Draft version February 18, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

On the prevalence of early mass transfer for very massive binaries

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ABSTRACT

Common phases of mass transfer in massive 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). Most stars see their radii significantly grow after the main sequence, making case B more common. However, very massive stars may already undergo significant expansion during the main sequence increasing the probability of case A mass transfer. We find that using convective boundary mixing informed by the width of the main sequence in 30 Doradus, 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

Binaries with orbital separation $a \lesssim 2500\,R_{\odot}$ undergo (at least one) mass transfer phase (Sana et al. 2012). For very massive donors ($\gtrsim 30\,M_{\odot}$), mass transfer most often occurs during the donor's hydrogen (case A) or helium core-burning phase (case B), together accounting for $\sim 99\%$ of the lifetime.

For a flat-in-$\log_{10}(a)$ initial distribution (Öpik 1924), case B is expected to be more common, since most stars greatly expand post-main sequence (e.g., van den Heuvel 1969). However, very massive stars may already drastically expand during their main sequence (e.g., Sanyal et al. 2015; Jiang et al. 2015). This may increase the rate of case A (de Mink et al. 2008), potentially affecting Wolf-Rayet+O-type binaries (e.g., Nuijten & Nelemans 2024), and X-ray binaries and gravitational wave progenitors (e.g., Mandel & Broekgaarden 2022).

The radius of the donor depends on poorly constrained stellar parameters, including winds (Renzo et al. 2017; Josiek et al. 2024), metallicity (Xin et al. 2022), treatment of close-to-super-Eddington layers (e.g., Joss et al. 1973; Jiang et al. 2015) rotation (e.g., Maeder & Meynet 2000) and consequently tides (e.g., Fabry et al. 2022) and convective boundary mixing (Anders & Pedersen 2023; Johnston et al. 2024). Here, we explore the radial evolution of very massive stars and its impact on when mass transfer starts and compare to models commonly adopted in rapid binary population synthesis.

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2. COMPARING DONOR RADII

We computed MESA models[1] (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.

When using overshooting (top), we adopt an exponential algorithm (Herwig 2000) fit to the step overshooting calibrated on the width of main sequence in 30 Doradus (~ 0.335 pressure scale heights, Brott et al. 2011) following Claret & Torres (2018), corresponding to `(f,f_0)=(0.0415,0.008)`. We also compute models without any convective boundary mixing (middle), and show the Pols et al. (1998) models including an effectively mass-dependent overshooting (bottom). These are the stellar models underpinning SSE (Hurley et al. 2000), which we generated using COMPAS (Stevenson et al. 2017; Vigna-Gómez et al. 2018; Riley et al. 2022).

[1] Available at doi.org/10.5281/zenodo.14757819

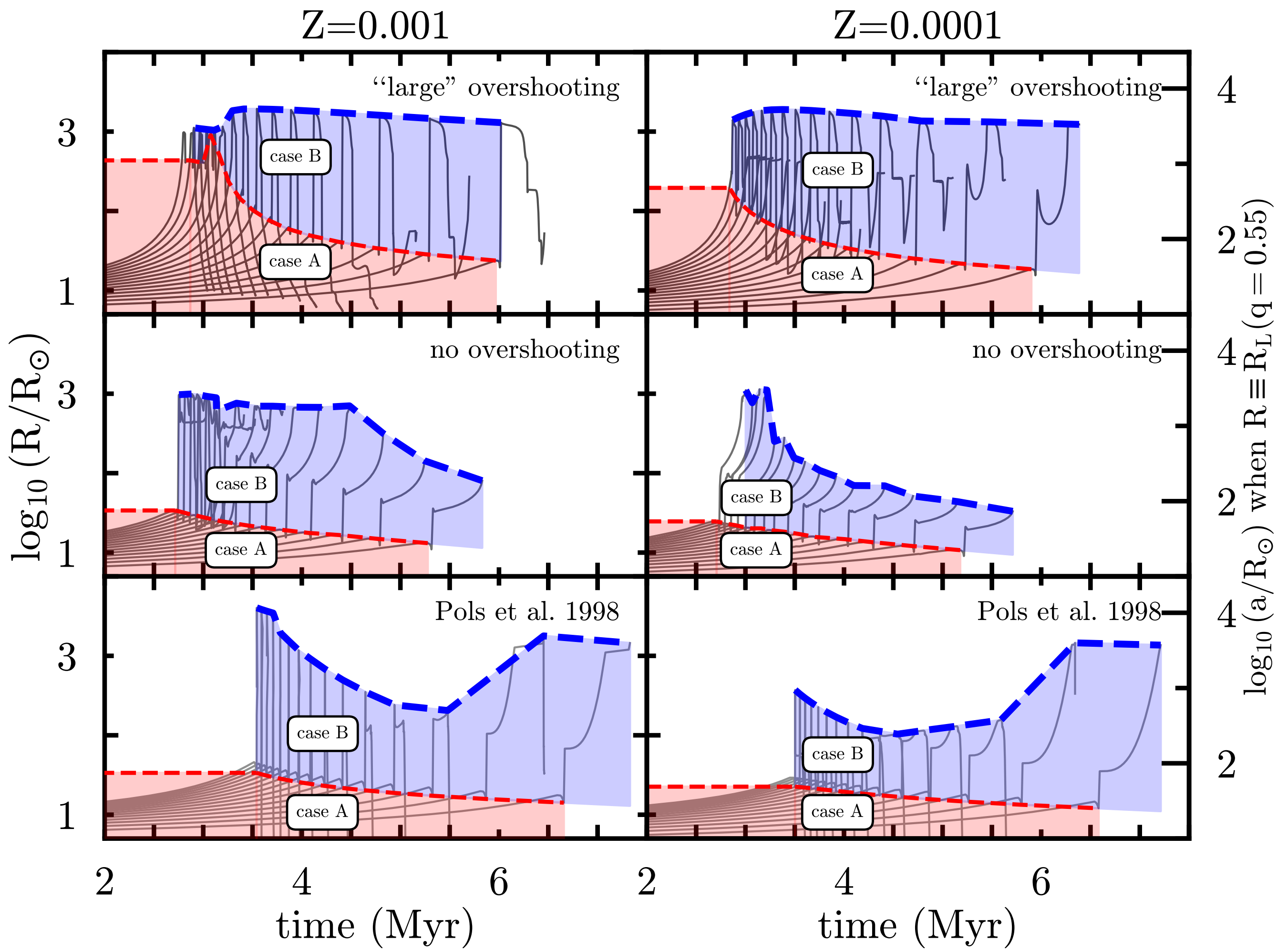

Figure 1. Each panel contains 15 stellar MESA models spanning from $30\,M_\odot$ star (longer lifetimes) to $100\,M_\odot$ (shorter lifetimes). The top panels show models with Brott et al. (2011)-like "large" overshooting (Claret & Torres 2018), the middle panels show models without overshooting, and the bottom panels plot models generated using COMPAS based on analytic fits to stellar models from Pols et al. (1998). The left (right) panels have metallicity $Z = 0.001$ ($Z = 0.0001$). Dashed red (blue) lines mark the maximum radius during the main sequence (during the model's runtime). The red (blue) shaded areas correspond to case A (case B) mass transfer.

Models with $M \geq 50\,M_\odot$ in the bottom panel are extrapolations.

The red and blue dashed lines in each panel of Fig. 1 denote the maximum main sequence radius and the maximum radius before helium depletion, marking the maximum Roche radius for a case A and case B donor, respectively. The right axis shows a for which the star fills its Roche lobe (Eggleton 1983), assuming a representative accretor-to-donor mass ratio $q = 0.55$. For $Z = 0.001$, when including overshooting (top left), donors with masses $\gtrsim 75\,M_\odot$ are more likely to experience case A. Removing convective boundary mixing reduces the stellar radii during the main sequence, preserving a window for case B. The overshooting implementation from Pols et al. (1998), while nonzero, still leaves a large window for case B up to at least $100\,M_\odot$. At $Z = 0.0001$ (right), stars are more compact, and all models allow case B mass transfer at all masses.

3. IMPLICATIONS FOR POST-MASS-TRANSFER BINARIES

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 mass transfer is sensitive to the evolutionary phase (e.g., Claeys et al. 2014). Therefore, whether a binary experiences dynamically unstable interactions depends on stellar radii and their reaction to mass changes, both in turn influenced by stellar physics assumptions.

Given the critical role of mass transfer, the fraction of systems experiencing case A in respect to case B significantly impacts predicted rates for post mass transfer binaries. In particular, the role of the stable mass transfer channel (e.g., Marchant et al. 2021; van Son et al. 2022) for (massive) binary black hole mergers is an active topic of discussion. Our results highlight that stellar uncertainties influence the mode of mass transfer and consequently the outcomes.

Software: This work made use of the following software packages: `matplotlib` (Hunter 2007) and `python` (Van Rossum & Drake 2009), http://github.com/TeamCOMPAS/COMPAS, and https://docs.mesastar.org MESA. Software citation information aggregated using `The Software Citation Station` (Wagg & Broekgaarden 2024; Wagg et al. 2024).

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