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WINDS FROM LOW MASS STARS: IMPACT ON THE ISM

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RESUMEN

Una parte importante de todas las estrellas, tras experimentar fuertes vientos al final de la Rama Asintótica de Gigantes (RAG), dejan tras de si un núcleo cuya masa está por debajo de la masa límite de Chandrasekhar. Este núcleo, en un momento dado, fotoionizará el material estelar previamente eyectado dando origen a una Nebulosa Planetaria (NP). Las NPs y las estrellas durante la RAG son, por tanto, los remanentes de estrellas que a través de sus vientos determinan el enriquecimiento químico del medio interestelar (MI) con elementos como He, C, N y O. Hemos investigado el impacto de esos vientos en el MI y en la formación y evolución de las envolturas circunestelares alrededor de estrellas durante la RAG y en las capas de las NPs. En las simulaciones encontramos que se produce la formación de capas enormes (de hasta 2.5 pc en radio) debido a la pérdida de masa durante la etapa de RAG. Si la estrella está en reposo respecto al MI estas capas contienen una importante fracción de material del MI que ha sido barrido por el viento estelar. Encontramos que si la estrella está en movimiento y para valores suficientemente altos de la presión se produce un mezclado significativo entre el material estelar eyectado y el material del MI debido a inestabilidades, sin embargo, la masa y tamaño total de la envoltura se ven fuertemente reducidos.

ABSTRACT

A large fraction of all stars, after experiencing heavy winds at the end of the Asymptotic Giant Branch (AGB) phase, leave behind a core that is below the Chandrasekhar mass limit. This core eventually photoionizes the stellar ejecta giving birth to a planetary nebula (PN). PN and AGB stars are therefore the remnants of stars that through their winds contribute to the chemical enrichment of the ISM with elements He, C, N and O. We have explored the impact of such winds in the ISM and in the formation and evolution of the circumstellar envelopes around AGB stars and PN shells. In our simulations, we find that huge shells (up to 2.5 pc in radius) are formed as a consequence of the mass-loss during the early AGB phase. When the star is at rest with respect to the ISM, these shells contain a large fraction of ISM material that has been swept up by the stellar wind. We find that when the star is moving and the ram pressure is high enough, significant dispersal between the stellar ejecta and the ISM material still takes place due to instabilities, however, the mass and the size of the envelope are highly reduced due to ram pressure stripping.

Key Words: **ISM: JETS AND OUTFLOWS — ISM: STRUCTURE — PLANETARY NEBULAE: GENERAL — STARS: AGB AND POST-AGB — STARS: WINDS, OUTFLOWS**

1. INTRODUCTION

After the completion of helium and hydrogen core ignition, low- and intermediate-mass stars move towards the Asymptotic Giant Branch (AGB) phase in the HR diagram. Stellar evolution predicts high mass-loss rates during this phase in the form of episodic mass-loss increases, a consequence of the thermal pulses in the star. This dense and low velocity wind removes most of the stellar envelope, returning the bi-products of nucleosynthesis in the stellar interiors to the ISM. The stellar wind during this phase plays also a key role in the formation of the different shells found around PNe and stars during the AGB phase.

The process responsible for the high mass-loss rates during the AGB phase is not well understood. In the commonly accepted scenario the mass-loss is thought to be driven mainly by a combination of two processes: shock waves caused by the Mira-like stellar pulsation and the acceleration of dust by radiation pressure (Wood 1979; Bowen 1988). The transfer of momentum from the dust to the gas ultimately drives the outflow. Calculation of mass-loss have to consider complicated dynamical model atmospheres, from which reliable mass-loss rates cannot yet be obtained. Mass-loss during this phase is extremely important as it determines the subsequent evolution of the star.

Because of the inherent difficulties in the mass-

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loss calculations and in recovering the history of mass-loss from observational studies, the exact evolution of the mass-loss during the AGB phase still remains unknown. The basically unknown mass-loss history of the star determines the geometry, radial density and temperature distributions of the circumstellar envelopes around AGB stars. Mass-loss also determines the properties of the AGB population itself, the distribution of white dwarf masses, the maximum white dwarf progenitor mass (and hence the minimum supernova type-II progenitor mass), the composition of the ISM and the PN structure.

We have performed numerical simulations with the aim of testing the wind predictions of the stellar evolutionary models. We have studied the dynamical gas evolution during the AGB and PN phases result of our simulations and compare it with the observed gas structure. We have followed the wind evolution for the range of initial masses of PN progenitors and we have also studied how the structure of the stellar ejecta changes when we allow the star to move.

2. HOW THE STELLAR EJECTA MIX WITH THE ISM

By directly using the results of stellar evolution[4] as inner boundary condition we study the time-dependent hydrodynamics of the circumstellar gas shells of AGB stars (Villaver, García-Segura, & Manchado 2002). 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 masses of AGB stars are usually estimated from observing the CSEs, with the assumption that all the observed mass has been ejected by the star. We find 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. In these static models, up to 70% of the mass in the envelope of a 1 $M_\odot$ star evolving through a high density medium (which can be representative of the Galactic plane) is actually ISM material.

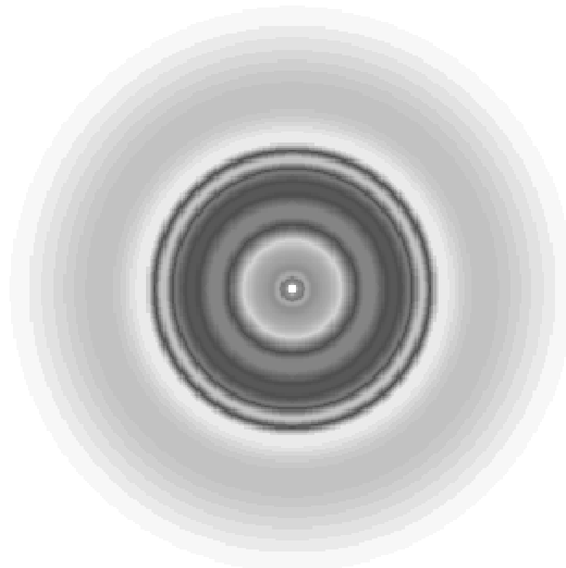

Fig. 1. Logarithm of the gas density at 1.7×10^5 yr of the AGB evolution of a 1 $M_\odot$ star. Time zero has been set at the begining of the thermal-pulse phase during the AGB. The radial size of the grid is 2 pc.

According to our models, the CSE is composed of ISM and wind material. The latter has been enriched by the stellar interior and brought to the surface of the star by dredge-up processes. According to our simulations based on the mass-loss predictions of one particular set of stellar evolutionary models, large CSEs (up to 2.5 pc) are expected around stars at the tip of the AGB.

2.1. *The case of a star moving through the ISM*

We consider a star moving with respect to the ISM in order to study how it affects the evolution of the stellar ejecta. In Figure 2 we show the logarithm of the gas density of an AGB star moving with 20 km s^{-1} through an ISM with density $n_o = 1$ cm^{-3}. We have computed only half of the $r-\theta$ plane (where r and θ are the radial and polar coordinates respectively). 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° (from

[4]Taken from the stellar evolutionary models of Vassiliadis & Wood 1993 during the AGB phase. For the PN we compute the evolution of the wind parameters and ionizing radiation field based on the position of the post-AGB star on the HR diagram given by Vassiliadis & Wood 1994.

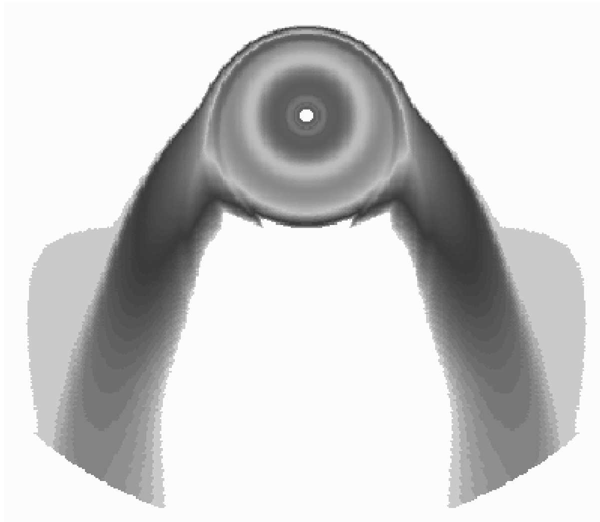

Fig. 2. Same as in Fig.1 but considering the star is moving with a velocity of $20\,\mathrm{km\ s^{-1}}$ through an ISM with density n_0=0.01 $\mathrm{cm^{-3}}$ (100 times less dense than the one shown in Fig. 1. The radial size of the grid is 2 pc and the resolution used 400x360.

the top to the bottom in Fig. 1).

In Villaver, García-Segura, & Manchado 2003 we show that even the ejecta of a star with a systemic velocity of $20\,\mathrm{km\,s^{-1}}$ moving through a low density medium will interact with the ISM and form bow-shock structures. In Figs. 1 and 2 we show the gas structure at the same time during the AGB evolution when the star is at rest and moving through the ISM respectively. The effect of the stellar movement is clearly seen. 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 dispersal with the ISM material. This fragmentation allows the UV radiation field to escape from the nebula at certain locations. In Szentgyorgyi et al. (2003) we considered a stellar motion with a velocity of $85\,\mathrm{km\,s^{-1}}$ in the study of the PN NGC 246. In our models, we can qualitatively reproduce the overall shape of the PN, which is consistent with what is expected in the fast interaction of the stellar ejecta 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 find that the interaction with the ISM plays a major role in stripping the wind from AGB stars and returning it to the ISM. Most of this enriched material is left behind of the star in its motion and therefore the CSE mass will be reduced.

3. THE GAS EVOLUTION DURING THE PLANETARY NEBULA PHASE

After the AGB, the stellar remnant becomes hot enough to ionize the previously ejected envelope. In the meantime, the wind velocity increases and shapes the inner parts of the envelope according to the so-called interacting stellar winds (Kwok, Purton, & Fitzgerald 1978). The evolution of the nebular gas from then onward depends on the energy provided by the CS through the wind and the radiation field, both of which depend on the stellar luminosity and effective temperature.

In Villaver, Manchado, & García-Segura (2002) we studied the PN formation from progenitors with initial masses between 1 and $5\,\mathrm{M_{\odot}}$. Photoionization has important effects on the dynamical evolution of the nebular gas during the PN phase, and since ZEUS-3D does not include radiation transfer, we use the approximation implemented by García-Segura & Franco 1996 to derive the location of the ionization front for arbitrary density distributions (Bodenheimer, Tenorio-Tagle, & Yorke 1979; Franco, Tenorio-Tagle, & Bodenheimer 1989, 1990). The position of the ionization front can be determined by assuming that ionization equilibrium holds at all times, and that the ionization is complete within the ionized sphere and zero outside. We apply this formulation by assuming that the nebula is composed of pure hydrogen, it is optically thick in the Lyman continuum and that the 'on the spot' approximation is valid.

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 order to study the kinematical evolution of the PN shells in our models, we computed the Hα synthetic line spectrum for the photoionized gas at each output of the simulations, and derived the expansion velocity of the brightest shell and the haloes.

All the models show expansion velocities $\sim$$20\,\mathrm{km\,s^{-1}}$ during the early stages when the dominant feature is the shell caused by the ionization front. The shell is accelerated when is forced by the thermal pressure provided by the hot bubble. From then onwards, this shell is driven at the expense of the thermal pressure of the hot bubble, and its velocity increases rapidly with time. As the CS evolves

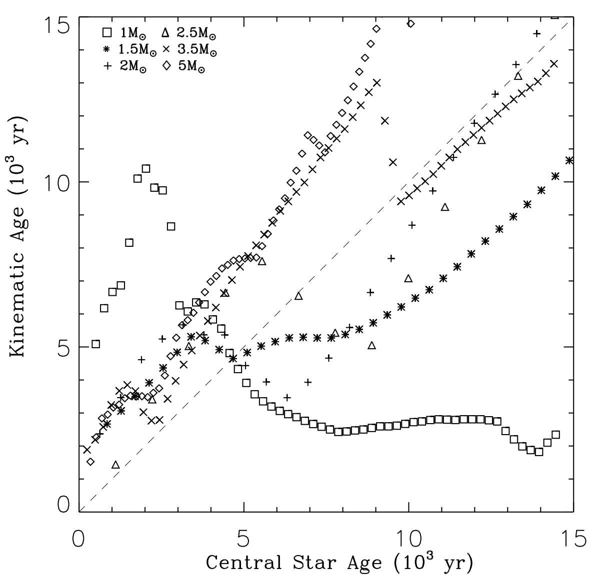

Fig. 3. Kinematical ages derived from our simulations using standard procedures are plotted versus the CS ages. The symbols used for the different models are shown in the top left corner of the plot.

towards lower effective temperature, the wind kinetic energy decreases, and, moreover, the adiabatic expansion of the hot bubble decreases its thermal pressure. These two processes combined explain why the velocity of the main shell is slowed down at later stages during the evolution.

The dynamical effects of ionization on the shell evolution alone can account for the observed disagreement between the kinematical ages and the age of the CSs for different progenitor masses (see Fig. 3). 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. Later on, the situation changes; when the hot bubble drives the main shell, the radius becomes smaller and the expansion velocity increases reducing the kinematical ages.

With the results of our models, we find a natural explanation for the disagreement between the kinematical timescales in PNe and the evolutionary status of their CSs, that is able to account for the observed characteristics. For young CSs the dynamical ages tend to overestimate the CS ages for all the models. At later stages of the evolution, when the sample is biased towards low-mass progenitors, the dynamical ages underestimate the evolutionary status of the CSs.

4. 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 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 pc) that contain most of the mass lost by the star plus an additional amount (up to 1 $M_\odot$ 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 effect of the interaction, apart from that on the morphology, is 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 downstream of the star's motion. The mass stripped away by the ISM when the star is moving might, by itself, be able to account for the problem of the missing ionized mass in PNe.

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