Radiating the Hydrogen Recombination Energy during Common Envelope Evolution

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Abstract

Using the stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA), we show that most of the hydrogen recombination energy that is released as the envelope expands during a regular common envelope evolution—namely, the initial dynamical phase or plunge-in phase—is radiated, and hence substantially increases the stellar luminosity. Only about 10% of the hydrogen recombination energy might be used to remove the envelope. We show that the key property of energy transport is that when convection becomes inefficient in the outer parts of the envelope, where the ionization degree of hydrogen falls below about 30%, photon diffusion becomes very efficient and removes the recombination energy. The expanding envelope absorbs most of the gravitational energy that is released by the spiraling-in process of the secondary star inside the common envelope, and so it is the hydrogen recombination energy that is responsible for most of the luminosity increase of the system. The recombination energy of hydrogen adds only a small fraction of the energy required to remove the common envelope, and hence does not play a significant role in the ejection of the envelope.

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

1. Introduction

Two open questions concerning the energetics of the common envelope evolution (CEE) that has attracted attention in recent years are the question regarding the role of hydrogen and helium recombination energy in facilitating envelope ejection, and the question regarding the role of the gravitational energy from the mass that the companion (secondary) star accretes from the giant envelope. The quest for extra energy sources comes from the results of hydrodynamical numerical simulations, which show that it is not straightforward to remove the common envelope in a short time by using only the orbital energy of the in-spiraling core-companion system (e.g., Ivanova & Nandez 2016; Kuruwita et al. 2016; Nandez & Ivanova 2016; Ohlmann et al. 2016a, 2016b; Staff et al. 2016a, 2016b; De Marco & Izzard 2017; Galaviz et al. 2017; Iaconi et al. 2017, 2018; MacLeod et al. 2018, limiting the list to the last three years).

Other sources might play a role over a longer period and at the termination of the CEE: these include the excitation of p-waves (Soker 1993), the interaction of the core-secondary system with a circumbinary disk (e.g., Kashi & Soker 2011; Kuruwita et al. 2016), envelope inflation followed by vigorous pulsation (Clayton et al. 2017), the stellar luminosity itself that exerts force on dust (e.g., Soker 2004; Glanz & Perets 2018), and jets that are launched by the secondary star (for a full list of processes see Soker 2017).

Jets might also play a role in helping envelope removal at earlier CEE phases (Soker 2016 for a review and, e.g., Moreno Méndez et al. 2017; López-Cámara et al. 2018 and Shiber & Soker 2018 for recent hydrodynamical simulations). A key question for jet activity is whether accretion disks or belts are formed (e.g., MacLeod & Ramirez-Ruiz 2015a, 2015b; Murguia-Berthier et al. 2017), and whether jets can allow a high mass accretion rate (e.g., Shiber et al. 2016; Chamandy et al. 2018). In extreme cases, a neutron star that launches jets inside a giant envelope might lead to a violent event called a common envelope jets supernova (CEJSN; Soker & Gilkis 2018), or a CEJSN impostor (Gilkis et al. 2018).

A stronger debate centers around the role of recombination energy, and whether it is important for envelope removal (e.g., Ivanova & Nandez 2016; Kruckow et al. 2016; Nandez & Ivanova 2016; Ivanova 2018 and references therein) or not (e.g., Sabach et al. 2017; Grichener et al. 2018, and references therein). The observations of Balmer emission lines, as well as an effective temperature of $\approx 6000$ K at early times from some intermediate luminosity optical transients (ILOTs; e.g., Munari et al. 2002; Smith et al. 2016), show that some recombination energy does leak out from expanding envelopes. The escape of recombination energy is more pronounced in Type IIP supernovae that show a plateau in their light curve (e.g., Galbany et al. 2016). It is the leakage of recombination energy that maintains a more or less constant luminosity during the plateau phase (e.g., Dessart & Hillier 2011; Faran et al. 2018). As for ILOTs, MacLeod et al. (2017) discussed a model for the transient event M31LRN 2015, where the outburst is a dynamically driven ejecta at the onset of a CEE phase with a progenitor of mass $3-5.5M_\odot$. In their model of this CEE event the recombination energy of the ejected gas is only $\lesssim 2\%$ of its kinetic energy. Indeed, recombination energy becomes less efficient as the star becomes more massive. Pejcha et al. (2016) suggested that mass loss through the outer Lagrange point before the secondary star enters the giant envelope can also power the radiation of ILOTs, as well as remove mass before the onset of the CEE.

In a recent paper Ivanova (2018) claimed that hydrogen recombination indeed plays an important role in common envelope ejection and criticized the opposing claim that we made in an earlier paper (Grichener et al. 2018). Ivanova (2018) further argued that the process that we study in Grichener et al. (2018) applies to the self-regulated CEE phase, though this assertion is not true as we studied the plunge-in (dynamical) phase when the envelope rapidly expands. In that respect, our work differs from the calculations of the
convective energy transport during the long self-regulated CEE phase (e.g., Meyer & Meyer-Hofmeister 1979; Podsiadlowski 2001; Ivanova et al. 2015). Ivanova (2018) further argued that convection and radiation cannot transport much of the recombination energy out. In the present study we raise arguments to the contrary.

2. Envelope Inflation

We describe here the relevant properties of the evolution from our earlier paper (Grichener et al. 2018, where all details can be found), and present new data from that simulation.

We run the stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA), version 9575 (Paxton et al. 2011, 2013, 2015, 2018) to follow the evolution of a star with an initial mass (on the zero age main sequence) of $M_{\text{ZAMS}} = 2 M_\odot$ and with a metallicity of $Z = 0.02$. When the star becomes an asymptotic giant branch (AGB) star with a mass of $M_{\text{AGB}} = 1.75 M_\odot$ and a radius of $R(t = 0) = 250 R_\odot$, we inject energy into the envelope to mimic a companion star of mass $M_\text{inj} = 0.3 M_\odot$ that spirals-in from the surface to an orbital separation of $a = 50 R_\odot$ in 1.7 years. We deposit the energy in the envelope zone that satisfies $50 R_\odot < r < 120 R_\odot$ with a constant energy per unit mass, and with a total power of $q = 4.5 \times 10^{37}$ erg s$^{-1}$ (see our earlier paper for details of the entire scheme). We run MESA in its hydrostatic module. Because the envelope inflation time of 1.7 years is longer than the dynamical time of the star of 0.3 year, even at its larger size, this treatment is justified.

In Figure 1 we present the evolution of the stellar luminosity $L$ (upper panel), the stellar radius $R$, and the radius at which hydrogen is ionized to a degree of $\chi = 50\%$, $R_{\text{ion,50}}$, and the mass coordinate, $m_{\text{ion,50}}$, of the zones where hydrogen is ionized to a degree of $\chi = 90\%$, $R_{\text{ion,90}}$, and $m_{\text{ion,90}}$, respectively.

Figure 1. Evolution of some stellar parameters of the AGB model during the energy injection period. Upper panel: the stellar luminosity. Middle panel: the radius of the photosphere (blue) and the radius $R_{\text{inj,50}}$ where hydrogen is $\chi = 50\%$ ionized (red). Lower panel: mass coordinates of the zones where hydrogen is ionized to a degree of $\chi = 10\%$ (purple), $\chi = 50\%$ (green), and $\chi = 90\%$ (orange).

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1.7 years to remove the envelope, rather than be radiated away, is given where the expansion time of the envelope. In our case it is about time to carry energy out by convection only. Let which operate simultaneously. Namely, the time to transport energy out, both by convection and radiation energy does not contribute at all to envelope removal, but rather that only a small fraction of the recombination energy is channeled to gravitational and kinetic energy. The reason is that, in this case, the extra pressure that comes from heating by radiation does work on the gas before the energy is transported out. The relation between the energy that is channeled to envelope removal, i.e., to gravitational and kinetic energy, and the energy that is carried out by photon transport depends on the expansion time of the envelope and on the energy transport time. We now present this approximate relation.

We emphasize that we do not claim that recombination energy does not contribute at all to envelope removal, but rather that only a small fraction of the recombination energy is channeled to gravitational and kinetic energy. The reason is that, in this case, the extra pressure that comes from heating by radiation does work on the gas before the energy is transported out. The relation between the energy that is channeled to envelope removal, i.e., to gravitational and kinetic energy, and the energy that is carried out by photon transport depends on the expansion time of the envelope and on the energy transport time. We now present this approximate relation.

We emphasize that we do not claim that recombination energy does not contribute at all to envelope removal, but rather that only a small fraction of the recombination energy is channeled to gravitational and kinetic energy. Let $t_{\text{tran}}$ be the time to transport energy out, both by convection and radiation which operate simultaneously. Namely,

$$ t_{\text{tran}} < \min(t_{\text{diffusion}}, t_{\text{convection}}), $$

where $t_{\text{diffusion}}$ is the time to carry energy out from radius $r$ by photon diffusion (radiative diffusion) only, and $t_{\text{convection}}$ is the time to carry energy out by convection only. Let $t_{\text{exp}}$ be the expansion time of the envelope. In our case it is about 1.7 years. The fraction of the photons' energy that can be used to remove the envelope, rather than be radiated away, is given approximately by (Equation (2) in Sabach et al. 2017)

$$ f_{\gamma} = \frac{t_{\text{tran}}}{t_{\text{tran}} + t_{\text{exp}}}. $$

This relation is based on the derivation of Arnett (1979), and comes basically from the relation $t_{\text{int}} = \frac{t_{\text{exp}}}{c^2} \frac{1}{\rho(r \kappa(r) dr)}$ which in turns comes from the first law of thermodynamics. Here $t_{\text{int}}$ is the timescale for the decrease in the internal energy of the expanding envelope as a result of expansion and radiation losses. The energy that is channeled to do work on the expanding envelope is $f_{\gamma} = \frac{t_{\text{exp}}}{t_{\text{tran}}}$, which is just Equation (2).

The implication of Equation (2) is as follows. When photons scatter and diffuse out, they lose energy. If the envelope does not expand, then the thermal energy is converted to more lower-energy photons that transfer energy out. This is the case, for example, in the present-day Sun. If the envelope expands on a shorter timescale than the energy transport time, i.e., $t_{\text{exp}} \ll t_{\text{tran}}$, then the thermal pressure does work on the envelope and the photon energy is transferred mainly to envelope removal. In this way, the fraction of recombination energy that is radiated away is only $t_{\text{tran}}/t_{\text{exp}} \ll 1$ (e.g., Kasen & Woosley 2009 for supernovae). In the present study, both $t_{\text{tran}}$ and $t_{\text{exp}}$ are known to high precision. We will take for $t_{\text{tran}}$ either the convection or the radiative diffusion time. As both operate simultaneously, the transport time in reality is shorter than what we will take in the estimates to come (Equation (1)). For that reason, in this study we actually somewhat overestimate the role of recombination in removing the envelope.

### 3.1. The Common Envelope Phase that We Study

As seen in Figure 1, the radius substantially increases during the 1.7 years time period studied here. From the upper panels in both Figures 3 and 4, we see that the luminosity substantially increases with radius in the ionization zone of hydrogen. This fast radius evolution and steep luminosity gradient indicates that we are dealing with the dynamical phase (plunge-in phase, or regular CEE as termed in Ivanova 2018). We are not dealing with the self-regulated CEE phase, where the evolution is much slower; e.g., the change of the photosphere radius with time is slow and the variation of luminosity with radius in the envelope is shallow. We do deal with the dynamical phase, contrary to what Ivanova (2018) attributed to our calculation.

### 3.2. Photon Diffusion

In our earlier paper (Grichener et al. 2018) we had already noticed that the photon diffusion times from the outer regions of the envelope are short. The expression for the photon diffusion time from a radius $r$ to the photosphere at $R_p$, that we use is $t_{\text{diffusion}} (r) \approx \frac{3}{c} (R_p - r) \tau(r) / \kappa$, where $c$ is the speed of light, $\tau(r) = \int_0^{R_p} \rho(r') \kappa(r') r' dr'$ is the optical depth at radius $r$ from where the photons start to diffuse, and $\kappa(r')$ is the opacity. From our graphs there we notice that from the radius $R_{\text{ion},30}$, namely where hydrogen is ionized to a degree of $\chi = 30\%$, the photon diffusion time is less than a year. At $t = 0$, 0.8 year and 1.7 years, the photon diffusion times from

\[ \tau_{\text{diff}} \] Where $\tau_{\text{exp}}$ of Arnett is $t_{\text{exp}}$ here, and $\tau_{\text{diff}}$ of Arnett is $t_{\text{tran}}$ here.
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3.3. The Actual Luminosity

From Figure 1 we learn that the mass coordinate of $\chi = 90\%$ hydrogen ionization, $m_{\text{ion,90}}$, decreases during the 1.7 years by about 0.2 $M_\odot$. At the same time $m_{\text{ion,50}}$ decreases by about 0.1 $M_\odot$, and $m_{\text{ion,10}}$ by about 0.05 $M_\odot$. We take the equivalent mass that completely recombines to be $M_{\text{rec}} = 0.1 M_\odot$, about the decrease in the mass coordinate of $m_{\text{ion,50}}$. For a solar composition this amounts to an energy of $E_{\text{rec,H}} = 1.8 \times 10^{45}$ erg. During the energy injection phase that lasts for 1.7 years, the average luminosity due to recombination alone is $L_{\text{rec,H}} = E_{\text{rec,H}}/1.7$ years $\approx 8800 (M_{\text{rec}}/0.1 M_\odot) L_\odot$.

From the upper panels of Figures 3 and 4 we see that the increase in the luminosity within the ionization zone of hydrogen, from about 95% ionization to the photosphere, is about $\Delta L(0.8) = 6900 L_\odot \approx 0.8 L_{\text{rec,H}}$ at $t = 0.8$ year, and $\Delta L(1.7) = 8800 L_\odot \approx L_{\text{rec,H}}$ at $t = 1.7$ years. Because we do not inject energy in that region, and because the expansion of the envelope absorbs energy, the increase in luminosity within that region must be due to recombination energy.

From the equality $0.8 L_{\text{rec,H}} \approx \Delta L \approx L_{\text{rec,H}}$ we conclude that the convection, according to the mixing length theory that MESA uses, can arrange itself to transport out most of the extra energy released by the hydrogen recombination. This is in contradiction with the claim of Ivanova (2018) that convection can carry only a negligible fraction of the hydrogen recombination energy.

3.4. Recombination inside Convective Cells

In Sabach et al. (2017) we followed Quataert & Shiode (2012) and adopted the following expression for the maximum convective flux $L_{\text{max,conv},0}(r) = 4 \pi \rho(r) r^2 c_s^2(r)$, where $\rho(r)$ and $c_s(r)$ are the density and the sound speed at radius $r$, respectively. This expression takes the heat content of the gas per unit mass to be $c_s^2$, namely the recombination energy is assumed to be zero.

In our previous paper (Grichener et al. 2018) we took a different approach and examined specifically what happens to the recombination energy when a convective cell moves out. If the photon diffusion time from radius $r$ to the photosphere is longer than the expansion time (as required if the recombination energy is to be used for envelope removal), so is the photon diffusion time out from convective cells. The reason for this is that the size of the convective cells is about the size of the mixing length $\Lambda$, which is not much smaller than the radius; we find from Figures 2–4 that the typical ratio is $\Lambda/r \geq 0.2$ in the relevant zones. When the convective cell moves outward, it cools and recombines. If the diffusion time is long, the cell carries all of its recombination energy out. For a solar composition the specific heat of the gas corresponds to a specific energy of

$$e_{\text{rec}}(H^+) = 13.6 \frac{X_H}{m_H} eV = 9 \times 10^{12} \text{ erg g}^{-1}$$

where $X_H$ is the mass fraction of hydrogen and $m_H$ is the hydrogen atomic mass. For the typical sound speed in the recombination zone, $c_s \approx 11$ km s$^{-1}$, we find that $\beta(H^+) \approx 7.5$ (Grichener et al. 2018). The maximum convective luminosity when recombination takes place in an expanding envelope, therefore, can be

$$L_{\text{max,conv,rec}}(r) \approx 4 \pi \beta \rho(r) r^2 c_s^2(r), \quad \beta \gg 1. \quad (4)$$

Christy (1962) gave the maximum convective luminosity as $L_{\text{max,conv},c}(r) \approx 4 \pi k_c r^2 e_{\text{rec}}(H^+) c_s(r)$, where he writes that $k_c$ is closer to 0.1 than to 1. With this value of $k_c$, this luminosity becomes $L_{\text{max,conv},c}(r) \approx 4 \pi r^2 c_s^2(r)$, as used by Quataert & Shiode (2012).

Ivanova (2018) took the maximum convective luminosity to be $L_{\text{max,conv},r}(r) = 4 \pi \rho(r) r^2 c_s T_{\text{rad}}$, where $c_s$ is the specific heat capacity and $T_{\text{rad}} = (d \ln T/d \ln P)_{\text{ad}}$ is the adiabatic derivative. The ratio of the maximum convective luminosity that we use to that of Ivanova (2018) reads

$$\frac{L_{\text{max,conv,rec}}}{L_{\text{max,conv}}} = \frac{\beta}{\nu_{\text{ad}}} \frac{c_s^2}{c_p T}. \quad (5)$$

To estimate the typical value of this ratio we present the values of $c_s^2/c_p T$ and $\nu_{\text{ad}}$ at three times in Figures 2–4. The small ratio $c_s^2/c_p T \approx 0.1$ in the relevant region results from the fact that the heat capacity includes the ionization/recombination energy. Inserting these values into Equation (5), we find that the two maximum convective luminosities are approximately equal

$$\frac{L_{\text{max,conv,rec}}}{L_{\text{max,conv}}} = \left( \frac{\beta}{20 \nu_{\text{ad}}} \right) \left( \frac{c_s^2}{0.05 c_p T} \right). \quad (6)$$

Our conclusion is that the maximum convective flux that we and Ivanova (2018) use are approximately the same.

Despite this similarity, Ivanova (2018) concluded that the convection cannot carry the recombination energy out based on her Equation (11) and Figure 5. However, according to Figure 5 of Ivanova (2018) the convective flux is much lower than the recombination flux only where the ionization fraction of

$R_{\text{ion,30}}$ are $t_{\text{diffusion}}^{30} = 0.2$ year, $t_{\text{diffusion}}^{30} = 0.8$ year, and $t_{\text{diffusion}}^{30} = 1.7$ year, respectively. All these are substantially shorter than the envelope expansion time of 1.7 years, and we find from Equation (2) that $f_s \leq 0.2$. Even from deeper zones where the hydrogen ionization fraction is $\chi = 40\%$, the diffusion time is shorter than 1.7 years, with values of $t_{\text{diffusion}}^{30} = 0.6$ year, $t_{\text{diffusion}}^{30} = 0.8$ year, and $t_{\text{diffusion}}^{30} = 1.7$ years.

The inequality $t_{\text{diffusion}}(m_{\text{ion,30}}) \leq 0.5$ year $< 1.7$ years during the evolution implies that most of the recombination photons from the outer region $m > m_{\text{ion,30}}$ can escape just by diffusion, even if convection would have been highly inefficient. About half of the recombination energy from the shell $m_{\text{ion,40}} \leq a \leq m_{\text{ion,30}}$ can also diffuse out as radiation, as $t_{\text{diffusion}} \approx t_{\exp}$ (by using Equation (2)). Therefore, photon diffusion from this outer zone, where $t_{\text{trans}} < 0.5$ year, by itself crudely takes away about a quarter of the recombination energy of hydrogen (by Equation (2)).
hydrogen is $\chi \lesssim 30\%$. But as we discussed in Section 3.2, from that zone the photon diffusion time is much shorter than the dynamical time, namely, less than half a year. Even from the deeper zone, where $\chi = 40\%$, the photon diffusion time is less than the envelope expansion time of 1.7 years. Ivanova (2018) took the region where the ionization fraction is $\chi = 20\%$ and claimed that the convection flux is too low to transport the recombination energy. However, from that region the photon diffusion time is very short and there is no problem carrying the energy out just by radiation. If convection is included, the energy transport time will be even shorter. We discuss this further below.

3.5. On the Energy Transport in the Outer Envelope

In her Equation (11) Ivanova (2018) compared the maximum convective energy flux with the flux that results from the hydrogen recombination energy. This expression includes two parameters: the ratio of the width of the hydrogen ionization zone to the stellar radius, $\alpha_H$, and the ratio of recombination energy to dynamical time, $\alpha_{\text{rec}}$. For our evolution the average values of these parameters are $\alpha_H \simeq 0.2$ and $\alpha_{\text{rec}} \simeq 1.7$ years/0.8 year = 2. When we take the factor $\alpha_{\text{rec}}/\alpha_H \simeq 10$ and multiply by the other terms of Equation (11) of Ivanova (2018), whose values are given in Figure 5 of Ivanova (2018), we find that when the hydrogen ionization fraction is $\chi \gtrsim 20\%$, convection alone can carry the recombination energy out. If we add the radiative flux, which is not much lower than the convective flux in these outer regions (see below), we see no problem for convection and radiation (photon diffusion) to carry the recombination energy out.

We can also see it for the simulations carried out here. We substitute the typical values in Equation (4) at $t = 0.8$ year, namely, in the middle of the plunge-in phase, and at the radius where $\chi \simeq 20\%$. These values are $r \simeq 360R_{\odot}$, $\rho \simeq 3 \times 10^{-9}$ g cm$^{-3}$, $\beta \simeq 10$, and $c_s^2 = 9$ km s$^{-1}$. We find that the maximum convective luminosity is $L_{\text{max,conv,rec}} \simeq 4.5 \times 10^4 L_{\odot}$. Replacing the maximum allowed convective velocity, namely the sound speed, by the convective velocity itself $u_{\text{conv}} = 4$ km s$^{-1}$, we find the maximum luminosity there to be $\approx 2 \times 10^4 L_{\odot}$. This is still larger than the recombination flux in our simulation $L_{\text{rec,fl}} \simeq 8800L_{\odot}$ (Section 3.3). Therefore, convection alone can carry the recombination energy out from regions where $\chi \gtrsim 20\%$.

Indeed, Ivanova (2018) noticed the problems with convection in the zone where the hydrogen ionization fraction is $\chi \lesssim 20\%$. However, in this outer zone the photon diffusion time is shorter than the convective transport time (Figures 6–8 in Grichener et al. 2018), and most of the extra recombination energy can be transported out by radiation alone. Again, we do not argue that all the recombination energy is radiated away during the plunge-in phase, but rather that most of it is. We estimate that only about 10% of the hydrogen recombination energy, i.e., $f_i \approx 0.1$ in Equation (2), and only of the outer envelope, is channeled to envelope expansion and removal during the plunge-in phase.

Let us now justify the usage of the photon diffusion time in the discussion at the end of Section 3.4. We note that in the above discussion we take the energy transport time in the outer envelope regions, where the hydrogen ionization fraction is $20\% \lesssim \chi \lesssim 40\%$, to be the photon diffusion time, even if in these regions the local convective flux is larger than the local photon diffusion flux (radiative flux). The reason for this is that we compare the total time for energy to be transferred out, and not the local flux. From the outer regions of the envelope, if energy would have been transferred out only by photon diffusion, then the energy transport time would have been only few times longer than if it would have been carried all the way out by convection only. Namely, photon diffusion is non-negligible. In reality, energy is carried for a short distance mainly by convection, and then mainly by radiation, and the real energy transport time is shorter than both the convective-only and radiative-only energy transport timescales, as expressed in Equation (1). Therefore, by only taking the photon diffusion time we actually use a longer energy transport timescale than what a full energy transport calculation would give, and hence we underestimate the fraction of the recombination energy that is radiated away. For that, the argument of Ivanova (2018), that we cannot use the photon diffusion time in these outer parts of the envelope, does not hold for the goals of our study. We simply take the pessimistic approach and show that even if we take the photon diffusion alone we still conclude that most of the hydrogen recombination energy is radiated away.

4. Summary

We continued the analysis of our numerical calculations presented in Grichener et al. (2018) regarding the role of hydrogen recombination in the ejection of the envelope in CEE. Following the criticism by Ivanova (2018) of our (Grichener et al. 2018) claim that during the CEE most of the recombination energy of hydrogen is radiated away, we further compared our claims with those of Ivanova (2018). The argument circles around the two-decades-old dispute of whether the recombination energy contributes to common envelope removal (e.g., Han et al. 1994) or not (e.g., Harpaz 1998). The key to understanding our claim is to realize that in the outer parts of the envelope, where convection becomes inefficient in transporting energy out, photon diffusion becomes very efficient (Section 3.2 and point 2 below). In our previous paper (Grichener et al. 2018) we injected energy in the inner part of the envelope of an AGB stellar model to mimic the initial spiral-in phase of the CEE (termed plunge-in or dynamical phase). By that we inflated the envelope by more than a factor of two in radius within 1.7 years, about the dynamical time of the giant (Figure 1). In the present study we further analyzed the properties of the inflated envelope.

We presented five points of disagreement in the five Sections 3.1–3.5. We can summarize these as follows.

1. We simulate the plunge-in phase and not the self-regulated phase of the CEE (that lasts longer), unlike what Ivanova (2018) attributed to us.
2. We showed that from the region where hydrogen is ionized to a degree of $\chi \lesssim 30\%$, the photon diffusion time out from the envelope is less than a third of the plunge-in time. This implies that radiation by itself, before we add convection, can carry about $\gtrsim 25\%$ of the recombination energy of hydrogen. When we included convection, we found that less than about 20% of the hydrogen recombination energy can be used to eject the envelope, with a more typical value of 10%. Our finding contradicts the claim of Ivanova (2018) that the amount of recombination energy that can be transferred away by radiation is negligible.
3. We used the MESA stellar evolution code to follow the inflation of the envelope. MESA uses the mixing length theory and, as we showed in the upper panels of Figures 3 and 4, convection carries most of the recombination energy out. This refutes the claim of Ivanova (2018), who used the mixing length theory to argue that convection can transport out only a negligible amount of the recombination energy.

4. In Section 3.4 we elaborated on the differences between the analysis of Ivanova (2018) and our analysis regarding the convective flux. We found that both Ivanova (2018) and our work derive approximately the same maximum convective flux (Equation (6)), and that convection can carry most of the recombination energy in inner regions where the ionization degree is $\chi \gtrsim 20\%$, out. Ivanova (2018) claimed that in regions where the hydrogen ionization fraction is $\chi \lesssim 20\%$ convection cannot carry energy out, and hence recombination energy will be used to eject the envelope. But, as we already discussed in point (2) above (Section 3.2), in those regions photon diffusion carry most of the recombination energy out.

5. Finally, in Section 3.5 we showed that for our model convection can carry the recombination energy when the ionization fraction of hydrogen is $\chi \gtrsim 20\%$. In the zones farther out, where $\chi \lesssim 20\%$, the photon diffusion time is shorter than the convection time, and therefore most of the recombination energy is carried out by photon diffusion. We also justified our usage of the photon diffusion time in the regions where the ionization fraction of hydrogen is $20\% \lesssim \chi \lesssim 40\%$, despite the fact that the convection flux is larger than the radiative flux there. This is justified for the goals of the present study, contrary to the claim of Ivanova (2018). By also including convection, we would have found that more recombination energy leaks out and radiates away. Namely, by using the photon diffusion time alone, we underestimate the fraction of the recombination energy that is radiated away.

In this study we considered only the hydrogen recombination energy. The two helium recombination zones, that of $\text{He}^+ \rightarrow \text{He}$, and of $\text{He}^+ \rightarrow \text{He}^*$, are much deeper in the envelope. The energy transport times from these zones to the surface are longer than the duration of the plunge-in phase. However, the location of these zones makes the recombination energy less efficient in boosting mass loss. The CEE starts with the envelope inflation as the secondary star spirals-in deep into the giant envelope. Hydrogen recombination takes place in the outer zone with little mass above the recombination zone. If all this energy could have been used (and we showed that it cannot), then it would have supplied the extra energy required to eject the very outer zone of the now-inflated envelope. The recombination energy of helium is released much deeper into the envelope, and its energy should remove a much larger mass. Its energy is actually added to the orbital energy that is also released deep inside the envelope. So, our expectation is that the effect of the recombination energy of helium is small, and its effect is comparable to the secondary star in-spiraling a little deeper into the envelope. Namely, the recombination energy of helium will increase the envelope inflation somewhat, but will not cause a massive outflow. Eventually, as the spiral-in process slows down, there will be enough time to transport the recombination energy of helium out.

We considered here only low-mass AGB stars. When we turn to massive stars and/or smaller stars, like sub-giant branch stars, the envelope binding energy is larger, and recombination energy plays an even smaller role.

We summarize by reiterating our previous results that during the CEE most of the hydrogen recombination energy is radiated away (about 90%). The recombination energy does not contribute much to the energy that is used to remove and accelerate the envelope. Our results show that the inclusion of recombination energy in the common envelope simulation should only be considered once radiation transport is included in the codes, or else the dynamics of the CEE simulation would be erroneously altered. It is our view that in cases where extra energy sources to the orbital energy are required, it is more likely that the companion star contributes the energy by accreting envelope mass and launching jets.

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