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# Ionization and Recombination During Common Envelope Evolution and their Role in Envelope Unbinding

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**ABSTRACT**
Energy released by the recombination of ions and electrons is often claimed to play an important role in common envelope evolution (CEE). Here, we study its role by comparing three otherwise identical hydrodynamical simulations involving a $2\,M_\odot$ red giant branch primary and $1\,M_\odot$ secondary modeled as a point masss: a run employing a realistic tabular equation of state (EOS) where energy released during recombination is locally thermalized, a run with a $\gamma = 5/3$ ideal gas EOS, and a run with the tabular EOS altered to remove the recombination energy. We find that ....

**Key words:** binaries: close – stars: AGB and post-AGB – stars: kinematics and dynamics – stars: mass loss – stars: winds, outflows – hydrodynamics

## 1 INTRODUCTION

In the common envelope (CE) scenario, typically a giant star engulfs a much smaller companion and the companion and core of the giant spiral in together until either the envelope is ejected or the core and companion merge (Paczynski 1976). The CE phase is shortlived and hence hard to observe. However, understanding CE evolution (CEE) is crucial for understanding phenomena as wide-ranging as neutron star-neutron star mergers, supernovae type Ia and planetary nebulae (for a recent review see Ivanova et al. 2020). While theoretical work on CEE has come a long way, simulating CEE up to a realistic end state (e.g. complete envelope ejection and stabilization of the orbit) has still not fully been achieved. The overarching reason for this is that simulating such a large dynamic range of spatial and temporal scales remains very challenging.

Nevertheless, such calculations have been useful in constraining the effects of various physical processes during CEE. One such process is the recombination of ions and electrons as the envelope expands and cools, which releases recombination energy. As has become somewhat standard in the CE literature, we define recombination energy as the *latent* energy contained by a plasma that would be released upon recombination. After this energy is released, it may help to unbind the envelope, but it does not have any effect before the ions and electrons recombine.

While the recombination energy content of the intial envelope is generally substantial and thus could potentially play an important role in envelope unbinding, its efficacy remains somewhat unclear. This is partly because some released recombination energy radiates away (Soker & Harpaz 2003; Ivanova et al. 2013; Sabach et al. 2017; Ivanova 2018; Grichener et al. 2018; Soker et al. 2018; Reichardt et al. 2020; Lau et al. 2022). The question of how much is radiated is not addressed in the present work. Rather, we ask: what difference does recombination energy make to CEE, assuming (optimistically) that released recombination energy is thermalized locally? In particular, at any given time, how much extra envelope mass is unbound owing to this effect, where in the envelope does this extra unbinding happen, and what are the relative contributions of the various ionic species? Even in this optimistic case that ignores radiation, some recombination energy would be released in already unbound gas, and would thus play little to no role in envelope unbinding. Clearly, there is an efficiency associated with the transfer of released recombination energy to binding energy of the remaining envelope.

Sometimes authors count gas as unbound if its total energy density, including that of the recombination energy, is positive. This is misleading because it greatly overestimates the role of recombination energy in envelope unbinding. First, this energy is still latent. Second, when it eventually gets released it might not contribute much to unbinding owing to the inefficiencies mentioned above. A more reasonable approach is to include only kinetic(including perhaps thermal) and potential energies in assessing whether material is unbound, and compare the unbound mass in a simulation with a realistic tabular EOS that includes recombination energy with a simulation that does not. If cooling is neglected, it is appropriate to use a $\gamma = 5/3$ ideal gas EOS for the latter simulation. When such a comparison has been made (Ohlmann 2016; Reichardt et al. 2020; Sand et al. 2020; Lau et al. 2022), it has been found that the unbound envelope mass is significantly higher in the tabular EOS run. Moreover, the fractional difference in the unbound mass curves between the runs usually increases with time, indicating that the effect becomes more important at late times.[1]

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[1] For a more extensive review of the literature on the effects of ionization/recombination on CEE, we refer the reader to Reichardt et al. (2020).

While it is perhaps generally agreed that recombination energy often helps envelope unbinding, the details are still emerging. Reichardt et al. (2020) was the first to include a spatial analysis of where recombination of the various species is happening during a CE simulation. They then compared this data with data of where unbinding is happening in both $\gamma = 5/3$ and tabular EOS runs, allowing them to infer how recombination affects unbinding. In this work we take a somewhat different and complementary approach by employing tracers to track gas of a given ionization species at $t = 0$. By comparing maps of these tracers at a given time $t$ with maps of the ionization state, it becomes possible to determine which gas has experienced net recombination or ionization, and how much energy this recombination (ionization) has released (absorbed).

The structure of the paper is as follows. In Section 2, we explain the methods used in the setup, running and analysis of the simulations. Then, in Section 3, we describe our physical model, including the initial conditions and the parameters of the runs performed. Results are then presented in Section 4. In Section 4.1 we present the evolution of the unbound mass with time, in Section 4.2 we analyze the transfer of energy between the various components, and in Section 4.3 we explore in detail the ionic evolution and the release of recombination energy. We discuss our results in Section 5 and conclude in Section 6. An assessment of the role of various numerical parameters is presented in Appendix A.

## 2 METHODS

Our study involves a binary system consisting of a red giant branch (RGB) primary star and a point particle (gravitation only) secondary representing a main sequence star or white dwarf. The initial density and pressure profiles of the primary are mapped to our 3D grid from a 1D Modules for Experiments in Stellar Astrophysics (MESA) snapshot (Paxton et al. 2011, 2013, 2015, 2019). The snapshot is taken from a MESA release 12778 simulation. It matches almost exactly the snapshot used for our previous RGB simulations using release 8845 (Chamandy et al. 2018, 2019b), except that this time we increased the spatial resolution by a factor of about 20 to make the profile smoother.

The pressure scale height near the core and at the stellar surface of the MESA profile are too small for a 3D simulation to resolve. Therefore, we cut out the RGB core and replaced it with a spline-softened gravitating point particle, with softening length $r_{\rm soft} = 2.41\,{\rm R}_\odot$, equal to the cut radius, along with a core density and pressure profile obtained by solving a modified Lane-Emden equation, which also incorporated an iteration to ensure that the mass below the cut radius is preserved (Ohlmann et al. 2017; Chamandy et al. 2018). The softening radius of the secondary is the same as that of the RGB core particle.

The ambient medium has uniform density $\rho_{\rm amb} = 1.0 \times 10^9\,{\rm g\,cm^{-3}}$ and uniform pressure $P_{\rm amb} = 1.0 \times 10^5\,{\rm dyn\,cm^{-2}}$. The value of $P_{\rm amb}$ is chosen such that by adding $P_{\rm amb}$ to the pressure everywhere, the RGB pressure profile effectively gets truncated just inside the outer radius of the star to avoid the small pressure scale height there. The value of $\rho_{\rm amb}$ is about 7 times smaller than the density at the outer radius of the star $R_1$; smaller values are possible but would result in a higher ambient temperature and prohibitively small timesteps. We find that we require at least eight resolution elements per scale height to adequately resolve the initial stellar profile. This number was determined by studying the smoothness and stability of both the core and surface, where the scale heights are smallest, during the first $\sim 1$ d of the simulations.[2]

We utilize the adaptive mesh refinement (AMR) code AstroBEAR (Cunningham et al. 2009; Carroll-Nellenback et al. 2013), and employ an HLLC Riemann solver. The simulation box of side length $1150\,{\rm R}_\odot$ is discretized into $512^3$ AMR level 0 cells, corresponding to a base resolution of $\delta_0 \approx 2.25\,{\rm R}_\odot$. Initially, the envelope and some of the ambient medium surrounding the RGB star was resolved at AMR level 4, or $\delta_4 \approx 0.140\,{\rm R}_\odot$, and this refinement zone reduced in size gradually as the particle separation $a$ reduced. However, unlike in our previous RGB simulations, AMR level 5, with $\delta_5 \approx 0.070\,{\rm R}_\odot$, was added around the point particles out to slightly farther than the softening sphere. This extra level of refinement helps to conserve energy and to avoid artificial reduction of the central density and pressure during the simulation. Buffer zones with 16 cells were included to smoothly transition between AMR levels. At $t = 25.2$ d, the softening radius around the particles was halved to $\approx 1.2\,{\rm R}_\odot$ and a sixth level of refinement was added, with $\delta_6 \approx 0.035\,{\rm R}_\odot$. At $t = 50.5$ d the softening radius was again halved to $\approx 0.6\,{\rm R}_\odot$ AMR level 7 was added, with $\delta_7 \approx 0.018\,{\rm R}_\odot$.

In Appendix A3 we track the change in the total energy of the simulation, and show that it does not exceed ??????% for any of the runs [Luke comments: angular momentum conservation], which gives us confidence that our numerical approach is reasonable.

### 2.1 Tracers

Tracers were added to track the core gas ($r_{\rm i} \leqslant r_{\rm soft}$), envelope ($r_{\rm soft} < r_{\rm i} \leqslant R_1$) and ambient ($r_{\rm i} > R_1$). Tracking the ambient material allows us to exclude it in postprocessing. Tracers were also added to track the initial hydrogen and helium ionization states of the gas. This way, by comparing the ionization state computed by the Saha equation with the original ionization state, one can deduce how the ionization state of the gas changes during the simulation. As the tracer density is equal to the total gas density where the tracer is located, tracers are not as useful for tracking ionic species from locations where they are not the dominant species, relative to other species of the same element. For this reason, we chose to place tracers for a given ionization state at locations where that ionization state was higher than others of the same element. Because the density of a given species depends exponentially on temperature, transitions in the dominant species are rather sharp, so this is not an important limitation. Because the mass fractions of all elements are constant within the envelope, as determined from MESA, one can simply multiply by the hydrogen mass fraction (0.69) or helium mass fraction (0.29) to obtain the approximate density of the tracer (e.g. gas that was originally HIII). Also, because the pressure very close to the stellar surface is replaced by the (larger) ambient pressure, the temperature at that location is higher than in the MESA snapshot. This causes gas at the surface to be ionized from $t = 0$, but the tracer is based on the MESA model.

[2] We did not perform a preliminary run to prepare the initial condition for the simulation. We found in the past that including such a relaxation run did not cause an important difference in the results, and our results have shown good quantitative agreement with similar simulations by other authors (Chamandy et al. 2019a). Moreover, we have found that artifacts due to the Cartesian grid can be magnified in such a preliminary run because the star is motionless.

### 2.2 Equation of State

Most of our simulations make use of the MESA tabular EoS, which has been adapted for use in AstroBEAR. However, we modified the MESA EoS by subtacting the radiation component of the specific energy $aT^4/\rho$, where $T$ is temperature, $\rho$ is gas density and $a$ is the radiation constant. In the original MESA RGB profile, the ratio of this component to the local gas thermal specific energy $3k_BT/(2\mu m_H)$, where $k_B$ is the Boltzman constant and $\mu$ is the mean molecular mass units of the hydrogen mass $m_H$, reaches a maximum of 20% at $r \approx 0.6\,R_\odot$, but the ratio of the net energy contributions over the entire star is $< 0.1\%$. If included, the radiation energy leads to a high internal energy density in the high-temperature ambient medium, which could help to artificially unbind the envelope through mixing; hence we chose to exclude it. Moreover, this choice is consistent with the fact that radiation pressure is not included in the MESA EoS, though it is included in the stellar models computed in MESA. On the other hand, when preparing the simulation initial condition, we chose to make the gas pressure equal to the total pressure (gas plus radiation) in the MESA 1D RGB profile.

## 3 MODEL

### 3.1 Initial conditions

[Luke comments: Discuss MESA models and present a few plots] The profile extends to $R_1 = 48.1\,R_\odot$. which is initialized at a separation $a_i = 49\,R_\odot$. Limits to computational resources prevent us from using a larger, more realistic, value of $a_i$. The primary is not made to rotate initially.

[Luke comments: Mention similarity to Ohlmann+16,Prust+Chang19]

In any case, our main goal involves a comparison between runs which use the same initial conditions, we consider these various choices to be reasonable.

### 3.2 Physical parameters of the runs

[Luke comments: Summarize the various runs]

## 4 RESULTS

### 4.1 Envelope unbinding

- Mass unbinding figure 1 (including factors of 2) + separation overplotted
- Mass unbinding figure 2 (excluding factors of 2) + separation overplotted

### 4.2 Energy transfer

- Show plot with various energy terms vs time (comparing run 277 with run 283 or 282)
- Show zoom in of the same plot to highlight the change in the recombination energy

### 4.3 Recombination and Ionization

#### *4.3.1 Spatial dependence*

- Do I want to combine the first 3 rows and keep only the dominant species in each?
- 1. He: Face-on frames 0, 25, 50
- 2. He: Face-on frames 100, 200, 400
- 3. He: Edge-on for a subset of those frames (100, 200, 400?)
- 4. H: Face-on for frames 0, 200, 400?

#### *4.3.2 Volume integrated results*

- Oops, mass evolution graphs do not take into account the mass fractions of H and He! Either multiply of else label plot differently.
- 1. Mass evolution of each tracer (15 panels, full page)
- 2. Mass evolution of each ionic species (6 panels)
- 3. Energy released by each transition (10 panels) – perhaps need to include only Figs 1 or 3
- 4. Total energy released (9 panels)

## 5 DISCUSSION

## 6 CONCLUSIONS

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**Table 1.** List of runs

| Run | Description | Physical scenario |
|---|---|---|
| A | MESA EoS, excluding radiation energy | Immediate local thermalization of released recombination energy |
| B | MESA EoS, excluding radiation and recombination energy | Immediate radiative loss of released recombination energy |
| C | $\gamma = 5/3$ ideal gas EoS | Constant uniform composition (no accounting for ionization and recombination) |

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## APPENDIX A: EFFECTS OF VARYING THE NUMERICAL PARAMETERS

### A1 Resolution

- 1. Figure showing separation, comparing different resolutions (low, standard, high)
- 2. Figure showing unbound mass (for at least one definition of unbound), comparing different resolutions (low, standard, high)

### A2 Ambient density

- 1. Figure showing separation, comparing different ambient densities (runs 277 and 271)
- 2. Figure showing unbound mass, comparing different ambient densities (runs 277 and 271)

### A3 Energy and angular momentum conservation

- 1. Figure showing energy conservation (for all the runs)
- 2. Figure showing angular momentum conservation (for all the runs)