The Origin of Outflows in Evolved Stars
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Mass transfer in AGB binaries - uncovering a new evolution channel by 3D radiation-hydrodynamic simulations

Zhuo Chen[1], **Natalia Ivanova**[2] **and Jonathan Carroll-Nellenback**[3]

[1]Department of Astronomy, Tsinghua University Beijing 100084, China
email: zc10@ualberta.ca

[2]Department of Physics, University of Alberta
Edmonton, AB T6G 2E1, Canada

[3]Department of Physics and Astronomy, University of Rochester Rochester, NY 14627, USA

Abstract. The origin of chemically peculiar stars and nonzero eccentricity in evolved close binaries have been long-standing problems in binary stellar evolution. Answers to these questions may trace back to an intense mass transfer during the asymptotic-giant-branch (AGB) binary phase. We use AstroBEAR to solve the 3D radiation hydrodynamic equations and calculate the mass transfer rate in AGB binaries that undergo the wind-Roche-lobe overflow or Bondi-Hoyle-Lyttleton (BHL) accretion. One of the goals of this work is to illustrate the transition from the wind- Roche-lobe overflow to BHL accretion. Both circumbinary disks and spiral structure outflows can appear in the simulations. As a result of enhanced mass transfer and angular momentum transfer, some AGB binaries may undergo orbit shrinkage, and some will expand. The high mass transfer efficiency is closely related to the presence of the circumbinary disks.

Keywords. Asymptotic giant branch; Symbiotic binary stars; Hydrodynamics

1. Introduction

Non-conservative mass transfer is an important but poorly understood picture in low-mass binary evolution. A low-mass binary may enter one or two asymptotic-giant-branch (AGB) binary phases as one of the stars ages. During this phase, the interaction between the stars becomes stronger because of the large size of the AGB star and the relatively slow ($\sim$10km/s) and dense AGB wind.

Previously, two fundamental non-conservative mass transfer modes during the AGB binary phase have been identified: Bondi-Hoyle-Littleton (BHL) accretion (Bondi & Hoyle 1944) and wind-Roche-lobe-overflow (WRLOF) (Podsiadlowski & Mohamed 2007). Without surprise, Mohamed & Podsiadlowski (2012) showed that WRLOF can enhance the mass transfer between the binary. Inspired by their work, we set up a 3D radiation hydrodynamic model and show that the WRLOF mass transfer mode may naturally lead to a new evolution morphology - circumbinary disks (CBDs). The inner radius of this kind of CBD is comparable to the binary separation. Possible candidates and examples of such CBDs include L2 Pup (Kervella et al. 2015) and AR Pup (Ertel et al. 2019).

2. Overview

The deciding factor in distinguishing the BHL accretion and WRLOF is the ratio ζ of the radius of the dust formation zone $r_{\rm dust}$ and the radius of the inner Roche-lobe $r_{\rm inner}$

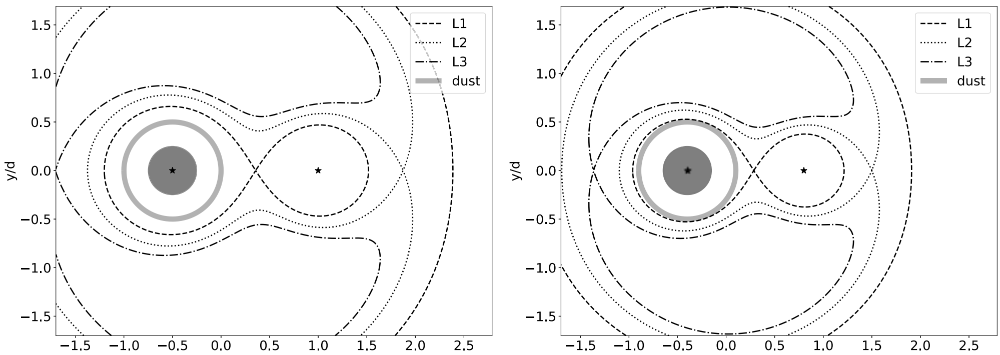

Figure 1. Illustrative plots of AGB binaries with L1, L2, and L3 potentials. Coordinate units are scaled to binary separations d. Left: AGB binary may undergo BHL accretion. Right: AGB binary will likely experience WRLOF. The grey rings represent the dust formation region near the AGB stars. The AGB star is represented by a big circle with a star at its center.

of the AGB star. When $\zeta < 1$, the BHL accretion occurs; when $\zeta \sim 1$, WRLOF may take place. Figure 1 illustrates the two scenarios.

The physical process that happen when $\zeta \sim 1$ is described as follows (see also Mohamed & Podsiadlowski (2012)):

(1) Pulsation near the surface of the AGB star drives a shock into its upper atmosphere, creating a dense and *shell* like environment.
(2) Dust condensates near $r_{\rm dust}$, the opacity of the gas and dust fluid increase by roughly 2 orders of magnitudes.
(3) The radiation pressure from the AGB star nearly balances its gravitational pull. The gas can become subsonic during this balanced period.
(4) The additional gravitational pull from the companion drags a significant amount of the gas of the *shell* toward it.
(5) The matter forms an accretion disk around the companion and is accreted onto the companion over time.

The oversimplified description of the process still points out several critical characteristics of WRLOF in AGB binaries. They are the pulsating AGB star, the dust formation zone, and the accretion disk around the companion. Together they should determine the mass transfer efficiency in large. However, the existence of a CBD cannot be straightforwardly inferred from this physical picture, and its existence will change the global evolution. To show that such a CBD may form, we dive into some physics.

One important physical aspect that is frequently missing in many AGB binary simulations is non-local radiation transfer. It is most convenient not to model the non-local radiation transfer if the outflow from the AGB binary is optically thin. On the contrary, as dust blocks light from the AGB star, the optical depth increases gradually and the balance between the radiation pressure and the gravitational force breaks down. An overall physical picture of the formation of CBD is described as follows.

(1) The AGB binary has a small binary separation so that the companion can pull the wind from higher latitudes to the equator, leading to a focused wind.
(2) The focused wind forms a dense tail behind the companion as the binary orbits.
(3) The tail blocks radiation from the AGB star and the dust in the shadow of the tail experiences smaller radiation pressure.

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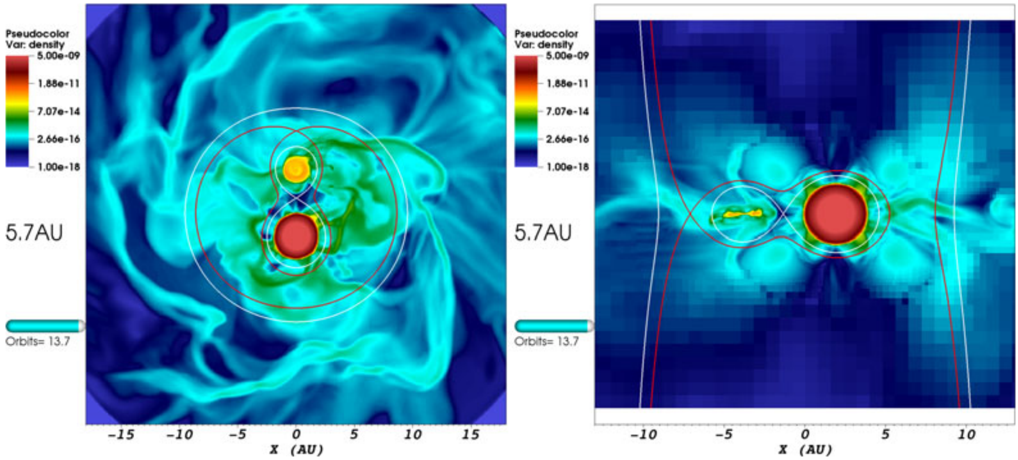

Figure 2. Left: equator density plot. Right: side view density plot. The binary separation is 5.7AU. The AGB star with a mass of $1.02\mathrm{M}_{\odot}$ is the red circle, which is pulsating. The companion, located above the AGB star, has a mass of $0.51\mathrm{M}_{\odot}$. An accretion disk forms around the companion and some gas material become gravitationally bound at a larger radius in the equator. The white and red contours are the L1 and L2 potential contours, respectively. The snapshot is taken at 13.7 binary orbits.

(4) Eventually, the radiation pressure cannot push the gas away from the AGB star and the companion. The gas starts to orbit the binary and forms a CBD.

We call this scenario "focused wind-induced CBD". We show in Figure 2 a snapshot of the simulations with a CBD formation, using a simulation presented in Chen, Ivanova, & Carroll-Nellenback (2020). A circumbinary structure as shown in the left panel forms; we think it represents the onset of the formation of a CBD.

A CBD may have many impacts on the evolution of the AGB binary. A direct result is the significantly enhanced mass transfer. Such an enhancement may be stronger than the normal WRLOF because the gas can stay in a CBD and be accreted by the companion after several orbits.

Another physical process that can become important after the formation of a CBD is angular momentum transfer between the binary and CBD (Muñoz, Miranda & Lai 2019).

Intense mass transfer not only changes the chemical composition of the companion, it may also have an impact on the long-term orbital evolution. In the mass transferring binary, the limiting cases of long-term evolution are the BHL accretion and conservative mass transfer. The BHL accretion incurs the least binary interaction and usually leads to a widening of the binary separation. On the other hand, the conservative mass transfer from the massive donor usually leads to a shrink of the binary separation. We plot $\dot{P}$ (P is the orbital period) of the two limiting cases in Figure 3 under the assumption that the mass-loss rate of the donor star is $\dot{M}_{\mathrm{AGB}} = 2.31 \times 10^{-7}\mathrm{M}_{\odot}{\cdot}\mathrm{year}^{-1}$, the same as in Chen et al. (2018). Simulated results are plotted as red stars and blue triangles. All simulations have a mass ratio $q = m_s/m_{\mathrm{AGB}} = 0.5$, where m_s and m_{AGB} are the mass of the companion and the AGB star, respectively.

Although the mass-loss rate and terminal wind speed of the AGB star of every simulation may be somewhat different, both results show a clear trend: $\dot{P}$ approaches the BHL accretion scenario when the binary separation is large and approaches the conservative mass transfer scenario when the binary separation is small. The transition of $\dot{P}$ from

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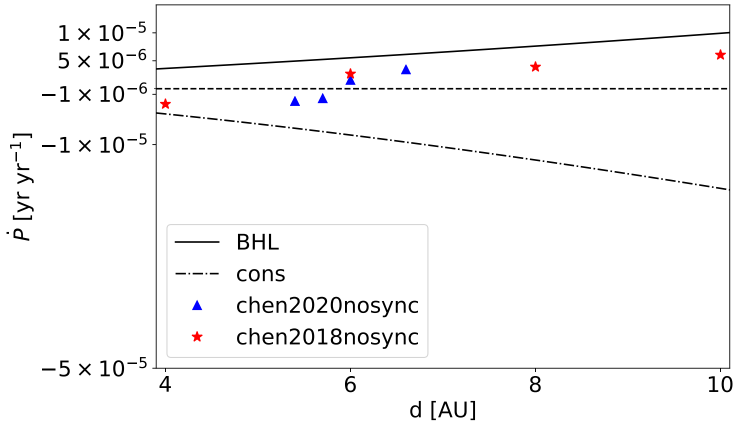

Figure 3. The solid line and dash-doted line show the $\dot{P}$ of BHL and conservative transfer case. The dashed line marks the $\dot{P}=0$. The red stars and the blue triangles are the simulation results from Chen et al. (2018) and Chen, Ivanova, & Carroll-Nellenback (2020), respectively. "Nosync" means the AGB star does not rotate in the lab-frame by assumption.

positive to negative happens around 6AU in our models. Generally, this number should change if one adopts another AGB star model, which is worth further studying.

3. Challenges in AGB binary evolution

In this section, we discuss some of the major challenges in AGB binary simulations.

Viscous accretion disk. If there is no viscosity, the accretion rate will be extremely low. Viscosity in an accretion disk may come from magneto-rotational instability (Balbus & Hawley 1991), but we could also use an α viscous disk model (Shakura & Sunyaev 1973) for simplicity. Currently, the grid based code cannot explicitly specify the viscosity due to unknown numerical viscosity. Smooth-particle hydrodynamic (SPH) simulations can specify viscosity and we hope to see more realistic SPH simulations in the future.

Dust formation. Dust formation is strongly coupled to radiation transfer and shock physics (Höfner & Freytag 2019). First principle simulations that start from a chemical network would be computationally expensive. However, due to its importance in WRLOF, we expect this challenge to be the next to solve.

Coevolution of the CBD and binary. In our simulations, we cannot resolve the long-term dynamics between the CBD and the binary as the angular momentum conservation is not precise. However, as an initial attempt to uncover the existence of CBDs, we hope our work can provoke more new ideas and attention to CBDs around AGB binaries. The thermodynamics and angular momentum transfer between the binaries and CBDs are potentially interesting topics.

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Discussion

Orsola: You have been mostly working on relatively wide binaries and binary interactions that leads to CBDs, can you venture to guess what differences the CBDs could have if they were form via closer binaries?

Zhuo: Thank you very much for the question. You just mentioned a very good research project. If the binary is at the very edge of Roch-lobe overflow, we may find an accretion disk and a CBD at a larger radius. The qualitative morphology may not change much but the thermodynamics and radiation hydrodynamics should be more violent in those binaries.

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