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COMMON ENVELOPE SHAPING OF PLANETARY NEBULAE

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RESUMEN

La evolución de envoltura común ocurre cuando una estrella en un sistema binario llena de manera inestable su lóbulo de Roche y la órbita de la otra estrella colapsa en la envoltura extendida. Este proceso normalmente provoca la expulsión de la envoltura, lo que lleva a una binaria cercana o a una fusión estelar. La envoltura que sale no es simétrica, por lo que puede romper la simetría de cualquier viento posterior más rápido, como el producido durante la fase de nebulosa planetaria. Trabajos anteriores han demostrado que el material denso expulsado en la fase de envoltura común puede explicar la forma bipolar de tales nebulosas. Para estudiar este proceso, hemos producido dos sistemas progenitores de nebulosas planetarias de envoltura común. Cada uno entra en una evolución de envoltura común en una fase evolutiva diferente con una cantidad diferente de energía de recombinación disponible. Esto puede ayudarnos a comprender cómo la energía de recombinación afecta la evolución de las nebulosas planetarias.

ABSTRACT

Common envelope evolution occurs when one star in a binary system unstably fills its Roche lobe, and the other star's orbit shrinks into the expended envelope. This process typically causes the ejection of the envelope, leading to a close binary or stellar merger. The outflowing envelope is not symmetrical, so it may break the symmetry of any subsequent faster wind, such as that produced during the planetary nebula phase. Previous work has shown that the dense material ejected in the common envelope phase can explain the bipolar shape of such nebulae. To study this process, we have produced two common-envelope progenitor systems of planetary nebulae. Each enters common envelope evolution at a different evolutionary phase with a different amount of available recombination energy. This can help us understand how recombination energy affects the evolution of planetary nebulae.

Key Words: methods: numerical — stars — stars: binaries: close

1. INTRODUCTION

During the evolution of a binary star system, if one of the stars fills its Roche lobe, intense mass transfer between the two stars could occur. This mass transfer can cause angular momentum loss from the system. Once the more compact companion star's orbit shrinks into the other star, they share the same envelope. This situation, in which the two stars share their envelope and evolve together, is called common envelope evolution (CEE) (Ivanova et al. 2020).

In the late stages of stellar evolution, low-mass stars eject their envelopes. The ejected envelope forms a shell of ionized gas known as a planetary nebula. Under this simple scenario, the shapes of planetary nebulae are expected to be roughly spherical or ellipsoidal. However, some of them are bipolar or barrel-type shapes. To produce this kind of shape, a slow, dense wind in the equatorial plane is needed. Common envelope evolution is an efficient way to produce this wind (García-Segura et al. 2018).

In this project, by setting up common envelope simulations for a model with a 2.5 $M_\odot$ primary star during its pre-main sequence (pre-MS) phase and a 0.36 $M_\odot$ white dwarf (WD), we produce 2 kinds of progenitor system for planetary nebulae. One enters common envelope evolution with a 2.49 $M_\odot$ red giant (RG) plus a 0.36 $M_\odot$ white dwarf; the other enters common envelope evolution with a 2.48 $M_\odot$ early-AGB star (EAGB) plus a 0.36 $M_\odot$ white dwarf.

2. MODELS

To produce the progenitor systems for planetary nebulae after common envelope evolution, we start from stellar evolution models using MESA (version 15140; Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023), and perform 3D hydrodynamic simulations using FLASH4 (Fryxell et al. 2000; Dubey et al. 2008). Since the 1D MESA single star model is spherically symmetric but the binary system is not, we also use SPHARG (Ricker et al., in

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TABLE 1

MODELS WE CONSIDERED

Model	2.5RG+0.36WD	2.5EAGB+0.36WD
$M_{\rm WD}$	0.36M$_\odot$	0.36M$_\odot$
$M_{\rm p,0}$	$2.50M_\odot$	$2.50M_\odot$
$M_{\rm p,CE}$	$2.49M_\odot$	$2.48M_\odot$
$a_{\rm init}$	$64.2R_\odot$	$67.7R_\odot$
$M_{\rm c,He}$	$0.344M_\odot$	$0.501M_\odot$
$M_{\rm c,C/O}$	—	$0.354M_\odot$

$M_{\rm WD}$: secondary white dwarf star mass; $M_{\rm p,0}$: pre-main sequence mass for the primary star; $M_{\rm p,CE}$: primary star mass when entering common envelope evolution; $a_{\rm init}$: initial separation; $M_{\rm c,He}$: helium core mass; $M_{\rm c,C/O}$: carbon/oxygen core mass.

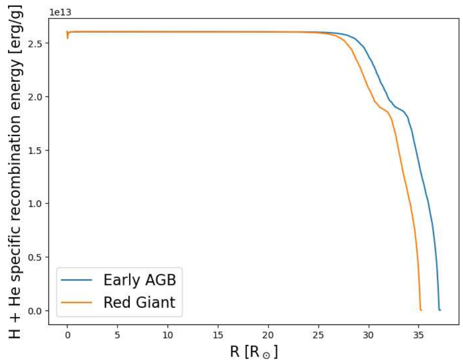

Fig. 1. Hydrogen and helium recombination energy for the initial models.

prep; Faber et al. 2010), a Smoothed Particle Hydrodynamics (SPH) code, to relax the single star model into a non-spherically symmetric binary star potential.

The two models we consider both start with a 2.5 M$_\odot$ single pre-main sequence star. We choose different stages for it to enter common envelope evolution. One enters the common envelope stage when it is a red giant (model 2.5RG+0.36WD), and the other enters common envelope evolution when it is an early-AGB star (model 2.5EAGB+0.36WD). The detailed properties for these two models are shown in Table 1. We terminate these simulations when we can no longer resolve the motions of the stellar cores.

Fig. 1 shows the initial recombination energy (E_{rec}) profile for the two donor stars. We can see that the RG and EAGB donor stars contain different recombination energies, and the 2.5EAGB+0.36WD case initially carries more since the EAGB donor star has a higher envelope temperature compared to the RG donor. Since recombination energy could be released during the common envelope phase, we expect it will affect the system evolution.

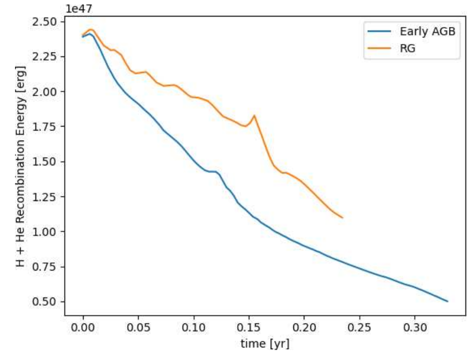

Fig. 2. Hydrogen and helium recombination energy evolution of the two models.

3. RESULTS

From Fig. 2 we can see that the EAGB case releases the recombination energy faster than the RG case. The EAGB donor has a lower envelope density; thus its envelope gas is more ready to be ejected. As the envelope is ejected more rapidly, the temperature also drops more quickly, so the EAGB recombination energy is released more quickly than for the RG. Comparing Fig. 3 and Fig. 4, we can see that the EAGB case shows a faster ejection of its envelope. Fig. 5, which displays the final azimuthally averaged density, shows that in the RG case, the envelope is also more equatorially concentrated than for the EAGB case.

4. DISCUSSION

Our simulations show that the donor star's evolutionary stage when the binary system enters common envelope evolution will cause different density distributions around the cores. These differences will potentially affect how the gas ejects during the planetary nebula phase, then lead to different shapes of planetary nebula. Although detailed post-processing hydrodynamics simulations focusing on planetary nebula phase expansion are needed to study the final morphology, our current results already show some differences. Previous studies (García-Segura et al. 2018, 2021, 2022) have shown that common envelope evolution plays an important role in the geometry of planetary nebula. Our results could provide a more robust initial condition for similar simulations.

5. CONCLUSIONS AND FUTURE WORKS

Based on our current models, we could investigate the influence of different common envelope evolution tracks on shaping planetary nebulae. To understand this process better, a post-common envelope evolution simulation that can trace that outflowing gas to a distance of a few parsecs is

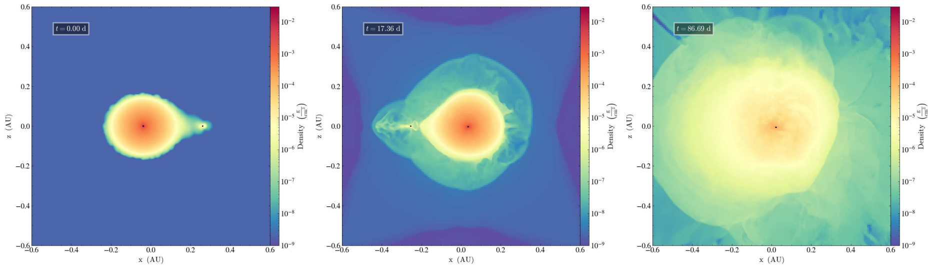

Fig. 3. Model 2.5RG+0.36WD density slice perpendicular to the orbital plane.

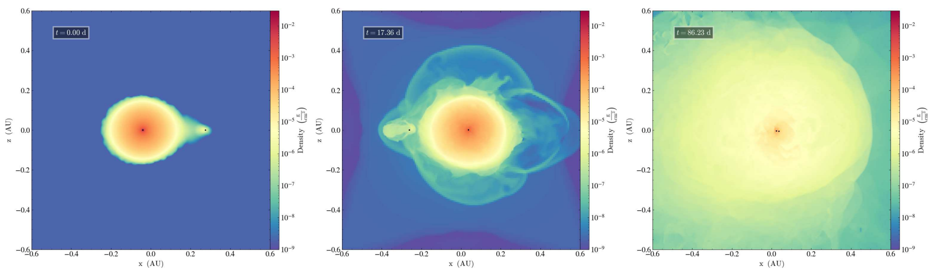

Fig. 4. Model 2.5EAGB+0.36WD density slice perpendicular to the orbital plane.

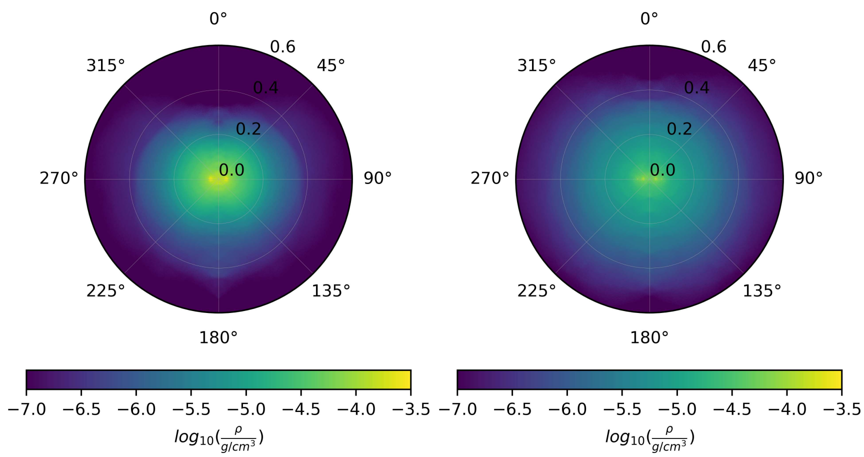

Fig. 5. Azimuthally averaged density distribution. Left panel: 2.5RG+0.36WD; Right panel: 2.5EAGB+0.36WD.

needed. Including magnetic field and radiation diffusion could also be important.

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