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PLANETARY NEBULAE WITH DOUBLE SHELLS AND HALOES: INSIGHTS FROM HYDRODYNAMICAL SIMULATIONS

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RESUMEN

Se combinan simulaciones hidrodinámicas con cálculos de evolución estelar basados en recetas de tasas de pérdida de masa para obtener una mejor comprensión de cómo se desarrolla con el tiempo la estructura y cinemática de la materia circumestelar durante la fase tardía de la Rama Gigante Asintótica (RGA) y las fases posteriores: post-RGA y evolución de la Nebulosa Planetaria.

ABSTRACT

We combined hydrodynamical simulations with stellar evolutionary calculations based on prescribed mass-loss rates in order to get a better understanding of how structure and kinematics of circumstellar matter develop with time during the late AGB and the following post-AGB and Planetary Nebula (PN) evolution.

Key Words: **HYDRODYNAMICS — PLANETARY NEBULAE: GENERAL — STARS: AGB AND POST-AGB — STARS: MASS LOSS — STARS: WINDS, OUTFLOWS**

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1. THE INITIAL PN MODEL

Density and velocity distributions of circumstellar matter around objects that have left the tip of the asymptotic giant-branch (AGB) are ruled by the previous heavy mass loss phases. In order to obtain consistent initial conditions for modeling the PN phase, we combined stellar evolutionary calculations with hydrodynamical simulations of dust-driven AGB winds. With prescribed mass-loss rates and stellar parameters computed consistently with the mass loss (Blöcker 1995a), we followed the evolution of spherical dusty wind envelopes by means of a two-component, implicit radiation-hydrodynamics code for given dust properties (cf. Steffen, Szczerba, & Schönberner 1998).

Since the mass-loss rates of radiation-driven winds depend sensitively on the stellar parameters, e.g., on the luminosity which varies considerably on time scales of 50 000 to 100 000 years because of thermal pulses, one cannot expect simple stationary AGB wind envelopes with constant rates and speeds to be valid. Instead, our computations show that, since for most of the time between thermal pulses the mass-loss rate increases, the density in the circumstellar shell will fall off steeper than $\rho \sim r^{-2}$ (Fig. 1b). The stages of high mass-loss rates are periodically interrupted by shorter phases of much lower outflow rates and speeds due to the luminosity dips associated with thermal pulses. At the leading edge of the denser and faster wind matter is being swallowed-up and compressed into a very thin shell (see Fig. 1b, at $r = 5\,10^{17}$ cm).

2. THE PLANETARY NEBULA STAGE

Starting out with the structures emerging from the AGB simulations as shown in Figure 1 we modeled the post-AGB evolution by applying another (one-component) radiation-hydrodynamics code. This explicit code is based on a second-order Godunov-type advection scheme and considers time-dependent ionization, recombination, heating, and cooling of all considered elements (usually 6) with all of their ionization stages (cf. Perinotto et al. 1998).

During the more advanced phases of the post-AGB evolution ionization and wind interaction become very effective in changing the existing density and velocity distribution by (i) creating a shell of ionized gas bounded by a shock that moves supersonically into the expanding AGB material, and (ii) by compressing the inner parts of that matter into a dense but rather thin shell by the thermal pressure of the shocked central-star wind material. We have now a double-shell structure which is typical for many round or elliptical PNe. When the surrounding still unaffected AGB matter becomes ionized too, it constitutes a halo of low surface brightness, sharply bounded at its leading edge ($r = 6.5\,10^{17}$ cm, Fig. 2a) by the thin shell described in the previous Section. The planetary NGC 6826 is known to have such a halo (Plait & Soker 1990).

Our simulations show further that the ther-

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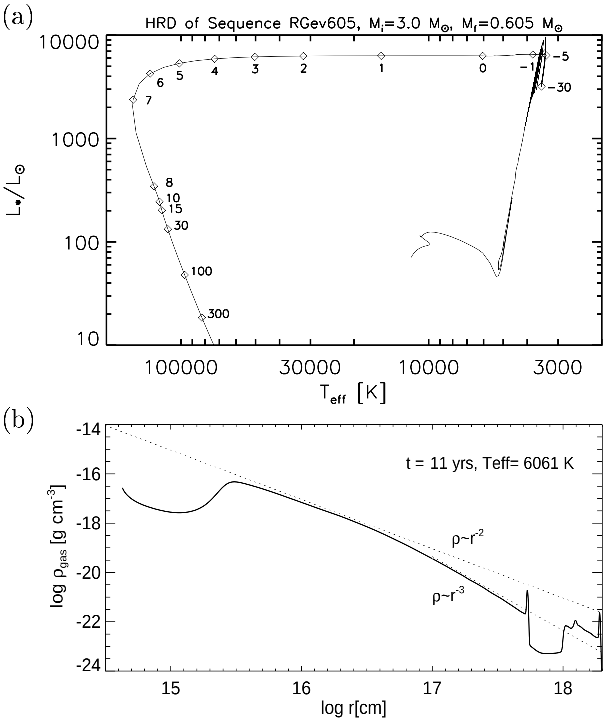

Fig. 1. (a) The 0.605 $M_\odot$ post-AGB evolutionary track used in our simulations. The figure displays the complete evolutionary path of a main-sequence star with 3 $M_\odot$ through all nuclear phases until it ends up, due to mass loss, as a 0.605 $M_\odot$ post-AGB star. The numbers indicate the evolutionary ages in 10^3 years, with age zero indicating the beginning of the post-AGB evolution (Blöcker 1995b). (b) Radial run of the gas density of the AGB envelope at the start of the post-AGB evolution ($t = 11$ yrs). The low-density region immediately before 10^{18} cm corresponds to the mass-loss minimum during the last thermal pulse on the AGB around $t = -30\,000$ years (cf. part a).

mal pressure of the ionized halo matter drives a rapid expansion, i.e., a much larger 'dynamical' halo develops which is also bounded by a shell of compressed matter. This is illustrated in Figure 2b where the halo has nearly doubled its original size (from $6.5\,10^{17}$ to about $11\,10^{17}$ cm) within 3 000 years. In the meantime the planetary proper has surpassed the size of the old halo ($r = 6.5\,10^{17}$ cm). However, the luminosity drop of the central star towards the white-dwarf regime

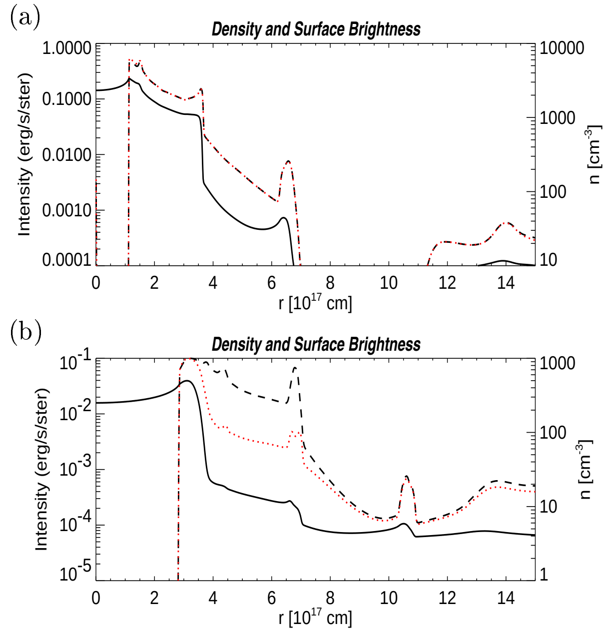

Fig. 2. Heavy particle (dashed) and electron densities (dotted) together with surface brightness (thick) in Hα+[N II] for two selected ages of our model sequence. (a) $t = 5\,037$ years, a double-shell planetary nebula with a limb-brightened halo, extending to $r = 6.5\,10^{17}$ cm. (b) $t = 7\,992$ years, a large part of the nebular shell has changed into a 'recombining' halo, and the border of the 'dynamical' halo is at $r = 10.5\,10^{17}$ cm.

(cf. Fig. 1a) causes the outer parts of the nebular shells to recombine, leading to a single-shell structure with *two* limb-brightened haloes, the inner one being the recombined outer nebular shell (Fig. 2b). Such a 'recombination' halo has recently been identified in NGC 2438 by Corradi et al. (2000).

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