On the prevalence of early mass transfer for very massive binaries

C. A. Burt,[1] M. Renzo,[1] and A. Grichener[1]

[1] *University of Arizona, Department of Astronomy & Steward Observatory, 933 N. Cherry Ave., Tucson, AZ 85721, USA*

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 undergo a mass transfer phase in which one donor star transfers mass to an accretor. For very massive stars ($\gtrsim 30\,M_\odot$), mass transfer most often occurs as case A or case B Kippenhahn & Weigert (1967).

Case B is expected more often than case A mass transfer, since stars in most mass ranges expand most prominently post-main sequence in the Hertzsprung gap (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; ?; ?), 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 60 MESA mode ls (version 24.03.1) from $30\,M_\odot$ to $100\,M_\odot$ at metallicity $Z = 0.001, 0.0001$ fol-

lowing the setup from Renzo et al. (2023) with and without overshooting and compared them to the Pols et al. (1998) models used in SSE/BSE Hurley et al. (2000) taken from COMPAS Stevenson et al. (2017); Vigna-Gómez et al. (2018); Riley et al. (2022). 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 a model that does not consider boundary mixing.

Individual models are shown in gray, and the red and blue lines in each panel of Fig. 1 denote the maximum radius during the main sequence and helium core burning phase respectively. The right axis shows orbital separations where the stellar radius meets the roche radius (Eggleton 1983) considering a typical 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. In the 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 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 (right), stars are more compact, and all models allow for case B mass transfer at all masses.

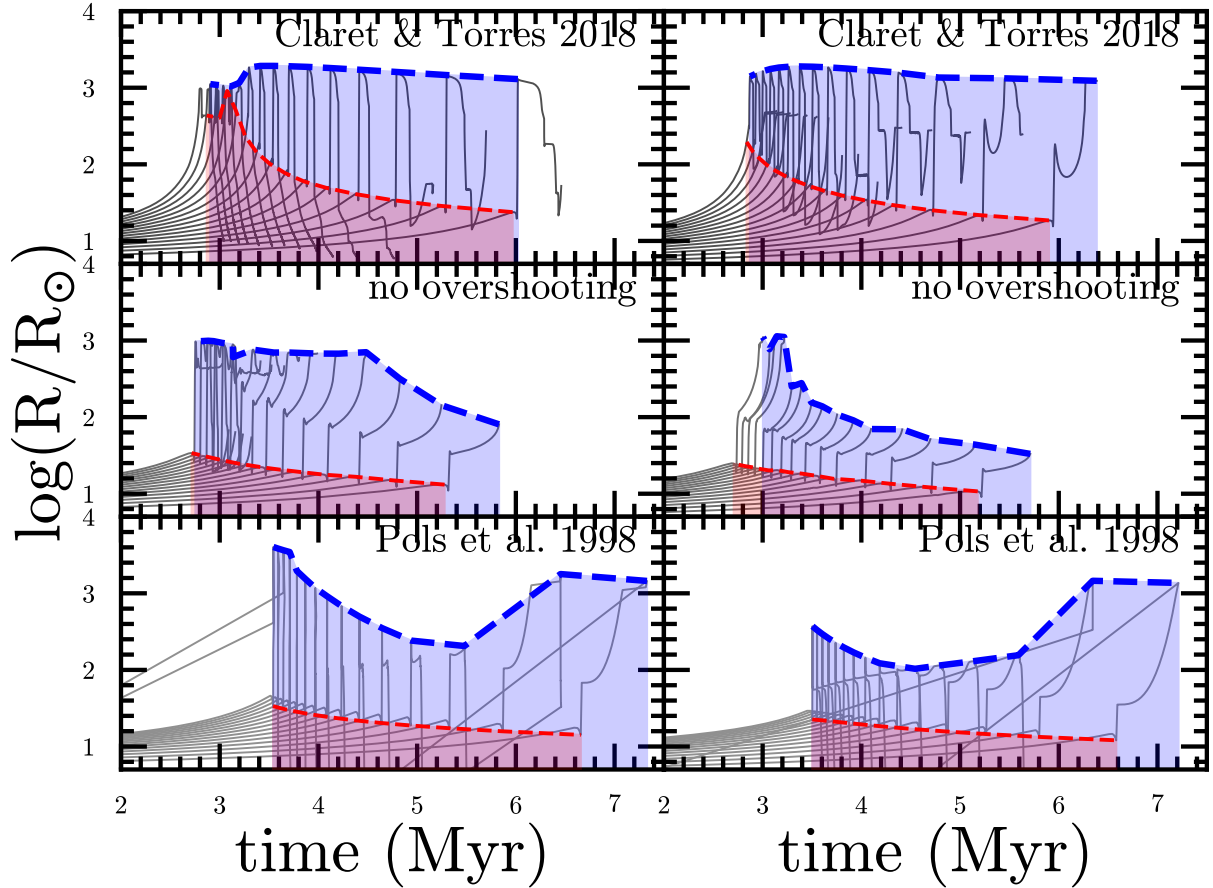## 3. IMPLICATIONS FOR POST-MASS-TRANSFER BINARIES

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 $Z = 0.0001$

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. Case A mass transfer occurs overall on a longer (nuclear) timescale, while case B occurs 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 $100\,M_\odot$. Given the critial role of the mass transfer phase in many astrophysical phenomena, 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.

REFERENCES

Anders, E. H., & Pedersen, M. G. 2023, Galaxies, 11, 56,

  doi: 10.3390/galaxies11020056

Brott, I., de Mink, S. E., Cantiello, M., et al. 2011, A&A,

  530, A115, doi: 10.1051/0004-6361/201016113

Claeys, J. S. W., Pols, O. R., Izzard, R. G., Vink, J., & Verbunt, F. W. M. 2014, A&A, 563, A83, doi: 10.1051/0004-6361/201322714

Claret, A., & Torres, G. 2018, ApJ, 859, 100, doi: 10.3847/1538-4357/aabd35

de Mink, S. E., Pols, O. R., & Yoon, S. C. 2008, in American Institute of Physics Conference Series, Vol. 990, First Stars III, ed. B. W. O'Shea & A. Heger (AIP), 230–232, doi: 10.1063/1.2905549

Eggleton, P. P. 1983, ApJ, 268, 368, doi: 10.1086/160960

Herwig, F. 2000, A&A, 360, 952, doi: 10.48550/arXiv.astro-ph/0007139

Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543, doi: 10.1046/j.1365-8711.2000.03426.x

Jiang, Y.-F., Cantiello, M., Bildsten, L., Quataert, E., & Blaes, O. 2015, ApJ, 813, 74, doi: 10.1088/0004-637X/813/1/74

Johnston, C., Michielsen, M., Anders, E. H., et al. 2024, ApJ, 964, 170, doi: 10.3847/1538-4357/ad2343

Josiek, J., Ekström, S., & Sander, A. A. C. 2024, A&A, 688, A71, doi: 10.1051/0004-6361/202449281

Joss, P. C., Salpeter, E. E., & Ostriker, J. P. 1973, ApJ, 181, 429, doi: 10.1086/152060

Kippenhahn, R., & Weigert, A. 1967, ZA, 65, 251

Klencki, J., Istrate, A., Nelemans, G., & Pols, O. 2022, A&A, 662, A56, doi: 10.1051/0004-6361/202142701

Marchant, P., Pappas, K. M. W., Gallegos-Garcia, M., et al. 2021, A&A, 650, A107, doi: 10.1051/0004-6361/202039992

Nuijten, M., & Nelemans, G. 2024, arXiv e-prints, arXiv:2412.00938, doi: 10.48550/arXiv.2412.00938

Paxton, B., Cantiello, M., Arras, P., et al. 2013, ApJS, 208, 4, doi: 10.1088/0067-0049/208/1/4

Pols, O. R., Schröder, K.-P., Hurley, J. R., Tout, C. A., & Eggleton, P. P. 1998, MNRAS, 298, 525, doi: 10.1046/j.1365-8711.1998.01658.x

Renzo, M., Ott, C. D., Shore, S. N., & de Mink, S. E. 2017, A&A, 603, A118, doi: 10.1051/0004-6361/201730698

Renzo, M., Zapartas, E., Justham, S., et al. 2023, ApJL, 942, L32, doi: 10.3847/2041-8213/aca4d3

Riley, J., Agrawal, P., Barrett, J. W., et al. 2022, ApJS, 258, 34, doi: 10.3847/1538-4365/ac416c

Sabhahit, G. N., & Vink, J. S. 2024, arXiv e-prints, arXiv:2410.22403, doi: 10.48550/arXiv.2410.22403

Sanyal, D., Grassitelli, L., Langer, N., & Bestenlehner, J. M. 2015, A&A, 580, A20, doi: 10.1051/0004-6361/201525945

Stevenson, S., Vigna-Gómez, A., Mandel, I., et al. 2017, Nature Communications, 8, 14906, doi: 10.1038/ncomms14906

van den Heuvel, E. P. J. 1969, AJ, 74, 1095, doi: 10.1086/110909

van Son, L. A. C., de Mink, S. E., Renzo, M., et al. 2022, ApJ, 940, 184, doi: 10.3847/1538-4357/ac9b0a

Vigna-Gómez, A., Neijssel, C. J., Stevenson, S., et al. 2018, MNRAS, 481, 4009, doi: 10.1093/mnras/sty2463

Xin, C., Renzo, M., & Metzger, B. D. 2022, MNRAS, 516, 5816, doi: 10.1093/mnras/stac2551