Common Envelope Shaping of Planetary Nebulae

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What is the common envelope phase?

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) [3].

How can common envelopes shape planetary nebulae?

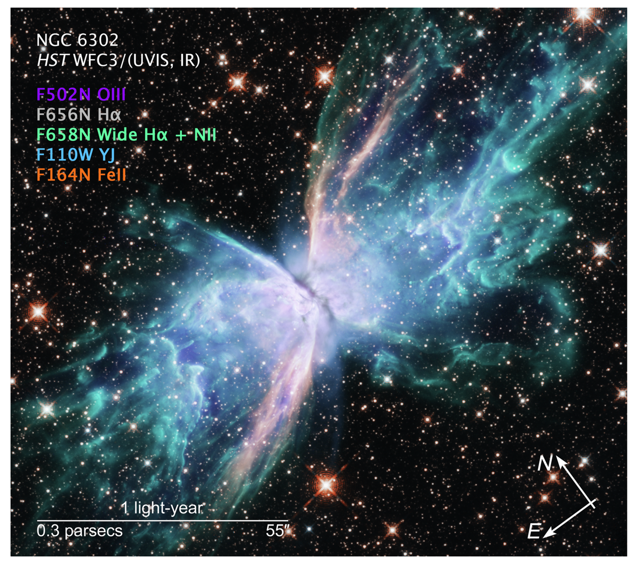

Figure 1: Butterfly Nebula. Credits: NASA, ESA, and J. Kastner (RIT)

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. One example is the Butterfly Nebula (NGC 6302). 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 [4].

Goal

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. Studying these models could help us study how different common envelope evolution tracks could influence the shapes of planetary nebulae.

Simulations

Table 1: Models we considered. $M_{p,0}$: pre-main sequence mass for the primary star. $M_{p,CE}$: Primary star mass when entering common envelope evolution. M_{WD}: Secondary white dwarf star mass.

Model	$M_{p,0}$	$M_{p,CE}$	M_{WD}	Phase Entering CEE
2.5RG+0.36WD	2.50$M_\odot$	2.49$M_\odot$	0.36$M_\odot$	RG+WD
2.5EAGB+0.36WD	2.50$M_\odot$	2.48$M_\odot$	0.36$M_\odot$	EAGB+WD

To produce the progenitor systems for planetary nebulae after common envelope evolution, we start from stellar evolution models using MESA (version 15140; [1]), and perform 3D hydrodynamic simulations using FLASH [2]. Since the 1D MESA single star model is spherically symmetric but the binary system is not, we also use SPHARG [6], 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. Figure 2 shows the 2.5RG+0.36WD model's orbital-plane density during common envelope evolution.

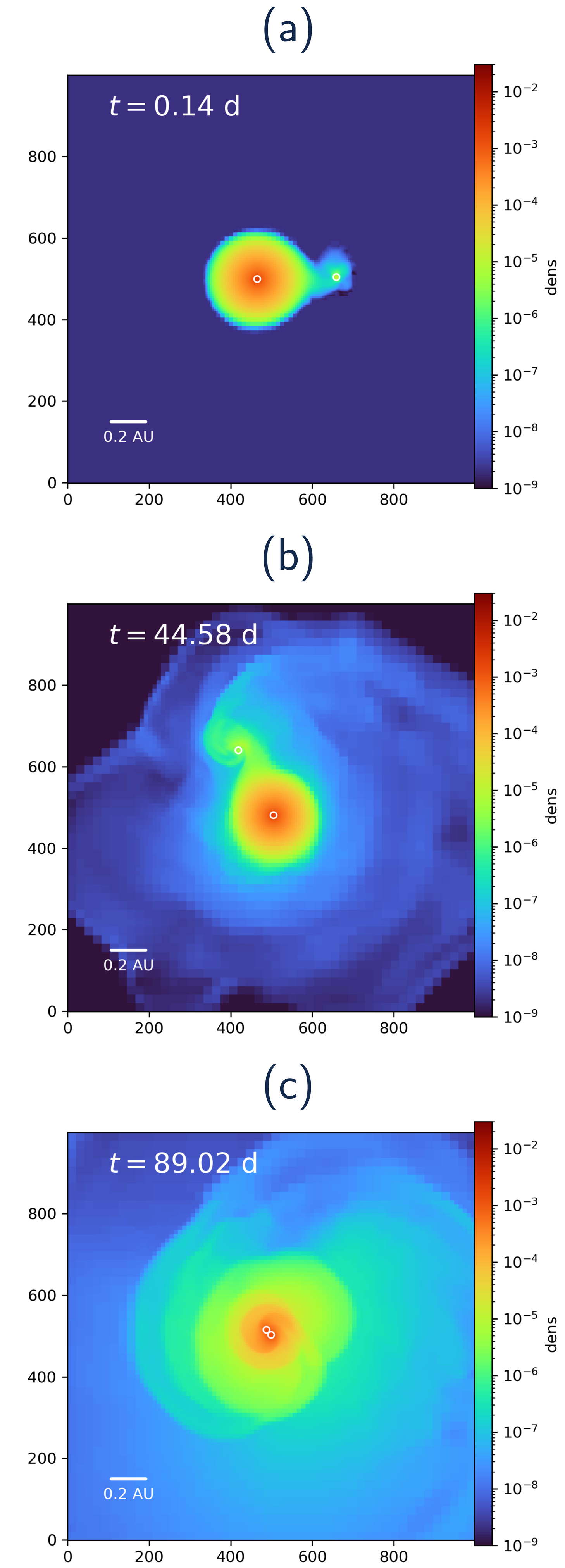

Figure 2: Density slice plot for the 2.5RG+0.36WD model.

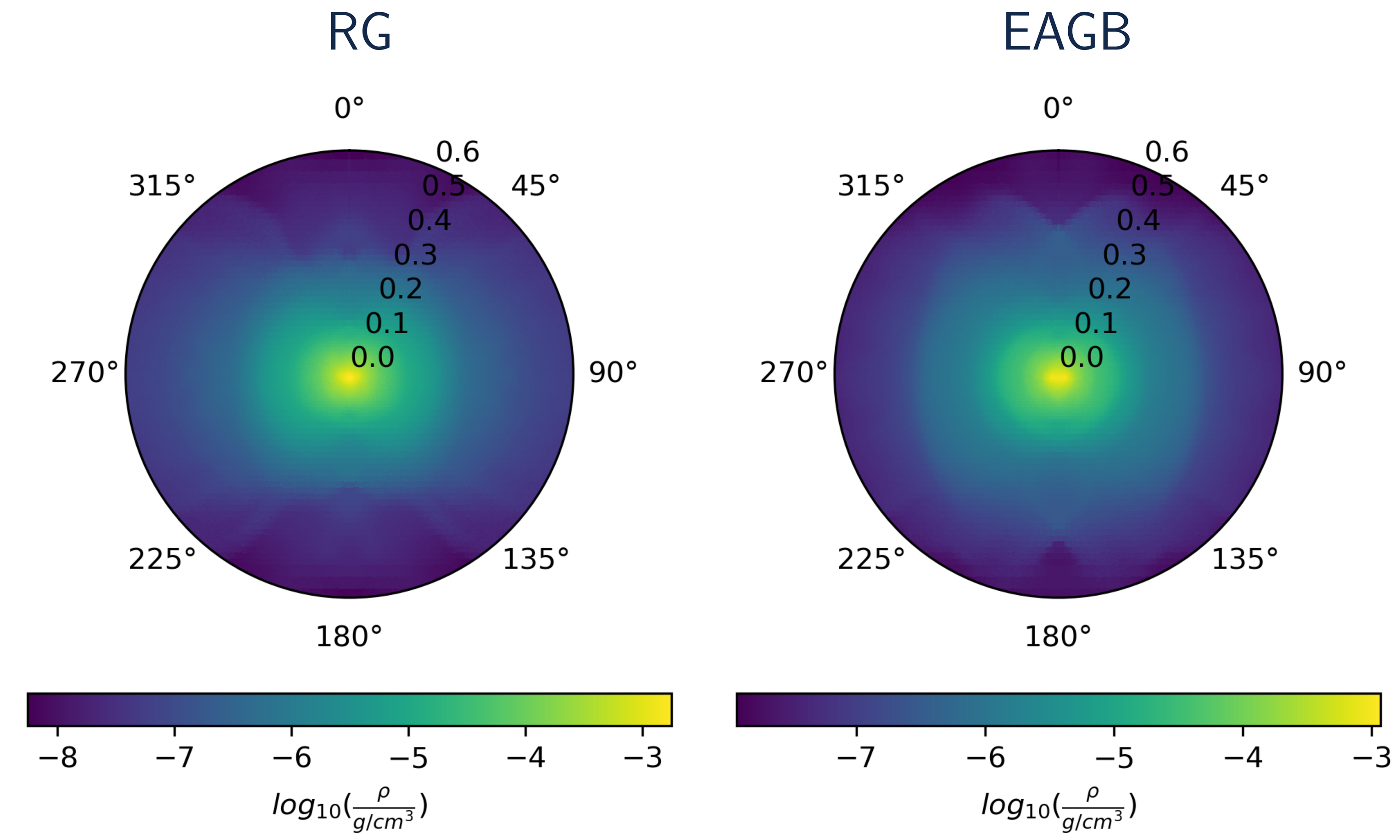

Figure 3: Azimuthally averaged density. The unit in the r-direction is AU. Left: 2.5RG+0.36WD; Right: 2.5EAGB+0.36WD.

Figure 3 shows the averaged density profile for both models in polar coordinates. Here we can observe that the equatorial plane ($\theta = 90^\circ$ and 270°) is denser compared to the polar direction ($\theta = 0^\circ$ and 180°). These equatorial materials could be ejected into space and probably produce non-elliptically shape planetary nebulae [5]. The major features of the two models are consistent, but there are some small differences in their morphology. It would be interesting to investigate whether the shape of planetary nebulae would be sensitive to this difference or not.

Future Work

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

References

[1] Paxton, B., Smolec, R., Schwab, J., et al. 2019, ApJS, 243, 10
[2] Fryxell, B., Olson, K., Ricker, P., et al. 2000, ApJS, 131, 273
[3] Ivanova, N., Justham, S., & Ricker, P. 2020, *Common Envelope Evolution*, IOP Publishing
[4] García-Segura, G., Ricker, P. M., & Taam, R. E. 2018, ApJ, 860, 19.
[5] García-Segura, G., Taam, R. E., & Ricker, P. M. 2022, MNRAS, 517, 3822.
[6] Faber, J., Lombardi, J., & Rasio, F. 2010, Astrophysics Source Code Library. ascl:1010.074