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Ionization and its Structural Impacts on the Evolution of Planetary Nebulae

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Abstract. We review our present knowledge about the formation and evolution of planetary nebulae and evaluate the relative importance of photoionization and wind interaction. It turns out that heating by photoionization drives the expansion of a planetary nebula during its entire life, while wind interaction accelerates and shapes the inner regions only during the later stages of evolution. We found observational evidence that the transition from spherical AGB-wind structures to more aspherical ones must occur when the star begins to evolve slowly off the AGB.

1. Introduction

The existence of planetary nebulae (PNe) is a direct consequence of the complicated interplay between stellar evolution and mass loss by winds:

- Along the asymptotic giant branch (AGB) mass loss from the surface exceeds the burning rate at the base of the star's envelope and abruptly terminates the evolution. The remnant, i.e. the stellar core with a tiny amount of still unprocessed envelope material, contracts rapidly until the cooling path at the hot luminous side of the Hertzsprung Russell diagram is reached. The remnant is now a slowly fading hot white dwarf with no significant energy production by nuclear fusion.

- With the evolution of the stellar surface parameters the wind properties change, too. For an AGB star we have dense but slow winds with large outflow rates, driven by radiation pressure on small grains with momentum transfer to the gas. During the post-AGB contraction, mass-loss rates are lower by orders of magnitude, but the wind velocities are substantially higher. The driving of the outflow occurs now via radiation pressure on lines (cf. Pauldrach et al. 1988).

- The fast post-AGB wind runs into the slow material ejected at earlier times during the AGB evolution and is thought to create and shape what we call a planetary nebula (Kwok et al. 1978). But it is important to realize that not only this wind interaction is responsible for the shaping of planetaries. The radiation field of the hot central object ionizes and heats up the circumstellar AGB material, and the thermal pressure of the heated gas significantly modifies the appearance of planetary nebulae in addition to the interacting-winds pressure.

Both the radiation field and the wind power vary in line with the central-star evolution on time scales comparable to the dynamics of the circumstellar matter and demand a radiation-hydrodynamical treatment. Furthermore, any successful modeling of PN evolution must consider the time dependence of important physical processes, including the proper central-star evolution. This is a challenge for future works but indispensable for getting reliable results. First steps in this direction have already been made for relatively simple structures (e.g., Marten & Schönberner 1991; Mellema 1994, 1995). An extensive parameter study with the purpose to disentangle the influence of different initial configurations and various central star models on the formation and evolution of spherical planetaries has recently been conducted by Perinotto et al. (2004).

2. Ionization

The passage of an ionization front through gas has a twofold impact: structures become easily observable in optical emission lines, and the flow may also be modified due to the changing pressure conditions. The property of an ionization front depends on how the number of ionizations, $N_{\rm io}$, compares to that of recombinations, $N_{\rm re}$:

$N_{\rm io} \gg N_{\rm re}$: The ionization front is of type R, and its propagation speed is highly supersonic with no immediate structural effects.

$N_{\rm io} \simeq N_{\rm re}$: We are close to ionization equilibrium, the ionization front is trapped and preceded by a shock, and both are moving slowly (but supersonically) into the ambient neutral gas (type D). Initial structures are changed or even wiped out.

$N_{\rm io} < N_{\rm re}$: Recombination and cooling dominate, with a corresponding loss of pressure.

In planetaries, all three cases can be found, depending on their stage of evolution. At first, the tenuous stellar wind becomes ionized by an ionization front of type R. By entering the much denser AGB wind, the ionization front turns into a D-type one and is headed by a strong shock wave. The density decreases by expansion, and the ionization front may eventually overtake the shock, changing back into the R-type mode and quickly ionizing the wind material ahead of the shock. When the stellar luminosity becomes small, outer parts of the planetary may recombine, leading again to structural changes (cf. Corradi et al. 2000).

3. Ionization vs. Wind Interaction

Modern radiation-hydrodynamics simulation of the formation and evolution of PNe have revealed that the interplay between ionization and wind interaction leads automatically to double-shell structures as they are frequently observed (Marten & Schönberner 1991; Marten, Gesicki & Szczerba 1993; Frank 1994;

Mellema 1994). The study by Perinotto et al. (2004) confirms that the double-shell configuration is robust and lasts as long as ionization and wind power are strong enough.

In detail, heating by photo-ionization drives a shock wave into the ambient neutral medium (D-type ionization front) and creates the so-called *shell* (notation of Frank, Balick & Riley 1990). After being overtaken by ionization, the shock front with its density jump defines the outer edge of the planetary. In the centre, the bubble of hot, shocked central-star wind expands into the *shell* and compresses its inner region into a geometrically rather thin but dense shell, called the *rim* because it appears in projection as a bright ring, surrounded by the bigger but much fainter *shell*.

According to current models for the central-star wind which are based on the theory of line-driven winds of hot stars (Pauldrach et al. 1988), the wind power, $\dot{M}v^2/2$, increases steadily while the star crosses the HR diagram, reaching its maximum close to the turn-around point where both the stellar luminosity and the mass-loss rate begin to drop rapidly (Schönberner & Steffen, 2001; Perinotto et al. 2004). One expects thus the development of the double-shell structure while the central star is crossing the Hertzsprung-Russell diagram. Indeed, Chu, Jacoby & Arendt (1987) showed already that the double-shell configuration is typical for the more advanced stage of round/elliptical PNe. The size ratio between *shell* and *rim* becomes smaller during the course of evolution, indicating a steady acceleration of the *rim* by the bubble's pressure.

Young and optically thick planetaries, however, appear as rather homogeneously filled disks with only marginal traces of wind compressed matter (see, e.g., the HST image of IC 418). We conclude that wind interaction appears to be rather unimportant during the early, optically thick PN phase. The shell dominates the appearance and expansion of a planetary, and this expansion is powered by photo-heating and not by wind interaction.

During the proto-PN phase the central star is not hot enough to ionize the dense, receding AGB wind envelope. This situation is illustrated in Fig. 1 for a 10 000 K hot star whose wind is fully ionized, but the AGB wind is not. Any emission observed from such an object would come from the ionized stellar wind which fills in the cavity of the receding dense AGB-wind matter and will accentuate any asymmetry produced by the dying AGB or the new fast wind.

4. General Expansion Properties

For a better understanding of how and when asymmetries in planetary nebulae develop, a more general discussion about the expansion behaviour is quite helpful. In particular, it is useful to know how the PN expansion depends on the initial conditions like AGB wind speed, AGB envelope structure, assuming $\rho \propto r^{-\alpha}$, and the stellar parameters. We report here on some basic results, drawn from a study in which the following envelope parameters were varied: α, $\dot{M}_{\rm agb}$, $v_{\rm agb}$, and $M_{\rm cpn}$. The corresponding hydrodynamical model sequences are described in more detail in Jacob (2003) and Perinotto et al. (2004).

The early expansion is always characterized by a D-type ionization front, i.e. the high pressure of the ionized region drives a shock through the neutral AGB medium (cf. Sect. 2.). When the central star becomes hotter, the temperature of

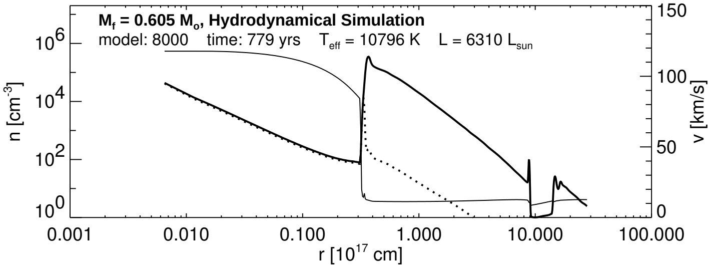

Figure 1. Radial run of the densities of heavy particles (thick line) and electrons (dotted line), and of the gas velocity (thin line) for a snapshot taken during the proto-planetary phase of a 1D hydrodynamical simulation of an AGB wind envelope. A detailed description of these models is given in Perinotto et al. (2004).

the H II region increases further, and the shock accelerates by an amount which depends on the heating time scale of the central star and the mass density of the AGB envelope, as demonstrated in Fig. 2 (left) for $\alpha = 2$. The shock acceleration depends, as expected, also on the density slope α (right panel of Fig. 2).

Once the ionization front passed the shock and changed to the R-type mode, the system has entered the 'champagne' flow phase for fully ionized, isothermal gases (Franco et al. 1990; Chevalier 1997; Shu et al. 2002). The size of the planetary nebula is now given by the radial position of the overtaken shock whose expansion rate is now *smaller* than during the previous acceleration phase (Fig. 3, left). It turns out that the shock expansion relative to the ambient flow is virtually *independent* of $\dot{M}_{\rm agb}$ and $v_{\rm agb}$, and for $\alpha = 2$ it is 13 – 14 km/s (see also Chevalier 1997, Tab. 1 therein).

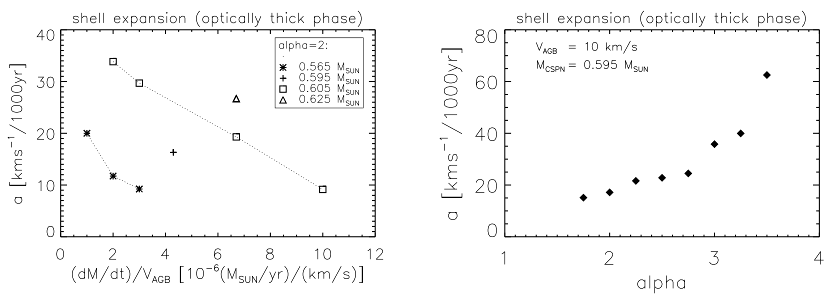

Figure 2. **Left**: Shock acceleration for a D-type ionization front in AGB flows with $\alpha = 2$ and different wind densities $\dot{M}_{\rm agb}/v_{\rm agb}$. The post-AGB evolutionary tracks used are labeled by their respective stellar masses (see inset). **Right**: Shock acceleration vs. α, the exponent of the radial power-law density distributions, for the 0.595 $M_\odot$ sequence. The initial wind envelopes are normalized to a particle density of $n = 10^5$ cm^{-2} at $r = 3 \cdot 10^{16}$ cm, with the inner boundary at $r = 4 \cdot 10^{14}$ cm and an initial velocity of $v_{\rm agb} = 10$ km/s.

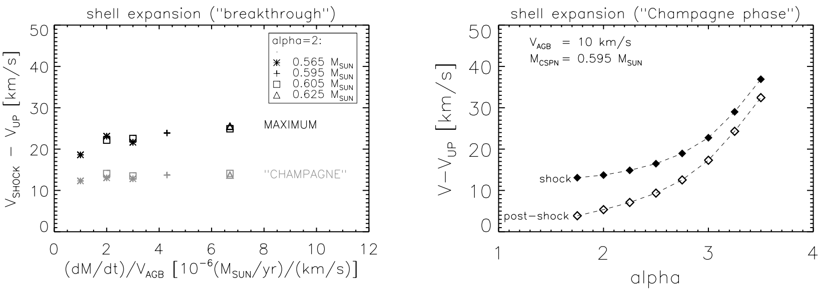

Figure 3. **Left**: For the same models as shown in Fig. 2, the maximum front speeds achieved and their values during the following 'champagne' flow phase are plotted relative to the ambient AGB flow. **Right**: Relative shock expansion and velocity jump across the front for 'champagne' flows vs. α.

Although the (relative) shock expansion properties of a 'champagne' flow are independent of the initial conditions like gas density and flow speed, they do depend on the slope of the density distribution, i.e. on α (Fig. 3, right). This figure gives not only the shock expansion rate relative to the upstream flow, but also the velocity jump across the front.

We emphasize that the post-shock gas velocity is a measurable flow variable, while the shock speed is not. For our reference case with $\alpha = 2$, the acceleration of the AGB wind by the shock is rather modest, and the difference to the shock speed is large, about 10 km/s. The shock strength increases with α, and the post-shock gas velocity approaches that of the shock. It appears that only for at least $\alpha \simeq 3$ the shock accelerates the (ionized) AGB wind to an amount consistent with observed gas velocities in PNe. Such a large α, however, means also that the mass-loss rate of an AGB giant must significantly *increase* towards the end of its evolution.

Contrary to the *shell* which is thermally-driven by photo-heating, the *rim* can be considered to be a wind-blown bubble whose size can be approximated by

$$R_{\rm rim} \propto \left(\frac{L_{\rm w}}{\rho_0}\right)^{\left(\frac{1}{5-\alpha}\right)} \cdot t^{\left(\frac{3}{5-\alpha}\right)},$$

where $L_{\rm w}$ is the wind power or mechanical luminosity (equ. 3.1 of Koo & McKee 1992). The basic assumptions are power-law density distributions, specified by α, and a constant stellar wind. Although these assumptions are hardly valid for PNe, the relation given above appears to be a useful approximation for the expansion properties of the *rim* (Jacob 2003).

5. Comments on Non-Sphericity

It is clear that all the considerations made in the previous section about the expansion properties of ionized gases and how they depend on the structure of the environment cannot replace real multi-dimensional (at least 2D) simu-

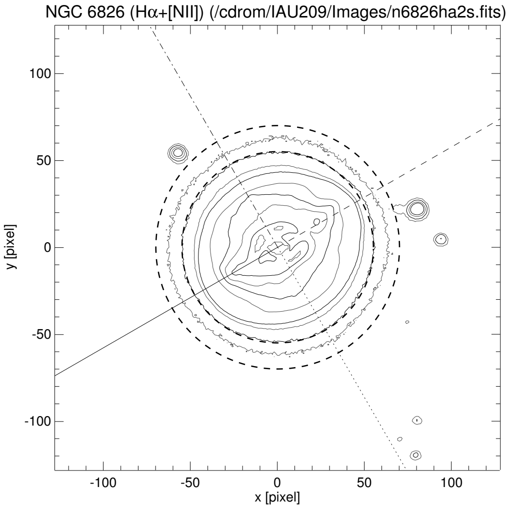

Figure 4. Image of NGC 6826 in Hα + [N II] from the catalogue of Corradi et al. (2003). Plotted are isophotes of the PN and its inner halo, together with two dashed circles centered on the star. The lines along the directions of the semi-axes indicate the cuts taken to determine the radial dependence of the halo's surface brightness.

lations since, for instance, lateral pressure gradients are not considered. Our study can, however, give some insight into the global structure and behaviour of asymmetrical systems.

Young and optically thick PNe are useful for constraining any differences between polar and equatorial mass-loss rates. From our parameter study we conclude that a D-type ionization front will trace and enlarge these asymmetries if they are existing. Most young PNe are only mildly elliptical, which indicates that differences between polar and equatorial mass-loss rates cannot be very large. The very existence of D-type ionization fronts at the poles (where the AGB wind densities are assumed to be lower) limits the polar mass-loss rates: they must be larger than about $3 \cdot 10^{-5}$ $M_{\odot}$/yr (Perinotto et al. 2004). On the other hand, existing 2D simulations prefer to have only $1 \cdot 10^{-5}$ $M_{\odot}$/yr or less at the poles. In these cases a D-type front cannot persist for long at the polar regions, and the outbreaking ionization front produces planetaries of bipolar shape (Mellema 1995, 1997).

If the whole system is optically thin and in the 'champagne' flow phase, the situation is different. The *shell's* expansion speed is ruled by the actual radial density *gradient* only, not by the density itself, and will change accordingly with α. The stellar wind compresses the inner regions of the shell into the *rim*, and any existing asymmetry of the expanding shell will correspondingly produce a highly asymmetric rim structure which will persist in time.

Finally we address the question at which evolutionary phases the turnover to asymmetrical structures may actually occur. It is well known from observations that the halos of PNe are in general spherical structures (cf. Corradi et al. 2003), and that the degree of asymmetry increases towards the star: the rims exhibit usually the largest deviations from sphericity.

The planetary NGC 6826 is a good example (Fig. 4). The circles show that the inner halo is quite spherical, in contrast to the *shell*. The *rim* close to the central star shows the largest deformations. The average radial dependence of the surface brightness (SB) within the circles, taken along the semi-axes, can be represented by $d \log SB / d \log r \propto -5.5$, which implies $\rho \propto r^{-3.25}$ and is a direct proof that the mass-loss accelerates towards the end of the AGB (cf. Sect. 4.). The *shell* is obviously now expanding into a nearly spherical environment, and its appearance will therefore become more round in the future. Based on the kinematical age of NGC 6826 of about 5 000 years and its position halfway towards the white-dwarf regime (Corradi et al. 2003), one may conclude that the development of asymmetrical structures must have started while the star was already evolving off the AGB.

Whatever the reason is, the transition from a spherical to a non-spherical stellar environment appears to be triggered by the contraction of the star!

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