Effects of Stellar-Mass and the ISM on the Evolving Morphologies of Planetary Nebulae

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Abstract.
A significant step forward in the understanding of Planetary Nebula (PN) formation can be achieved by exploring the connection of PN with stellar evolution. In particular, the initial mass of the star plays a crucial role, as it determines the evolutionary timescales, the density structure of the gas and the amount of energy injected into the nebula. Here we summarize our study of the effects of stellar mass in PN formation. Our numerical simulations include the evolution of the stellar wind for different initial progenitor masses and the influence of the ISM. We also investigate how the systemic velocity of the star with respect to its surrounding medium affects the PN formation. We find that unless the star is moving, most of the mass lost by PN progenitors can be found in the low surface brightness extended halos, where the stellar ejecta is mixed with ISM material. For a moving central star, the interaction with the ISM considerably reduces the mass of the circumstellar envelope during the AGB and PN phases owing to ram pressure stripping.

1. Introduction

Towards the end of the Asymptotic Giant Branch (AGB) phase, stellar evolution predicts episodic mass-loss increases, a consequence of the thermal pulses in the star. Although the occurrence of this modulated mass-loss has played a key role in the interpretation of the different shells found around PNs and AGB stars, hydrodynamic models describing the evolution of the wind in this phase still need to be considered. Because of the inherent difficulties in the mass-loss calculations and in recovering the history of mass-loss from observational studies, the exact evolution of mass-loss during the AGB still remains unknown. For this it is fundamental that the grid used in the numerical computations allow the study of the whole stellar ejecta. It is only then, by comparing the models with the PN structure at large scales that constraints can be placed on the treatment of mass-loss in models stellar evolution models. Previous models have always truncated the computational grids to small scales.

Stellar evolution predicts that stars with main sequence masses in the range of ∼1–5 $M_\odot$ will produce PN, whilst PN nuclei and white dwarfs mass distributions peak around 0.6 $M_\odot$. Since most of the mass-loss occurs on the AGB phase,
it should be easily observable as ionized mass during the PN stage. However, observations of Galactic PNs reveal on average only 0.2 $M_\odot$ of ionized gas.

Another important aspect that needs to be considered is the role played by the stellar progenitor mass in the PN formation. The central star provides the wind and the radiation field that determines the evolution of the nebular gas during this phase. The details of the post-AGB evolution of the star, and therefore the energy injected in the nebular gas are mainly determined by its core mass. Despite this, most of the numerical studies of PN evolution in the literature have been restricted to a 0.6 $M_\odot$ post-AGB evolutionary track.

2. **The evolution of the stellar ejecta during the AGB phase.**

In Villaver, García-Segura, & Manchado (2002) we studied the time-dependent hydrodynamics of the circumstellar gas shells of AGB stars. We directly used the results of stellar evolution (predictions for the wind evolution from Vassiliadis & Wood 1993) as inputs to the simulations.

We find that the wind variations associated with the thermal pulses lead to the formation of transient shells with an average lifetime of 20,000 yr and, consequently, do not remain recorded in the density or velocity structure of the gas. The formation of shells that survive at the end of the AGB phase occurs via two main processes: shocks between the shells formed by two consecutive enhancements of the mass-loss or continuous accumulation of the material ejected by the star in the interaction region with the ISM. We do not find the signature of discrete mass-loss recorded in the density or in the velocity structure of the circumstellar envelope (CSE). Consequently, we argued against the use of the different observed shells as dynamical clocks.

The mass of the AGB stellar progenitors are usually estimated from observing the CSEs, with the assumption that all the observed mass has been ejected by the star. We find, however, that the final mass of the CSE contains a significant fraction of swept-up ISM material. Thus, in order to obtain unbiased AGB-progenitor mass estimates, it is vital that this effect is taken into account. We also predict that the CSEs are a mix of the ISM and the wind material that has been enriched by the stellar interior and brought to the surface of the star by dredge-up processes. This effect should be taken into account for abundance analysis. According to our simulations based in the mass-loss predictions of one particular set of stellar evolution models, large CSEs (up to 2.5 pc) are expected around stars at the tip of the AGB.

3. **The connection between the stellar progenitor and the PN shell’s evolution**

To study PN formation we used a set of computational grids large enough to study the full stellar ejecta, and a set of grids small enough to resolve the processes taking place close to the central star. In Villaver, Manchado, & García-Segura (2002) we considered the evolution of the post-AGB wind and the ionizing radiation field for PN nuclei evolving from progenitors with initial masses between 1 and 5 $M_\odot$ (taken from Vassiliadis & Wood 1994). We show the importance of the dynamical effects of ionization on the shell evolution, which can
account for the observed disagreement between the kinematical ages and the age of the CSs for different progenitor masses. We find that the evolution of the main shell is controlled by the ionization front rather than by the thermal pressure provided by the hot bubble during the early PN stages.

The halos have sizes up to 2.3 pc (more than twice the size of the main shell) and are formed during the AGB phase. They produce Hα emissivities between 10 and 5000 times fainter than the main shell and contain most of the total ionized mass lost by the stellar progenitors. Given the low surface brightness of the halos, previous observations have underestimated the ionized masses in PNs.

4. The interaction of PNs with the ISM

Several PNs show bow-shock structures, suggesting the interaction of the nebular shell with the ISM while the star is moving. We have approached the problem of PN-ISM interaction through a realistic perspective by considering a low-mass star evolving during the AGB and PN phases while moving through the ISM. In Villaver, García-segura, & Manchado (2003) we showed that even the ejecta of a star with a systemic velocity of 20 km s$^{-1}$ moving through a low density medium will interact with it and form bow-shock structures qualitatively similar to those observed.

An increase of ram pressure (due to e.g a higher velocity) leads to the development of instabilities that lead to a partial fragmentation of the shell and to a more efficient mixing with the ISM material. This fragmentation allows the UV radiation field to escape from the nebula at certain locations. In Figure 1 we show the logarithm of the gas density during the latest stages of the evolution for a star moving with 80 km s$^{-1}$ through a low density ISM ($n_o=0.05$ cm$^{-3}$). Figure 1 shows only half of the $r-\theta$ plane, (where $r$ and $\theta$ are the radial and polar coordinates respectively) the star is fixed in the grid and the ISM flows in from the top to the bottom. We assume that the ISM moves relative to the star perpendicular to the line-of-sight by fixing the position of the star at the center of the grid and allowing the ISM to flow into the grid at the outer boundary from 0° to 90°. In Szentgyorgyi et al. (2003) we considered a stellar motion with a velocity of 85 km s$^{-1}$ in the study of the PN NGC 246. We qualitatively reproduce the overall shape of the PN, due to the interaction which we find consistent with what is expected in the fast interaction with a rarefied medium at the position of the PN in the Galaxy.

We find that due to ram-pressure stripping, most of the mass ejected during the AGB phase is left downstream of the star in its motion, an effect that might be able to account for the small amount of ionized mass recovered in PN shells. We conclude that the interaction with the ISM plays a major role in the PN formation process even during the early AGB evolution and its interaction with the ISM cannot be studied using simple ram pressure balance arguments.

5. Summary

We have studied the PN formation by following the evolution of the stellar wind as predicted by stellar evolutionary models and considering the influence of the
Figure 1. Logarithmic density gas distribution around the central star during the AGB phase at times of 390, 420, and $450 \times 10^3$ yr. The fourth panel correspond to the transition time and the last panel to a PN that is $8000$ yr old. The relative movement takes place at a velocity of $80 \text{ km s}^{-1}$ with density $0.05 \text{ cm}^{-3}$ and a temperature of $6000 \text{ K}$.

external ISM. We find that although the mass-loss history during the AGB phase is very different for low- and high-mass progenitors, the final nebular structure is very similar. The mass-loss during the AGB gives rise to the formation of large shells (with sizes up to $3 \text{ pc}$) that contain most of the mass lost by the star plus an additional amount (up to $1 \text{ M}_\odot$ of ISM material) which is ISM material swept up by the stellar wind. We find that the movement of the CS with respect to its surrounding medium considerably alters the PN formation. The main effects of the interaction, apart from that on the morphology, are that the total size of the outer PN shell (halo) is reduced considerably and most of the mass ejected during the AGB phase is stripped by the ram pressure of the ISM and left in the downstream direction of the stellar movement. The mass stripped away by the ISM when the star is moving might be able by itself to account for the problem of the missing ionized mass in PNs.

References

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