3D MHD Simulations of Mass Loss Immediately Before Common-Envelope Onset

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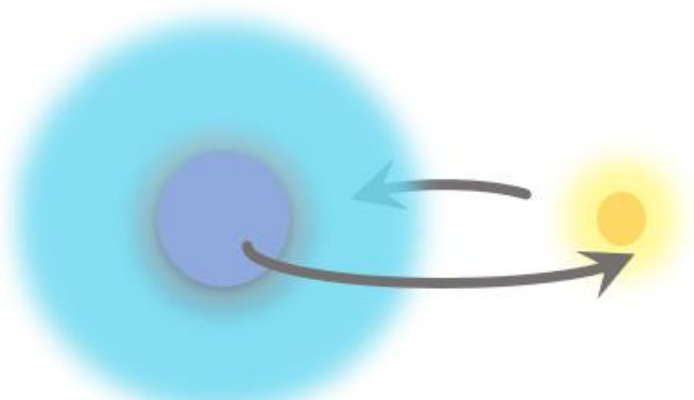
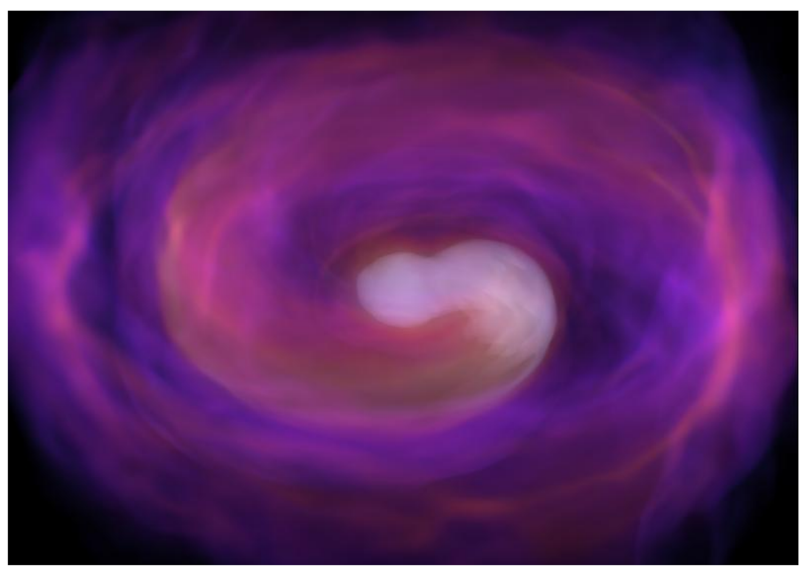
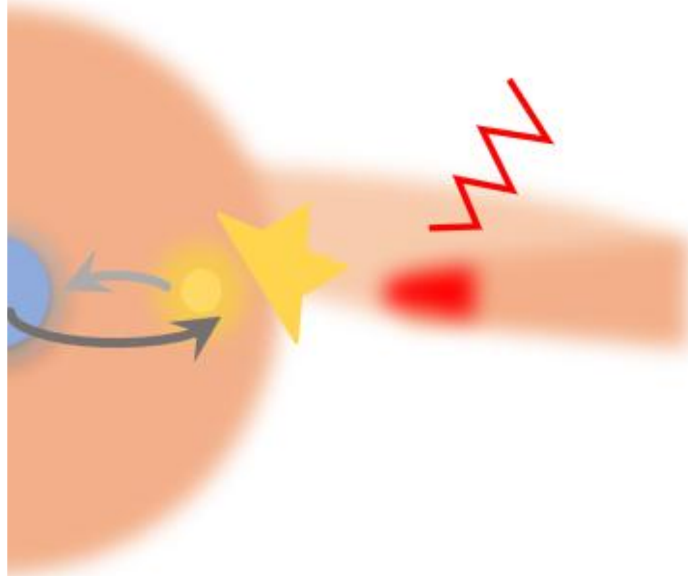
Introduction

Red giants and red supergiants, can undergo strong binary interactions when they fill their Roche lobes, potentially leading to the onset of a **common-envelope (CE)** phase or a stellar merger. **Luminous red novae (LRNe)** are widely interpreted as observational counterparts of such events [1, 2]. Their light curves can be powered by **shocks between fast ejecta and pre-existing circumbinary material** [3]. In current models, this material is set by assumed prescriptions for **pre-dynamical mass loss** [4], still largely unconstrained by multidimensional simulations. With the upcoming Rubin Observatory LSST sample [5], physically grounded models for pre-CE mass loss are essential. Here, we perform three-dimensional MHD simulations of binaries immediately before CE to **test pre-CE mass-transfer prescriptions** and characterize the resulting circumbinary environment.





Angular momentum transport from the stellar cores to the envelope → Orbital shrinkage



The ejecta produced at binary contact **interact with the pre-existing gas** producing the observed emission.

Methods

Basic equation: MHD with gravity

$$\frac{\partial(\rho \boldsymbol{v})}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}\otimes\boldsymbol{v} - \boldsymbol{B}\otimes\boldsymbol{B} + p_{\mathrm{tot}}\, I) = \rho \boldsymbol{a}_{\mathrm{ext}}$$

External forces including inertial terms

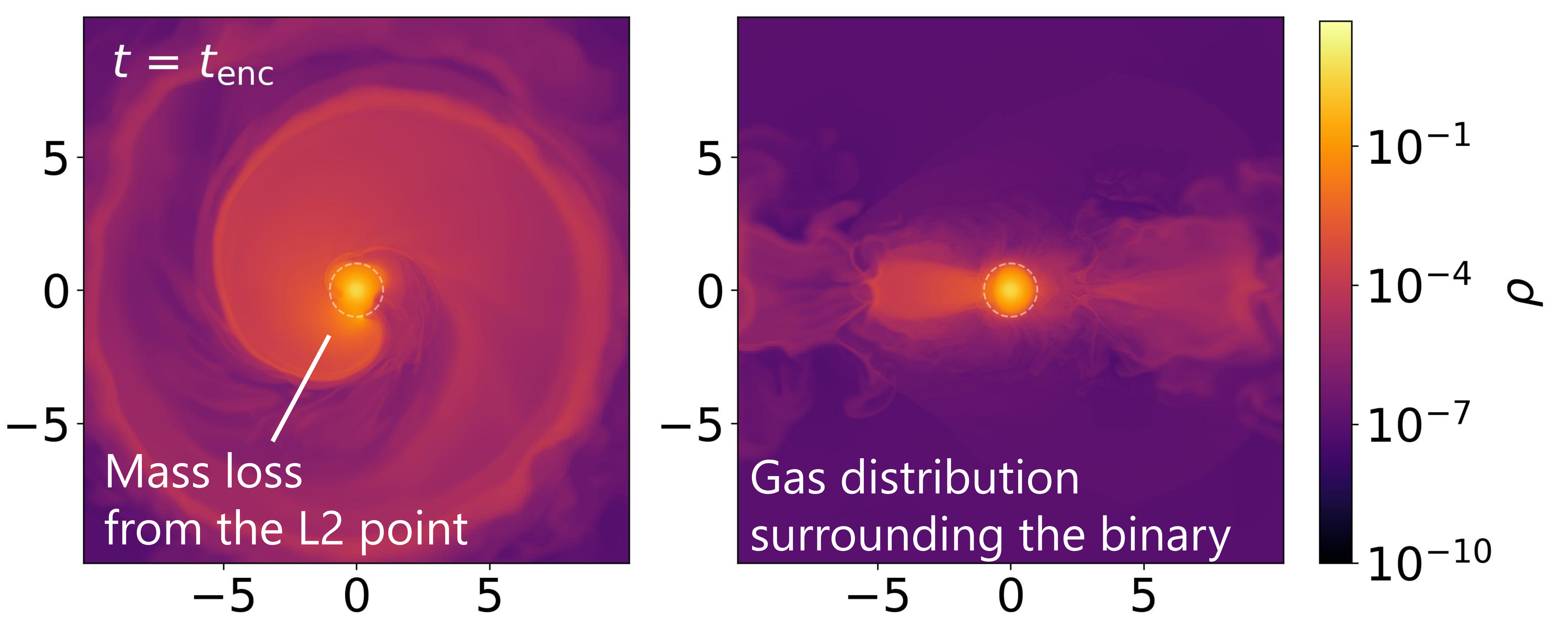
$$\boldsymbol{a}_{\mathrm{ext}} = \boldsymbol{g}_1 + \boldsymbol{g}_2 - \boldsymbol{a}_{1,\mathrm{inertial}} \quad [5]$$

Orbital evolution of the companion

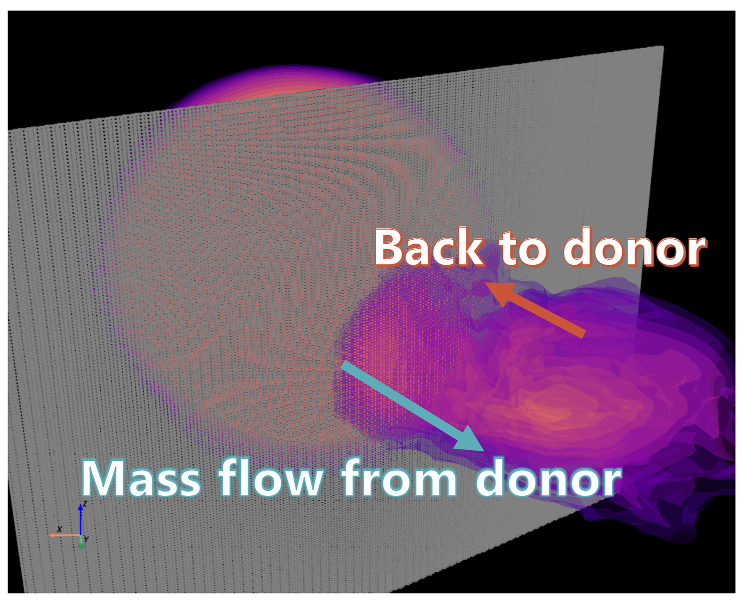
$$\boldsymbol{a}_2 = \boldsymbol{g}_1 + \int_V \frac{G\rho dV}{|\boldsymbol{r}-\boldsymbol{r}_2|^3}(\boldsymbol{r}-\boldsymbol{r}_2) - \boldsymbol{a}_{1,\mathrm{inertial}}$$

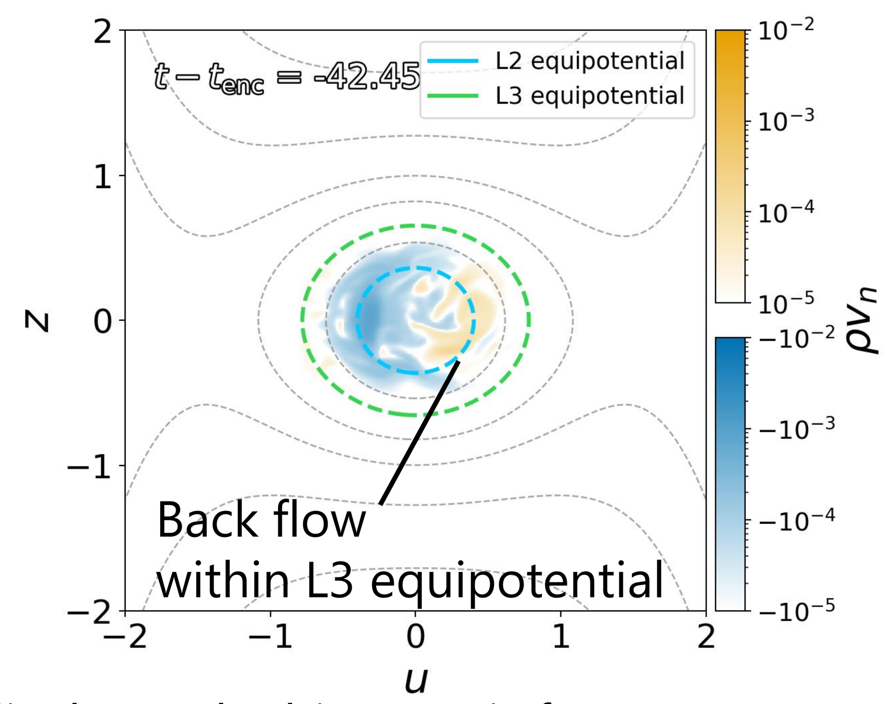
Code: Athena++ (Stone et al. 2020)
Numerical flux: HLLD Riemann solver (Kusano & Miyoshi 2005)
Second-order accuracy in space and time
Resolution: $\Delta x = 0.01\, R_1$ (near the primary and along the orbit)
Coordinate system: Cartesian, centered on the primary
Mass ratios: q = 0.25, 0.5, 0.75
Initial magnetic field: dipole magnetic field with $\beta_{\mathrm{surf}} = 10^{3 \text{ or } 20}$
Evolution tracked to: separation = initial primary radius

Results

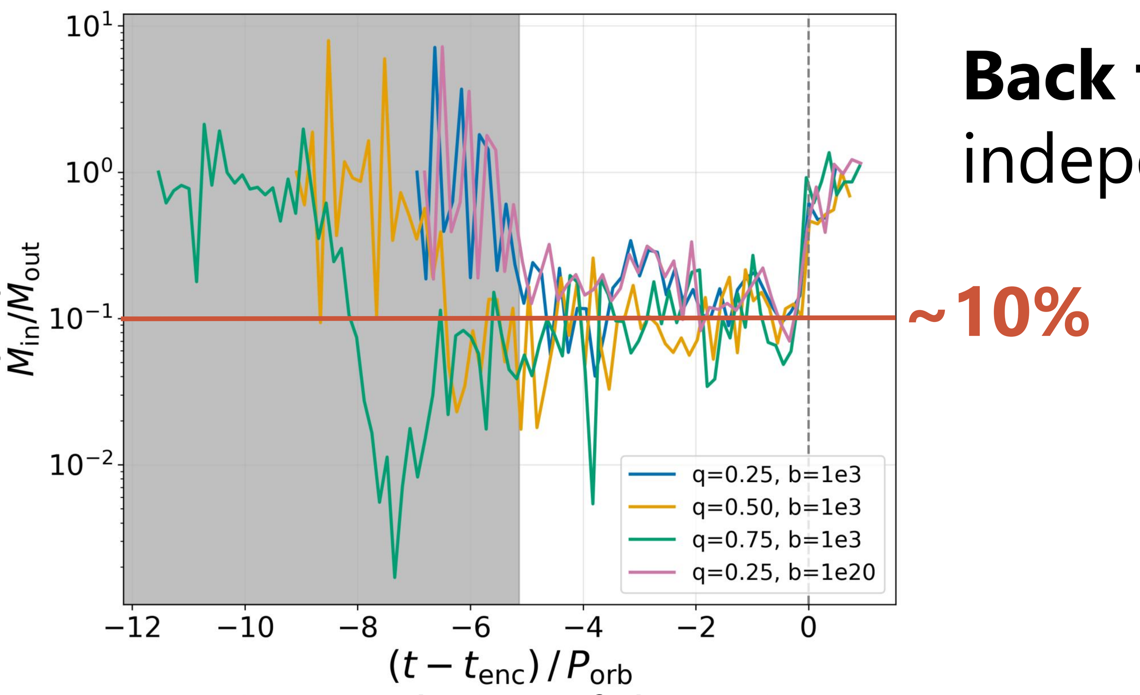


Density distribution at the time of companion engulfment: orbital plane (left) and perpendicular plane (right) for q = 0.25





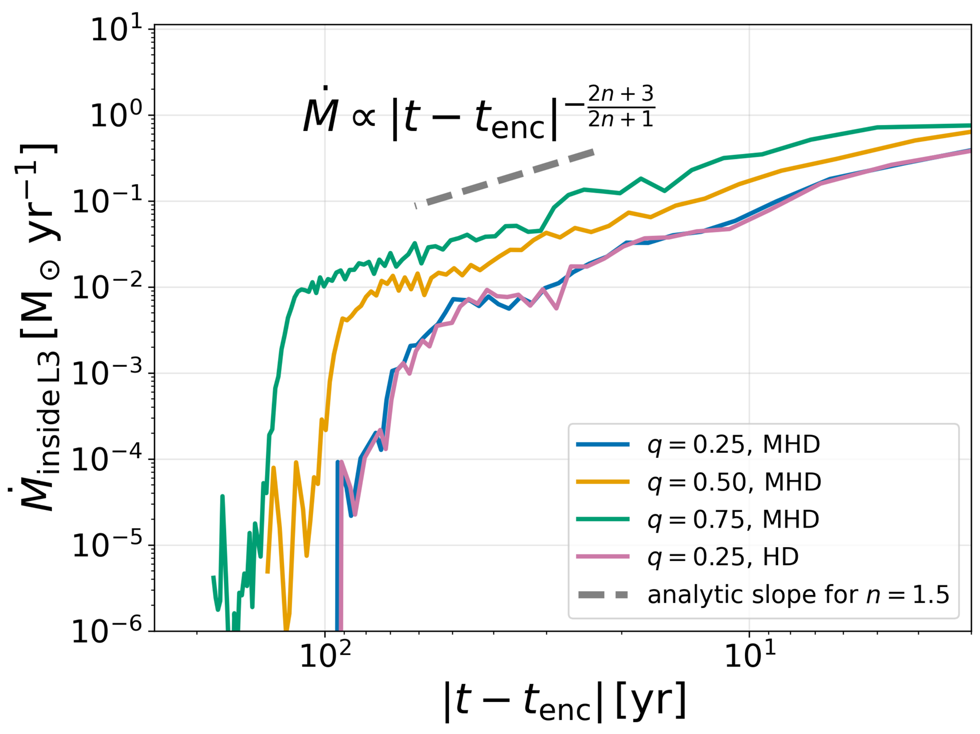
Mass flux on a plane perpendicular to the binary axis for q=0.25



Time evolution of the ratios of mass transfer rates

Back flow reaches ~10% near $t = t_{\mathrm{enc}}$, independent of mass ratio and magnetic fields.

Despite the presence of back flow, **the mass-loss rate is consistent with analytic models** [4] across mass ratios and with or without magnetic fields.



Time evolution of the mass-loss rate

Summary

- We performed 3D MHD simulations of binaries immediately before CE onset to characterize pre-dynamical mass loss.
- The measured **mass flux through L1 region** shows a time evolution **in agreement with analytic models**.
- Although about 10% of the gas returns toward the donor as back flow, this multidimensional circulation **does not prevent the L1 mass flux from following the analytic scaling**.
- These results provide a physically grounded basis for pre-CE mass-transfer prescriptions used in LRN shock-interaction models, which will be increasingly important for interpreting future LSST discoveries.

References

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[2] V. R. Karambelkar, M. M. Kasliwal, N. Blagorodnova, et al., 2023, ApJ 948, 137
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