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PLANETARY NEBULA IN THE BINARY ERA

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RESUMEN

El proyecto que se presenta es un estudio completo de la interación dinámica que producen la radiación y los vientos estelares con el medio interestelar. Este proyecto está basado en una estrecha comunicación entre dos grandes pilares de la astrofísica moderna: la evolución estelar y la magneto-hidrodinámica, incluyendo una pieza fundamental actual que es la binariedad.

ABSTRACT

The project presented in this talk is a complete study of the dynamical interaction that produce radiation and stellar winds with the interstellar medium. This project is based on a close communication between two great pillars of modern astrophysics: stellar evolution and magneto-hydrodynamics, including a current fundamental piece that is binarity.

Key Words: planetary nebulae — stars: mass-loss, binaries

1. INTRODUCTION

Stellar radiation and winds, as well as supernova explosions, have a profound influence on the structure of the surrounding gas, heating it, sweeping it into large shells, and changing its chemical composition. Stars go through phases with very different mass losses during their evolution, producing a wide variety of structures in the surrounding gas. Although this mass loss is in the form of constant winds for most of their lives, the final phase can be a supernova explosion, depending on the initial mass. One result of this long process is the ejection of materials synthesized in nuclear reactions. Such ejections change the abundance of the circumstellar medium, enriching it with heavier elements. The kinetic energy deposited on the medium by massive stars, in turn, is the main source of hot coronal gas in the interstellar medium. The shock waves produced can even induce star formation. Both steady winds and supernova ejections produce shock waves that sweep through the ambient gas, forming ring nebulae (including planetary nebulae) and supernova remnants respectively. An example of the need to take into account the full history of stellar mass loss is the discovery of the previously formed nebula surrounding the 1987 A supernova.

We have shown in previous works that to understand ring nebulae, the history of the central star must be taken into account (García-Segura et al. 1996a, 1996b). Stellar evolution simply tells us that there are multiple dynamic interactions with the circumstellar medium, the final conditions of a first stage are the initial conditions of a second phase, as can be clearly seen in the case of SN 1987 A. The complete dynamical evolution is a very complex problem.

Although stellar evolution calculations are sufficiently precise to predict a number of observational parameters, such as abundances and surface temperatures, the rate at which mass is lost from the central star is still subject to large uncertainties, especially after the main sequence phase. In previous calculations we (Langer et al. 1999) emphasized that ring nebulae are extremely sensitive to wind speed and mass loss history. The high degree of sensitivity allows us to combine stellar evolution calculations with hydrodynamic studies to verify the structures predicted by the computed mass loss. In other words, by combining stellar evolution with circumstellar evolution, we can visualize the printing of stellar models, and compare directly with observed images.

Stellar evolution was of great importance in the 20th century and laid the foundations for practically all advances in astrophysics. Its interaction with the interstellar medium has been fundamental to understanding many of the very important observations for modern cosmology, such as all types of super-

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novae with their brightness decay, especially due to the interaction with the circumstellar medium, especially SN Ia and gamma-ray burst among other objects that can or could be used as distance indicators.

However, these studies focused primarily on the stellar evolution of isolated stars. Already in the 21st century, it has become clear that almost all important events have to include binarity in their work schemes. For example, LIGO detections are unthinkable if there is no common envelope evolution in stars, which give way to mergers of stellar black holes (BH-BH), neutron stars (NS-NS), combinations of these (BH-NS), and recently the SN Ia candidates from white dwarf mergers (WD-WD). Thus, we see, for example, that the study of common envelope evolution has become of vital importance for astrophysics, and yet, this phenomenon is not observed directly, since it is very difficult statistically to observe it by its short duration.

What can be easily observed are the nebulae that form after the common envelope evolution process, and it is here where planetary nebulae take on a unique role, due to their large number. Every day more and more short period binary stars (hours, days) are confirmed in planetary nebulae, in addition to hydrodynamic studies, teaching us that only with common envelope evolution is it possible to explain their morphology. For example, to explain the planetary nebula NGC 3231 recently observed with the James Webb Space Telescope (De Marco et al. 2022), a system of four stars is needed (two of them produce a common envelope evolution). Even now the need for a binary process to explain the formation of the Homunculus, the nebula surrounding Eta Carina, is debated.

Another important point is that the great advances in the 20th century were made by the magnificent resolution of the HST in the optical regime, vital for observing large objects in the interstellar medium. But with the arrival of ALMA and the James Webb Space Telescope, we can now reach unimaginable resolutions in millimeter and infrared, and these new observations are being key in understanding many events close to the stars that are engulfed by dust, since the majority of common envelope events occur in the red super giant phases (RSG) and in the asymptotic giant branch (AGB). For example, ALMA observations of water fountains involving AGB stars, are revealing the very early stages of proto-planetary nebulae, with the formation of accretion disks and jet launches, such as the case of W43A (Tafoya et al. 2020).

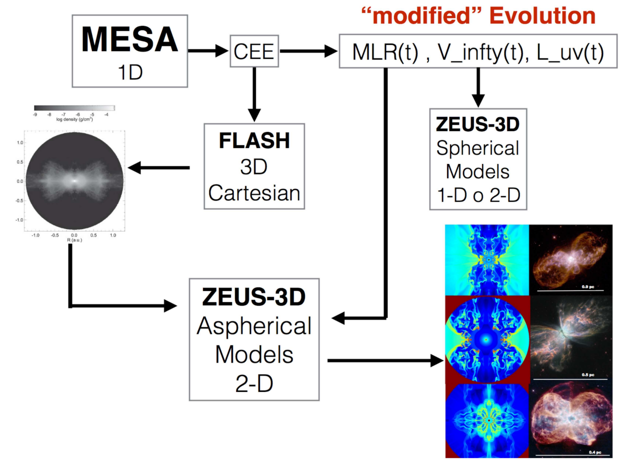

Fig. 1. Working scheme showing the different used codes

2. GOALS OF OUR PROJECT

It is proposed to study the dynamical interaction of radiation and stellar mass loss with the circumstellar medium using numerical methods, including the effects of binaries. The project contemplates the computation of stellar evolution models using MESA, for a whole range of initial stellar masses, between low-mass stars that are precursors of planetary nebulae and massive stars that form Wolf-Rayet ring nebulae and blue luminous variables (LBV), as well as the respective hydrodynamical calculations of the gas response around such stars, especially the hydrodynamic calculations of the common envelope events. The direct and indirect results from the MESA stellar evolution code, such as ionizing photons, wind speeds and stellar mass loss-rates, will be used as internal boundary conditions for the magnetohydrodynamics models, using the ZEUS-3D code (see Figure 1). All this including binary as a new ingredient. In turn, MESA models are used to calculate the stellar structure at the time of the common envelope evolution event. The 1-D radial structure is extrapolated into 3-D in FLASH in Cartesian coordinates (Ricker& Taam 2012). As we already did in our recent articles (García-Segura et al. 2018, 2020, 2021, 2022), FLASH's 3-D Cartesian results are averaged in 2-D spherical coordinates, which are what we use in ZEUS. Note that the FLASH models are computationally very expensive. However, they are not able to follow the ejection of the envelope for a long time, only for a few tens or hundreds of years. That is why, to follow the expansion for thousands of years, typically of planetary nebulae, we use 2-D expanding grids in ZEUS. This way of working is precisely what has made us pioneers in the computation of planetary nebulae that come from a common envelope evolution, since otherwise, the computation is prohibitive and inefficient.

3. FIRST PROJECTED CALCULATIONS

The fragmentation of planetary nebulae has been a recurring theme in several of our previous works. We have shown that photoionization is the most effective method for breaking up nebulae when the shells are partially opaque to ionizing radiation. Recently, the fragmentation produced by the photoionization front has served to explain the James Webb Space Telescope observations of the planetary nebula NGC 3132, and the formation of the molecular "spikes" observed in Molecular Hydrogen. Our hydrodynamic simulations included in this study gave an explanation of the molecular structures in De Marco et al. (2022). Since new observations from the James Webb Space Telescope are showing structures never seen before in the near and mid-infrared, in the first study we will focus on the fragmentation of planetary nebulae, emphasizing the molecular structures that are observed and would be observed in the shadows of the clumps due to lack of photoionization, especially in the phases of stellar evolution when the stars enter in the cooling track towards white dwarfs. This has not yet been well studied. To do this, we will use the models for single stars of 1, 1.5, 2, 2.5, 3.5 and 5 solar masses, and we will calculate the emissions in molecular Hydrogen in the fragmented phases. Later we will confront these models with new ones that include the common envelope phase. The difference between the latter lies in the fact that the expulsion of the AGB envelope is violent and sudden compared to the slow and gradual ejection of isolated stars, considerably increasing the circumstellar density very close to the central star, with much larger opacities. A specific goal would be to measure the molecular mass in the simulations, since this is difficult to do in the observation of molecular Hydrogen.

There are still important questions in common envelope evolution. For example, the efficiency of envelope ejection and the role played by recombination energy, the effects of convection in the circumbinary bound gas, and the role of the mass ratio of the stars in the final morphology of nebulae. It is unknown what the survival time of the circumstellar and circumbinary disks that originate magnetic jets and winds is, and what are the true causes for the formation of nebulae with point symmetry. It is also unknown how long the "Roche-Lobe-Overflow" phase usually lasts prior to the evolution of the common envelope. These and many other questions will be addressed in this project.

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