Coping with loss: stability of RLOF revisited (in prep.)

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Introduction

Mass transfer is a crucial process in the evolution of many binary systems. Whether the onset of Roche-lobe overflow in a particular binary leads to stable or unstable mass transfer produces a qualitative difference in the future evolution. Different assumptions regarding mass-transfer stability therefore strongly affect predictions for, e.g., white-dwarf binaries and their associated transients. Despite its importance, only few systematic studies of the stability of mass transfer have been performed.

We present a systematic study of mass-transfer stability for Roche-lobe overflow from intermediate-mass donor stars, i.e., important for the population of white-dwarf binaries.

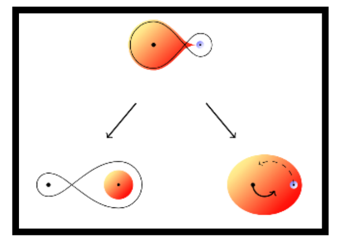

Figure 1: Schematic representation of mass transfer. Mass transfer can be either stable (bottom left), resulting in a typically wide binary, or unstable (bottom right), resulting in a common envelope that engulfs both components.

Numerical method

- We use MESA [1] r12115 to simulate the evolution of non-rotating single stars with masses of $1 - 7M_{\odot}$
  - We set Z=0.02 and mainly follow the solar-calibrated assumptions of [2]
- We save single star models at pre-determined radii
  - such that $\Delta logR_d \leq 0.2$ along all tracks (see Figure 1 on the bottom)
  - Used as starting points in our MESA binary simulations.
- We then initialize the binary simulations at these points:
  - Per point: 12 binary systems with mass ratios ($q = M_a/M_d$) ranging from 0.1 to 1.2
  - We approximate the accretor with a point mass and do not evolve it.
  - Mass transfer is assumed to be fully conservative in both mass and angular momentum.
- We then find the critical mass ratios above which mass transfer is stable

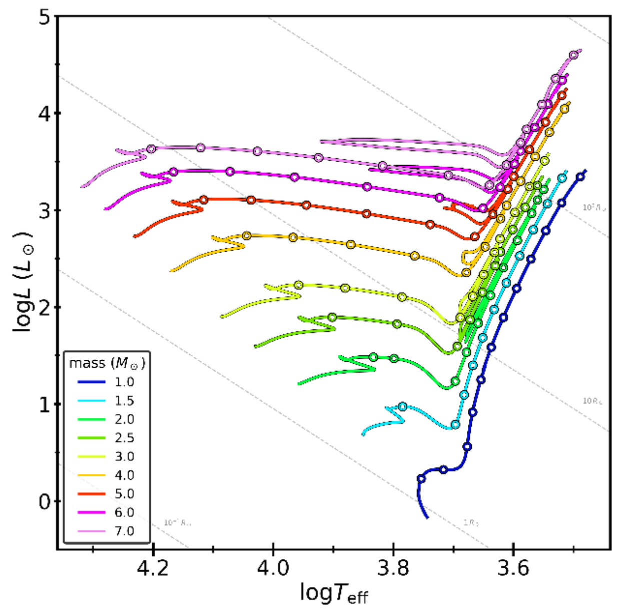

Figure 2: Our single star models (colour indicates initial mass; see legend). Open circles indicate where we initialize mass transfer.

References

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[2] Choi, J., Dotter, A., Conroy, C., et al. 2016, The Astrophysical Journal, 823, 102

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Criteria for unstable mass transfer

Defining robust criteria for the onset of unstable mass transfer in 1D simulations is challenging. It is insufficient to assume that numerical breakdown of a 1D stellar-evolution code during mass transfer indicates physical instability. Multiple physically-motivated criteria have been proposed to identify unstable mass transfer. Indeed, there are multiple physical reasons why mass transfer might become unstable (see, e.g. [3]). In this section we describe different criteria that aim to identify unstable mass transfer. We apply these different criteria to our simulations and compare the resulting critical mass ratios. Our main results are based on the local thermal structure criterion.

Dynamical evolution

- Dynamical-timescale mass transfer is commonly assumed to be unstable
  - If $R_d - R_L$ persistently increases, the mass transfer rate 'runs away'
  - A common envelope forms that engulfs both components
- We consider evolution dynamical if:
  - $\max\left(\left|\dot{M}_d/M_d\right|, \left|\dot{a}/a\right|\right) \cdot P > 0.05$
- The critical mass ratio is the lowest value of $\left(M_a/M_d\right)$ for which the above condition is not met
- Results are sensitive to chosen threshold of 0.05
  - This is most important for evolved giants
- During highly dynamical evolution, Roche geometry assumptions break down
  - Interpret results with care in this regime

Outer lobe overflow

- Alternatively, one could consider the overflowing of the outer Lagrange point (see white crosses in Figure 3 below) by the donor star as the onset of a dynamical instability
- Significant AM loss is thought to dramatically shrink a binary's orbit and render the system dynamically unstable.

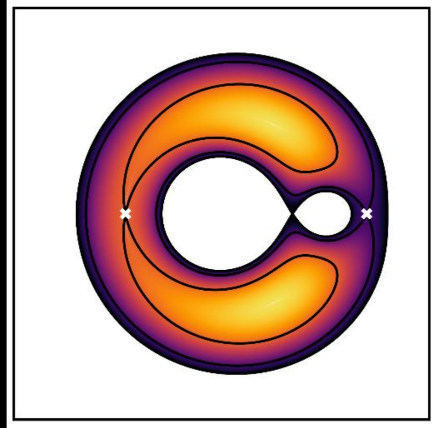

Figure 3: Illustration of the Roche potential (colours). Highlighted are the levels of the L1, L2 and L3 potentials.

- The critical mass ratio is the lowest value of $\left(M_a/M_d\right)$ for which the donor star does not experience OLOF during the entire first phase of mass transfer.
- During extreme OLOF, spherical symmetry assumptions could break down
  - Interpret results with care in this regime

Local thermal structure

- Local thermal structure allows donor star to locally readjust on very short timescales
- Estimate limiting mass-loss rate (see Figure 4 below):

$$\dot{M}_{d,th} = M_d/\tau_{th} \ ; \ \tau_{th} = \max\left(\frac{1}{L}\int_{m}^{M_d} c_P(m')T(m')dm'\right)$$

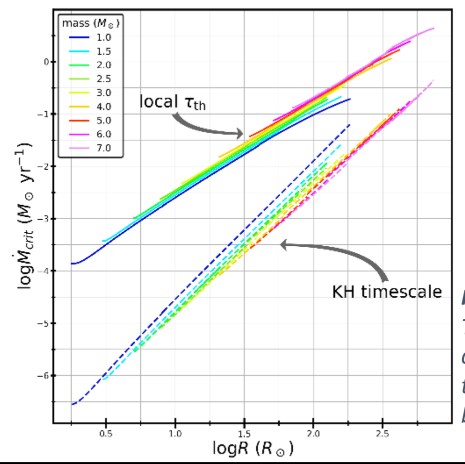

Figure 4: Thermally-limited mass-loss rates. The colours correspond to different initial donor masses. Solid lines are based on local thermal properties, whilst dashed lines are based on global properties only.

- The critical mass ratio is the lowest value of $\left(M_a/M_d\right)$ for which the donor star is unable to thermally re-adjust on timescales shorter than the mass-loss timescale, i.e. $\dot{M}_d \leq \dot{M}_{d,th}$
- This is our main stability criterion

Critical mass ratios for stable mass transfer

- For most of our parameter space, the critical mass ratio is smaller than 1 (see Figure 5)
  - The maximum main critical mass ratio we find is 1.05
- There is a clear distinction between giant stars and HG stars
  - The radiative HG stars have typical critical mass ratios around $M_a/M_d \sim 0.25$
  - A significant part of the outer layers of giant stars is convective.
    - Mass is lost at higher rates. This results in significantly larger values for the critical mass ratios.
    - As giants evolve, their local thermal timescales decrease and mass transfer becomes more stable
  - For giant stars, there is no visible discontinuity values between donor stars evolving along the RGB and AGB
- Different criteria lead to vastly different critical mass ratios
  - Thermal criterion typically results in the lowest critical mass ratios
    - Thermal trend is opposite to dynamical and OLOF ones
  - Dynamical and OLOF mass transfer need not be runaway!

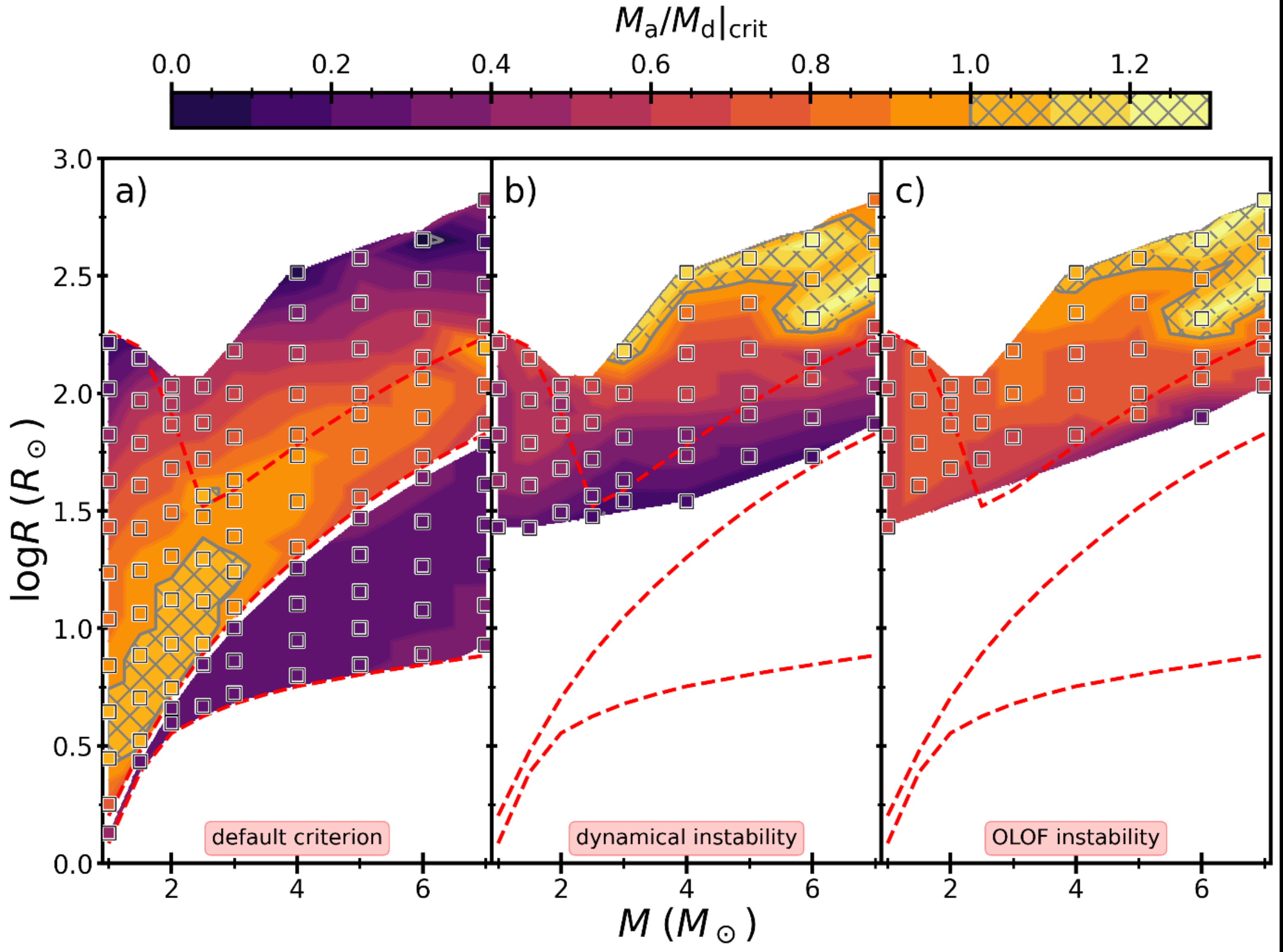

Figure 5: Critical mass ratios for stable mass transfer. The three panels show the lowest mass ratio above which mass transfer is stable according to different criteria (as indicated in the panels). The colours indicate the value of the critical mass ratios, as shown in the legend. The contours were obtained through linear interpolation of our results (coloured squares). The red dashed lines indicate minimum radii of stars during the HG,RGB and AGB phase (bottom to top).