High-mass X-ray Binaries: Illuminating the Passage
from Massive Binaries to Merging Compact Objects
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Formation of the SMC WO+O binary AB8

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Abstract. Wolf-Rayet (WR) stars are stripped stellar cores that form through strong stellar wind or binary mass transfer. It is proposed that binary evolution plays a vital role in the formation of WR stars in low metallicity environments due to the metallicity dependance of stellar winds. However observations indicate a similar binary fraction of WR stars in the Small Magellanic Cloud (SMC) compared to the Milky Way. There are twelve WR stars in the SMC and five of them are members of binary systems. One of them (SMC AB8) harbors a WO type star. In this work we explore possible formation channels of this binary. We use the MESA code to compute large grids of binary evolution models, and then use least square fitting to compare our models with the observations. In order to reproduce the key properties of SMC AB8, we require efficient semiconvection to produce a sufficiently large convective core, as well as a longer He-burning lifetime. We also need a high mass loss rate during the WN stage to assist the removal of the outer envelope. In this way, we can reproduce the observed properties of AB8, except for the surface carbon to oxygen ratio, which requires further investigation.

Keywords. Stars, Wolf-Rayet, stellar evolution, binary

1. Introduction

Wolf-Rayet (WR) stars are hot and luminous stars characterised by broad emission lines. They are believed to be in a late evolutionary phase of massive stars. Due to their strong stellar wind, they provide an important contribution to the chemical enrichment of galaxies (for a review of WR stars, see Crowther 2007). They may be progenitors of long gamma-ray bursts (GRBs, Woosley & Bloom 2006), and explode as type Ib/c supernova. Thus it is of great importance to study the formation and evolution of WR stars.

Based on the intensity of spectra lines, WR stars are divided into three subtypes: WN type with strong He and N lines; WC type with strong He and C lines; and WO type with strong He, C and O lines. This difference is believed to be the result of different nuclear processed material being exposed at stellar surface (Lamers *et al.* 1991; Crowther & Hadfield 2006). Generally a star firstly exposes the H-burning products at its surface due to stellar wind or binary interaction and is seen as a WN type star, then exposes the He-burning products and is observed as a WC/WO type star (Crowther 2007 and references there in).

It is important for us to study massive star evolution in low metallicity environment, since the strong stellar wind can be avoided, making it possible for us to check the influence of other processes such as binary interaction. In the SMC, binary interaction should play a more important role in the formation of WR stars than in the Galaxy. However Foellmi *et al.* (2003) found that the binarity in the SMC is similar to that in the Galaxy as well as in the LMC. Apparently single WR stars have been studied by

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Schootemeijer & Langer (2018), who concluded that they may in fact be undetected binaries. In this work we investigate the formation channel of the binary system AB8 that consists the only observed WO star in the SMC.

2. Method

We use version 8845 of MESA code (Paxton *et al.* 2011; Paxton *et al.* 2013; Paxton *et al.* 2015) to establish binary models, taking into account the physics of mass-loss, rotation and binary interaction.

We use Ledoux criterion for convection and the mixing length parameter $\alpha = l/H_P$ is set to be 1.5. We use step-overshooting to extend the convective core by 0.335 H_P, where H_P is the pressure scale height at the boundary of the convective core. We consider both inefficient and efficient semiconvection with parameter $\alpha_{\rm sc} = 0.01$ and $\alpha_{\rm sc} = 1$ respectively. The efficiency parameter for thermohaline mixing is $\alpha_{th} = 1$.

For stellar wind mass loss, we follow Brott *et al.* (2011), with wind for main sequence hydrogen rich stars computed following the recipe by Vink *et al.* (2001). For temperatures below that of the bi-stability jump, we take the maximum of the rate of Vink *et al.* (2001) and Nieuwenhuijzen & de Jager (1990). When surface hydrogen abundance is lower than 0.4, we use prescription from Hamann *et al.* (1995). For stars that have surface hydrogen abundances in range of $0.4 - 0.7$, we interpolate between the mass loss rate of Vink *et al.* (2001) and Hamann *et al.* (1995). Stellar mass loss rate scales as $\dot{M} \propto Z^m$. For Hamann *et al.* (1995) prescription we check $m = 0.85, 0.75, 0.65$ and 0.55 to account for different mass loss rate during WR phase, while for other prescriptions we assume $m = 0.85$ (Vink *et al.* 2001). During Roche lobe overflow the accretor spins up. If the star reaches $\Omega/\Omega_{crit} = 0.99$, we implicitly increase the mass loss rate such that the star could rotate just below the critical value.

Rotational mixing is modeled as a diffusive process, including the effects of dynamical and secular shear instabilities, the Goldreich-Schubert-Fricke instability, and Eddington-Sweet circulations, as described in Heger *et al.* (2000). We also include the transport of angular momentum due to magnetic fields from the Tayler-Spruit dynamo (Spruit 2002). Mass transfer is modeled using a contact scheme as described in Marchant *et al.* (2016).

We use a standard χ^2 minimization algorithm to find the best-fitting model in our dataset. We take into account six observables: $\log T_1$, $\log T_2$, $\log L_1$, $\log L_2$, $X_{H,1}$, and P corresponding to the temperature of the two stars, the luminosity of the two stars, the surface H abundance of the primary star and the orbital period in units of days. Then the standard χ^2 value is expressed as:

$$\chi^2(\log M_{i,1}, q_i, \log P_i, t) = \sum_{n=1}^{6} \left(\frac{O_n - E_n(\log M_{i,1}, q_i, \log P_i, t)}{\sigma_n} \right)^2 ,$$

where O_n are the six observables and $E_n(\log M_{i,1}, q_i, \log P_i, t)$ is corresponding theoretical values at time t defined by the three initial parameters. σ_n is the corresponding observational error. The observational data are listed in Table 1.

3. Results

We establish binary systems with the initial primary mass $\log M_{i,1}$ ranging from 1.65 to 2.10 in intervals of 0.05, the mass ratio $q = M_{i,2}/M_{i,1}$ from 0.3 to 0.95 in intervals of 0.05 and the initial orbital period $\log P_i$ from 0.0 to 2.5 in intervals of 0.025. All of the binary systems are assumed to be initially synchronised by tidal interaction and are in circular orbits.

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Table 1. Different properties of our best fitting models, and observed properties of AB8 from Shenar *et al.* (2016)

	m=0.55	m=0.65	m=0.75	m=0.85	AB8
$\log T_{\mathrm{eff},1}$	5.154	5.182	5.121	5.106	$5.149^{+0.154}_{-0.066}$
$\log T_{\mathrm{eff},2}$	4.632	4.636	4.616	4.616	$4.653^{+0.046}_{-0.051}$
$\log L_1/\mathrm{L}_\odot$	6.15	6.17	6.16	6.20	$6.15^{+0.1}_{-0.1}$
$\log L_2/\mathrm{L}_\odot$	5.81	5.82	5.87	5.87	$5.85^{+0.1}_{-0.1}$
$M_1/\mathrm{M}_\odot$	35	35	35	37	19^{+3}_{-8}
$M_2/\mathrm{M}_\odot$	51	51	53	53	61^{+14}_{25}
$X_{\mathrm{C,s}}$	0.46	0.43	0.00	0.00	$0.30^{+0.05}_{-0.05}$
$X_{\mathrm{O,s}}$	0.26	0.37	0.00	0.00	$0.30^{+0.1}_{-0.1}$
$R_1/\mathrm{R}_\odot$	2.0	1.8	2.3	2.6	2^{+1}_{-1}
$R_2/\mathrm{R}_\odot$	14.6	14.5	16.9	16.8	14^{+6}_{-4}
$P_{\mathrm{orb}}/\mathrm{days}$	16.58	16.21	16.34	16.14	16.6
$\log \dot{M}_{\mathrm{WO}}/\mathrm{M}_\odot \mathrm{yr}^{-1}$	-4.20	-4.27	-4.38	-4.40	$-4.8^{+0.1}_{-0.1}$

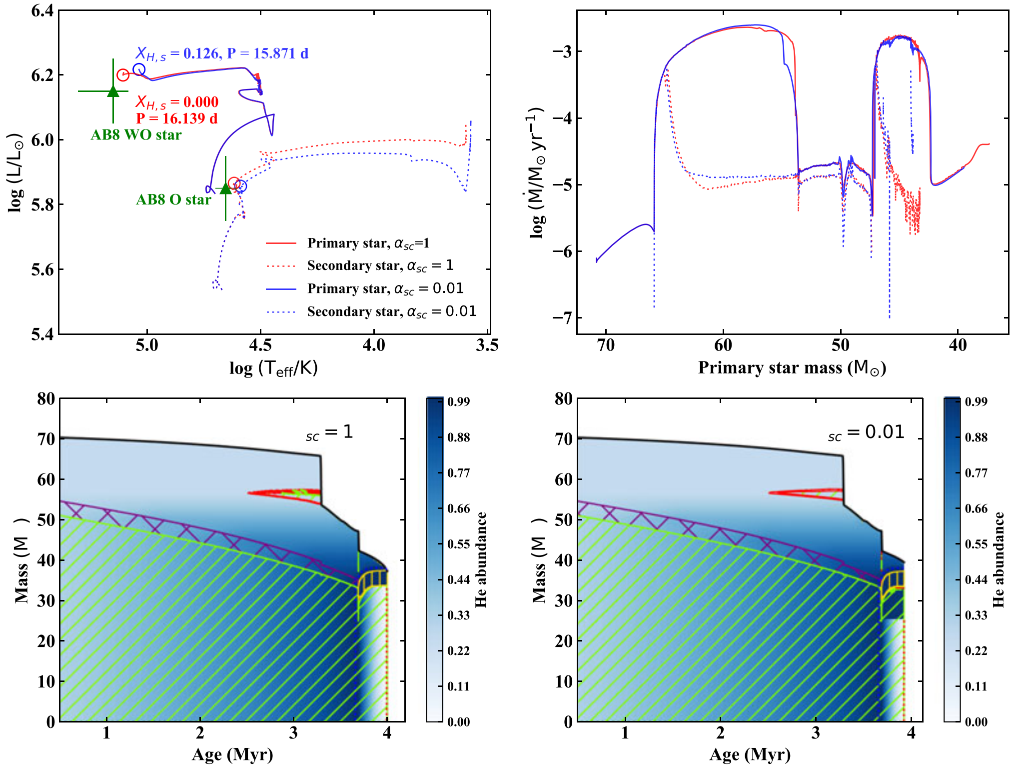

Figure 1. Evolutionary history of the model that can best reproduce the observed properties of AB8 by adopting $\alpha_{\mathrm{sc}} = 1$ and $m = 0.85$. This model has initially $M_{i,1} = 70\,M_\odot$, $M_{i,2} = 50\,M_\odot$ and $P_i = 12.5$ days. The system with the same initial parameters but computed with $\alpha_{\mathrm{sc}} = 0.01$ is also shown. The first panel shows their evolutionary paths in the HR diagram. Solid and dotted lines correspond to the evolution of the primary and secondary stars, respectively. Green triangles represent the observations. Circles indicate the best fitting positions. The surface H abundances as well as the orbital periods at the best fitting time are listed. The second panel shows the mass transfer history of the two systems. We use the same labels as in the first panel. The third and fourth panels are Kippenhahn diagrams for the primary stars computed from different α_{sc} values. We use green, purple, red and yellow lines to delineate the convective, overshooting, semiconvective and thermohaline mixing regions, respectively.

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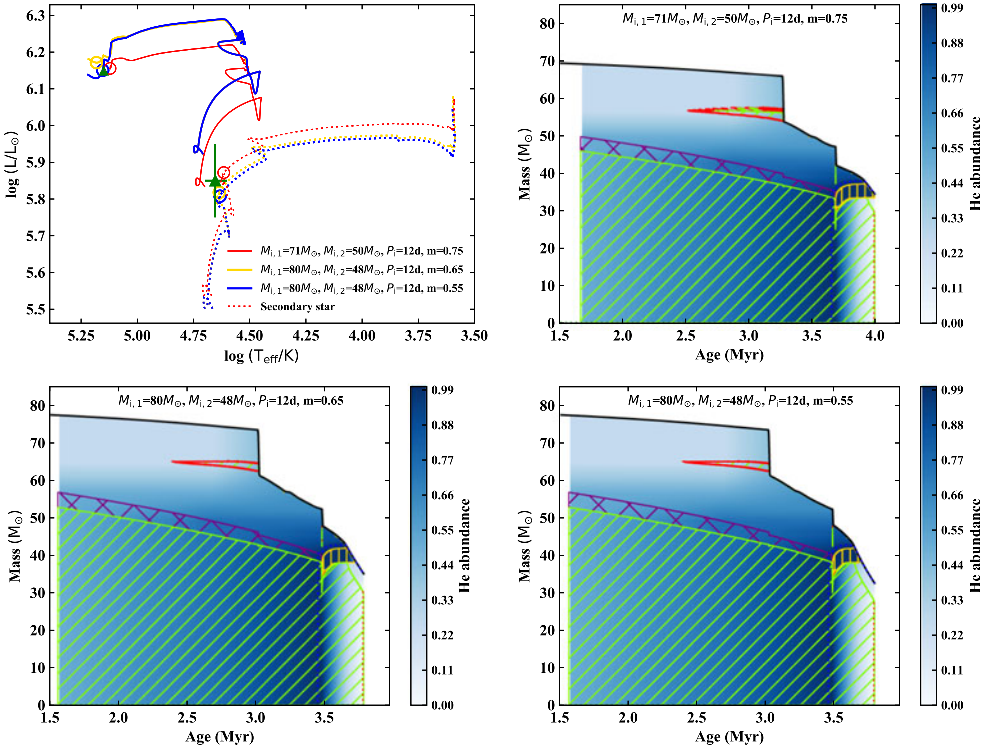

Figure 2. Models that can best reproduce the properties of AB8 adopting $\alpha_{\rm sc} = 1$ and different m values. In the first panel, solid and dotted lines with different colors correspond to the evolution of the primary and secondary stars in binaries with different intial parameters and different m values, respectively. The second to fourth panels are the Kippenhahn diagrams for the primary stars. The inital parameters and adopted m values are listed in each panel.

Fig. 1 shows the evolutionary history of the model with log $M_{i,1}/M_\odot = 1.850$, $q_i = 0.700$ and log $P_i/d = 1.100$ ($M_{i,1} = 70\,M_\odot$, $M_{i,2} = 50\,M_\odot$ and $P_i = 12.5$ d). This model best reproduces the observations, based on the assumption of $\alpha_{\rm sc} = 1$ and $m = 0.85$. We also show the system with the same initial parameters but computed with inefficient semiconvection. With inefficient semiconvection $\alpha_{\rm sc} = 0.01$, there is a thin H layer left at the best fitting time. With efficient semiconvection, the CO core mass is $\sim 8\,M_\odot$ larger. The He core mass is nearly the same in the two situations. However with efficient semiconvection, due to the injection of fresh nuclear fuel, the primary star has a longer He burning lifetime (~ 0.07 Myr longer), making it possible to expose its He core. Still this WR star model has a thin pure He layer left, meaning that it is a WN type star rather than a WC/WO type star.

The highly uncertain WR stellar wind mass loss rate may play an important role in the formation of WC/WO stars in low metallicity environments. The most uncertain part in the prescription of the WR mass loss is its dependence on metallicity. Therefore we increase the stellar wind during the WR phase by changing the power of the metallicity dependance m to 0.75, 0.65 and 0.55 which will increase the stellar wind mass loss rate by a factor of 1.23, 1.51 and 1.86, respectively.

Fig. 2 depicts the models that can best reproduce the observations, computed from assuming $\alpha_{\rm sc} = 1$ and different m values. The initial parameters are listed. We can see from the third and fourth panels that with the help of an enhanced stellar wind, the pure He layer of the primary stars can be totally removed. In this way, we can obtain

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progenitors that can fit the observed properties of AB8. The best fitting model has initially $M_{i,1} \simeq 80\,M_\odot$, $M_{i,2} \simeq 48\,M_\odot$, $P_i \sim 12\,\mathrm{d}$.

4. Conclusions

In this work we have evolved tens of thousands of binary systems with SMC metallicity. The initial parameter space is $1.65 \leqslant \log M_{i,1} \leqslant 2.10$, which securely covers the progenitors of the WO star in AB8 based on current assumptions, the mass ratio $0.3 \leqslant q_i \leqslant 0.95$ and the orbital period $0.0 \leqslant \log P_i \leqslant 2.5$. We have calculated models using both inefficient and efficient semiconvection with $\alpha_{\rm sc} = 0.01$ and $\alpha_{\rm sc} = 1$, respectively. We have also varied the metallicity scaling of the WR wind mass loss rate with, $m = 0.85, 0.75, 0.65$ and 0.55.

Our main results are:

(a) WC/WO systems can be produced in low metallicity environments through binary interaction.

(b) In order to reproduce a hydrogen-free WR star, we need efficient semiconvection that can extend the stellar life during core He burning such that the primary star can lose more of its envelope through stellar wind.

(c) In order to reproduce SMC AB8, we need to adopt a high stellar wind mass loss rates. In our models we can find progenitor systems with both, $m = 0.65$ and $m = 0.55$.

(d) The SMC WO+O binary AB8 formed most likely from a ZAMS binary with $M_{i,1} \simeq 80\,M_\odot$, $M_{i,2} \simeq 48\,M_\odot$ and an initial orbital period of $\sim$ 12 days, through stable highly non-conservative mass transfer.

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