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On the prevalence of early mass transfer for very massive binaries

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ABSTRACT

Common phases of mass transfer in stellar binaries are case A (during the donor's main sequence) and case B (after the donor's main sequence but before helium core depletion). For most masses, radii significantly grow after the main sequence, making case B more common. However, depending on uncertain stellar physics, very massive stars may already undergo significant expansion during the main sequence increasing the probability of case A mass transfer. For observationally-informed convective boundary mixing, case A mass transfer dominates for donor masses $\gtrsim 75\,M_\odot$. This is not the case without convective boundary mixing or in the stellar models commonly used in rapid binary population synthesis. Therefore, case A mass transfer may be more dominant than commonly assumed, with potential impact on rates of all post mass transfer binaries, from Wolf-rayet-O-type binaries, to X-ray binaries, and gravitational wave progenitors.

1. MASS TRANSFER IN VERY MASSIVE BINARIES

Binary stars with a sufficiently small orbital separation ($a \lesssim 2500\,R_\odot$) undergo (at least) a mass transfer phase in which the donor star transfers mass the initially less massive accretor. For very massive stars ($\gtrsim 30\,M_\odot$), mass transfer most often occurs during the donor's hydrogen core-burning main sequence (case A) or helium core-burning (case B), which together cover $\sim 99\%$ of the donor's lifetime (Kippenhahn & Weigert 1967).

For a flat in $\log_{10}(a)$ initial initial separation distribution (Öpik 1924), case B is expected more often than case A mass transfer, since most stars expand dramatically post-main sequence (van den Heuvel 1969). However, very massive stars may already undergo a drastic expansion in radius during their main sequence. (e.g., Sanyal et al. 2015; Jiang et al. 2015; Sabhahit & Vink 2024). This may increase the rate of case A (de Mink et al. 2008), which could have significant implications on the rates of Wolf-Rayet+O-type binaries (e.g., Nuijten & Nelemans 2024), X-ray binaries, and gravitational wave progenitors. The radius of the donor is dependent on unknown stellar parameters, including stellar winds (Renzo et al. 2017; Josiek et al. 2024), metallicity (Xin et al. 2022), close-to-super-Eddington-layers (e.g., Joss et al. 1973; Paxton et al. 2013; Jiang et al. 2015; Agrawal et al. 2022; Jermyn et al. 2023), and convective boundary mixing (Anders & Pedersen 2023; Johnston et al. 2024). Here, we illustrate this comparing the radial evolution of very massive stars varying convective boundary mixing, metallicity, and models commonly adopted in rapid binary population synthesis.

2. COMPARING DONOR RADII

We computed MESA models (version 24.03.1, Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023) from $30\,M_\odot$ to $100\,M_\odot$ in steps of $5\,M_\odot$ at metallicity $Z = 0.001$ and 0.0001 following the setup from Renzo et al. (2023). The gray lines in Fig. 1 show their radial evolution as a function of time.

We explore models with (top panel) and without overshooting (middle panel) and compared them to the Pols et al. (1998) models (bottom panel) used in SSE/BSE (Hurley et al. 2000) taken from COMPAS (Stevenson et al. 2017; Vigna-Gómez et al. 2018; Riley et al. 2022), which extrapolates for masses $\geq 50\,M_\odot$.

When using overshooting, our MESA models implement an exponential algorithm (Herwig 2000) fit to the step overshooting calibrated on the width of main sequence in 30 Doradus (Brott et al. 2011) following Claret & Torres (2018). This relatively "large overshooting" model is compared to models not including any convective boundary mixing, and to the Pols et al. (1998) models including an effectively mass-dependent overshooting.

The red and blue dashed lines in each panel of Fig. 1 denote the maximum radius during the main sequence and helium core burning phase, respectively. These mark the maximum Roche radius for a case A and case B donor, respectively. The right axis shows orbital separations a where the stellar radius meets the roche radius (Eggleton 1983), neglecting orbital widening due to

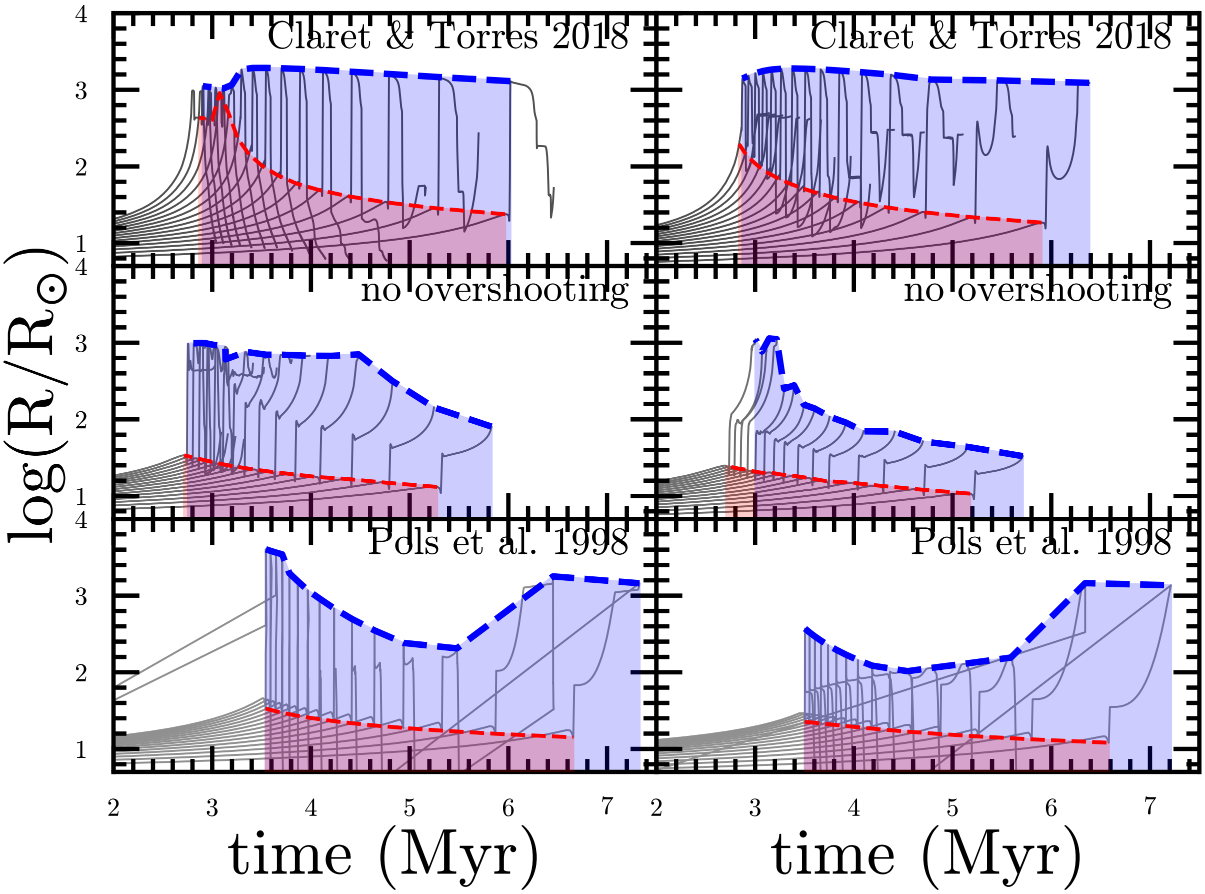

Figure 1. Each panel contain 15 stellar models spanning from a 30 $M_\odot$ star on the right to a 100 $M_\odot$ with intervals of width 5 $M_\odot$. The top panels plot models that feature broad convective boundary mixing, the middle panels plot models that do not feature overshooting, and the bottom panels plot models generated from COMPAS using data from Pols et al. (1998). The left panels have a metallicity $Z = 0.001$ and the right panels have a metallicity $Z = 0.0001$

winds (included in the stellar models) and assuming a representative accretor-to-donor mass ratio of $q = 0.55$. The red regions denote binaries which will undergo case A mass transfer and the blue regions denote binaries which will undergo case B mass transfer.

For $Z = 0.001$, when including overshooting (top left panel), donors with masses $\gtrsim 75\,M_\odot$ can only experience case A. Removing convective boundary mixing (middle) keeps main sequence radii smaller, preserving the blue region above the red line for case B mass transfer at all masses. The overshooting implementation from Pols et al. (1998) (bottom), while nonzero, still leaves a large window for case B up to 100 $M_\odot$. At even lower metallicities of $Z = 0.0001$ (right), stars are more compact, and all models allow for case B mass transfer at all masses.

3. IMPLICATIONS FOR POST-MASS-TRANSFER BINARIES

Convective boundary mixing (Brott et al. 2011; Johnston et al. 2024) and metallicity have a strong effect on stellar radii, which determine when a donor fills its Roche lobe. Other effects on stellar radii have been explored elsewhere, including the adopted wind mass loss rates (e.g., Smith 2014; Renzo et al. 2017; Josiek et al. 2024), rotation (and consequently tides, e.g., Maeder & Meynet 2000), and the treatment of energy transport in correspondende of opacity bumps in the envelope (e.g., Joss et al. 1973; Agrawal et al. 2022; Cheng et al. 2024).

After a thermal-timescale initial phase, Case A mass transfer occurs overall on a longer (nuclear) timescale, while case B occurs entirely on a much shorter (thermal) timescale (but see Klencki et al. 2022). Moreover, the dynamical stability of the orbit during mass transfer is sensitive to the evolutionary phase of the stars involved (e.g., Claeys et al. 2014). Therefore, whether a given binary experiences a common envelope depends on more than just the mass ratio. Here, we show the depence on donor mass, metallicity, and convective boundary mixing. Comparing rows in Fig. 1 shows that the stellar evolution models commonly used in rapid population synthesis are qualitatively similar to our no overshooting models, in the sense that they allow for case B mass transfer up to inital masses of $100\,M_\odot$ for metallicities relevant to galactic and gravitational astronomy.

Given the critial role of mass transfer for the formation of many binaries of interest, the fraction of systems experiencing case A in respect to case B may significany impact predicted rates for post mass transfer binaries, including Wolf-Rayet+O-type binaries, X-ray binaries, and gravitational wave progenitors. In particular, the role of the stable mass transfer channel (e.g., Marchant et al. 2021; van Son et al. 2022) for binary black hole mergers is currently hotly debated. Our results highlight that stellar uncertainties influence the mode of mass transfer and consequently the outcomes.

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