hurley et al. (2002). The initial masses and periods obtained in (1) will serve as input parameters. It is necessary to determine the distribution of supernova kicks and the efficiency parameter of the CE phase as they play an important role in the evolution of a HMXRB.

#### 2.2.1 Supernova kicks

Asymmetric supernova (SN) explosions may impart an additional kick to a binary system. This may encourage the binary to disrupt or even help stabilize the orbit. Modelling SN kicks is therefore essential in massive binary evolution.

The direction of the kicks is presumed to be random. As for its magnitude, neutron star (NS) natal kicks are modeled with a Maxwellian distribution peaked at 300 km/s. Black hole (BH) kicks are assumed to obey reduced NS kicks owing to conservation of momentum (Repetto et al. 2012). For example, a 10 $M_\odot$ BH will receive ∼60% the kick of a 1.4 $M_\odot$ NS.

#### 2.2.2 Common envelope evolution

If mass transfer occurs on dynamical timescales, faster than the compact object can accrete, then the excess matter will lead to the formation of a common envelope (CE) around both stars. As the compact companion orbits around the donor's core, the envelope creates a drag force on the two stars that dissipates their angular momentum and causes them to spiral in. The outcome of this scenario is either a successful ejection of the CE or a merger.

As the stars spiral in, if enough gravitational energy is released and converted to kinetic energy into the envelope, the CE may be blown away. However, as there are non-conservative forces, some energy will be lost. The survivability of the system depends on its efficiency in transferring orbital energy into the envelope.

Treatment of the CE evolution in Hurley et al. (2002) introduces two free parameters: $\alpha_{\rm CE}$, the efficiency, and $\lambda$, a corrective term in the envelope's binding energy that depends the donor's mass-density structure. It is common practice to set $\lambda$ at 0.5 (de Kool 1990) and the efficiency typically varies from 0 to 1. Therefore, in this study, $\lambda$ is left constant at this default value and only $\alpha_{\mathrm{CE}}$ was varied.

# 3 Results

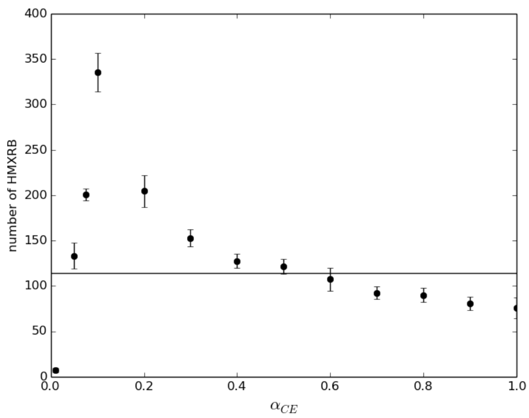


**Fig. 1:** Number of HMXRBs as a function of the efficiency. The number of initial synthetic binaries is kept constant at 12000. The solid horizontal line indicates the cut off for 114 HMXRBs.

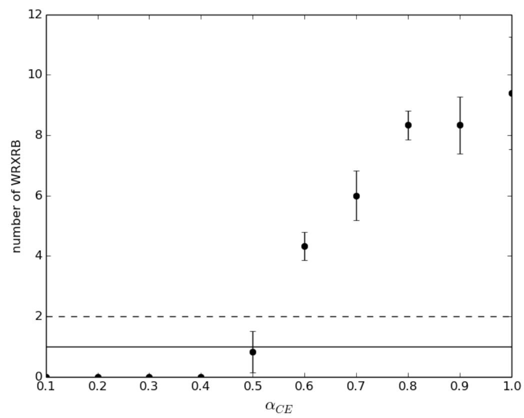


**Fig. 2:** Number of WRXRBs as a function of the efficiency. The number of initial synthetic binaries is adjusted to produce roughly 114 HMXRBs. The solid and dashed horizontal lines respectively correspond to the thresholds for 1 WRXRB (Cyg X-3) and 2 WRXRBs (Cyg X-3 and possibly another unidentified WRXRB, such as WR 148).

In Figure 1 we illustrate how the efficiency parameter effects the number of resulting HMXRBs with a constant initial population of 12000 binaries. The efficiency ranged from 0 to 1 with an increment of 0.1.

Similarly, depicted in Figure 2 is the number of WRXRB for a given efficiency. For each value of $\alpha_{\mathrm{CE}}$, the initial population of generated OB binaries is calibrated (by trial and error) to ensure that there are $\sim$114 HMXRBs.

# 4 Discussion

Of interest is the value of $\alpha_{\mathrm{CE}}$ to require all but a single HMXRB to merge from an initial sample of 114 HMXRBs. However, obtaining a constant population of 114 HMXRBs is difficult because it is sensitive to the efficiency. This indicates that there may be a CE phase prior to the SN of the original primary. If this were the case, then intuitively one would expect the number of HMXRBs to decrease as the efficiency drops. And yet, as seen in Figure 1, the number of HMXRBs appear to rise for $\alpha_{\mathrm{CE}}$ decreasing to 0.1.

A CE phase, while both stars are still on the main sequence, has an unprecedented effect on the disruption rate of a binary subsequent to a SN. As the efficiency drops, the pre-SN binaries that survive a CE phase (if a CE phase occurs) will have a much reduced orbital separation. As a result, these tighter binaries will have a better chance of surviving the first SN, thus creating more HMXRBs. This is valid for an efficiency between 0.1 and 1. However, below $\alpha_{\mathrm{CE}} = 0.1$, the energy conversion isn't efficient enough for the binaries to survive the pre-SN CE phase and so the number of HMXRBs decline rapidly.

The surviving HMXRBs face another hurdle. Their evolution and fate is often subject to a CE phase once again. This is because unstable mass transfer is easily triggered if the binary components have a large mass ratio (i.e. $q \geqslant 1$). This is most likely the case for puffy OB stars orbiting around a compact object. Binaries that are successful at ejecting their CE can have their orbital separations drastically reduced by up to a factor of 100 (Tauris & van den Heuvel 2006). This can explain Cyg X-3's extremely short period of 4.8 hours.

Considering the typical lifetimes of a WR compared to its O-star progenitors, we would expect around 10% of the HMXRBs to evolve into WRXRBs. Thus naively, if there were no CE mergers, we would predict $\sim$11 WRXRB in the Galaxy. This is what is shown in Figure 2 at 100 % efficiency (within error). As suspected, the number of WRXRBs decreases along with the efficiency. Below 40% efficiency, all HMXRBs have merged and there are no WRXRBs. Setting $\alpha_{\mathrm{CE}}$ to 0.5 allows us to obtain the ideal merger rate.

These results are valid in the assumption that $\lambda = 0.5$. However, the true determination of this coefficient is still subject to much debate. Nevertheless, we are fortunate that the CE evolution depends on the product $\alpha_{\rm CE}\lambda$ and not on the individual values themselves. Therefore, if $\lambda$ is ever better constrained, the validity of this work is not changed as long as $\alpha_{\rm CE}$ is adjusted so that the quantity $\alpha_{\rm CE}\lambda$ remains equal to 0.25.

## 5 Conclusion and future work

We demonstrated how the transition from HMXRB to WRXRB can be impeded due to unstable mass transfer which leads to the formation of a common envelope. The apparent lack of WRXRB in comparison to the number of HMXRB can hence be explained by CE mergers. We obtain an efficieny of 0.5 during the CE phase to reproduce the current WRXRB to HMXRB ratio.

It is important to note that this study relies on the premise that Cyg X-3 is the only WRXRB in our galaxy. There are however other candidates worthy of investigation, namely WR 148 (HD 197406). WR 148 is a single lined spectroscopic binary classified as a WN8h + B3IV/BH (Hamann et al. 2006). To determine the nature of the companion we have obtained high signal to noise spectra (above 1000 per pixel in the continuum once combined) from the Keck observatory with the ESI spectrograph, providing a range of 3900 Å to 10900 Å. A meticulous study of these spectra is currently underway.

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**Jennifer L. Hoffman:** How sure are we that only one WR+cc binary exists in our Galaxy? Could we have missed a couple?

**Melissa Muñoz:** It is unlikely because while gas might hide many such systems, it is transparent to X-rays, which are prominent in X-ray binaries. However, there are a couple of unique cases, such as WR 148, which may in fact have compact companions.