PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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The Formation and Evolution of Planetary Nebulae

Detlef Schönberner and Matthias Steffen

Astrophysikalisches Institut Potsdam, Germany

Abstract. We review our present knowledge about the formation and evolution of planetary nebulae and discuss the relevant processes responsible in creating and shaping planetary nebulae out of a cool AGB wind envelope. Based on 1D simulations we show that a hydrodynamical treatment along the upper AGB leads quite naturally to more realistic starting configurations for planetaries with density slopes steeper than r^{-2}. Taking into account photoionization and wind interaction in a realistic manner, the hydrodynamics of post-AGB wind envelopes leads to density structures and velocity fields in close resemblance to observations of spherical or elliptical planetary nebulae.

1. Introduction

The very existence of planetary nebulae (PNe) is a direct proof that stars which do not explode as a supernova lose a significant fraction of their mass immediately before they end their active nuclear live as a white dwarf. To understand how they form and evolve is of paramount importance for the whole field. For instance, PNe enrich the interstellar medium by freshly synthesized nuclei, thereby providing indispensable hints for the nucleosynthesis within stars, they contain information of the mass-loss processes that rule the late asymptotic giant branch (AGB) evolution, and last but not least, PNe are very useful in probing mass distributions of galaxies from their kinematics and in establishing a reliable Hubble constant by their luminosity function.

2. Typical Structures of Planetary Nebulae

If we dismiss all bipolar objects, the gross structure and (internal) kinematics of a typical planetary nebula can be described as follows:

- There are one or two, in most cases axisymmetrical, shells which enclose a rarefied region containing the central star and expand rapidly outwards. The frequency of double-shell structures is high (cf. Manchado, these proceedings), and the outer shell is always the fainter one. In many cases an even fainter, rather extended spherical shell exists, the so-called halo (see Corradi, these proceedings; for a more precise definition of the different shells and haloes; cf. also Chu, Jacoby, & Arendt 1987).
- The flow velocities increase very often with distance from the central star (Wilson 1950; Solf & Weinberger 1984), and in the cases where also the velocity

within the outer faint shell has been determined, it is found to be distinct from that of the inner, bright shell in the sense that it expands, with few exceptions, faster (Sabbadin, Bianchini, & Hamzaoglu 1984; Gęsicki, Acker, & Szczerba 1996; Gęsicki et al. 1998).

The shells, however, do not expand freely since we observe central gaps and sharp outer boundaries. When Mathews (1966) performed the first, rather simple hydrodynamical simulations of expanding gas shells around central stars it became clear that one has to invoke a certain mass outflow from the stellar surface (now called *wind*) in order to keep the gas from falling back! A significant break-through in understanding the basic physics underlying the shaping of planetary nebulae occurred when Kwok, Purton, & Fitzgerald (1978) introduced the concept of interacting stellar winds where a fast but tenuous central-star wind snowplows into the slow but dense AGB wind, thereby setting up a dense shell of compressed gas headed by a shock. A further important ingredient for the shaping is the heating of the gas by photo-ionization due to the hot central star (Schmidt-Voigt & Köppen 1987).

There are still considerable uncertainties about i) the origin of axisymmetric structures, ii) the origin and evolution of clumps (cf. Dwarkadas & Balick 1998) or of the so-called FLIERS (Balick et al. 1998), and ii) the bipolar outflows studied in detail by e.g. Miranda & Solf (1992).

Although perfectly round PNe are quite rare, studies based on spherical systems appear to be important for at least two reasons. The first is a more physical one: the use of spherical models allows a detailed study of basic physical processes without having to worry about influences caused by non-spherical structures. The other reason is a technical one: the presently available computing power is too limited to follow the evolution of non-spherical model planetaries over their whole life with sophisticated physics and good spatial resolution. It is expected that basic physical processes work similarly in systems with a more complex geometry. They set the stage for the other phenomena responsible for the development of non-spherical structures and should always be considered.

3. The Basic Physical System and its Modeling

The evolution of an AGB star is determined by mass loss from its surface by strong winds: The mass-loss rate exceeds the (hydrogen) burning rate at the base of the stellar envelope and abruptly terminates the evolution. The remnant, i.e. the stellar core with a tiny amount of still unprocessed envelope material, contracts rapidly bluewards into the planetary-nebula domain. Eventually the burning shells extinguish and the white dwarf cooling path is reached where the evolution virtually stops. The post-AGB evolutionary time scale is extremely sensitive to the remnant's mass (see Blöcker, these proceedings, for a more detailed discussion). For the typical case of a 0.6 $M_\odot$ remnant the contraction across the Hertzsprung-Russell diagram to a white dwarf occurs within $\sim 10\,000$ years, which is less than the dissipation time of the expanding AGB envelope.

With the evolution of the stellar surface parameters the wind properties change, too. For an AGB star we have winds driven by radiation pressure on small grains with momentum transfer to the gas. The outflow rates depend on the star's luminosity and effective temperature (cf. Sedlmayr & Dominik 1995; Arndt, Fleischer, & Sedlmayr 1997) and range between about 10^{-7} and up to 10^{-4} $M_\odot$, with outflow velocities from 5 to 25 km/s that are close to or even below the surface escape velocity. During the post-AGB contraction, mass-loss rates are lower by orders of magnitude, but the wind velocities are substantially higher since they scale with the surface escape velocity. The radiation pressure on lines drives the outflow, and typical values are 10^{-8} $M_\odot$/yr for the rate and up to few thousands of km/s for the velocity (cf. Pauldrach et al. 1988).

The driving force for the formation and evolution of a PN is obviously the fast blueward evolution of the central stellar object with its concomitant changes of the radiation field and wind power: The fast central-star wind runs into the slow AGB matter ejected at earlier times, compresses it into a shell of increasing density and creates and shapes thereby what we call a planetary nebula (Kwok, Purton, & Fitzgerald 1978). But not only wind interaction is responsible for shaping planetaries. The radiation field of the hot central star ionizes and heats up the wind-compressed AGB material, and the thermal pressure of the heated matter competes with the flow pressure in modifying the appearance of PNe significantly. The radial distance at which this happens depends mainly on the transition time of the remnant from the tip of the AGB towards the hotter region of the HR diagram, and to a lesser extent on the relative flow velocities.

Simply speaking, a typical PN consists of an evolving star, a wind driven from its surface, and a circumstellar envelope of previously ejected stellar material. The interaction of the stellar wind with the circumstellar envelope produces shock waves, while the evolving star produces ionization/recombination, and, indirectly, shocks as well. It is clear that any satisfying description of the formation and evolution of PNe must involve a solution of the hydrodynamical equations together with a fully time-dependent treatment of all the physical processes involved, including the central-star evolution. This is, even with the assumption of spherical flows, a time consuming task, given the large number of possibilities for combining mass-loss rates, wind speeds and central-star masses into a useful model.

Important achievements in reaching this goal have been gained by the works of Schmidt-Voigt & Köppen (1987), Marten & Schönberner (1991), Frank (1994), Mellema (1994). The only work considering 2D models is that of Mellema (1995). Provided the slow AGB wind is not too tenuous and the fast central-star wind behave similar like predicted by Pauldrach et al. (1988), the main points are:

• Once the temperature of the central star has become large enough, the thermal pressure of ionized AGB material drives a shock wave into the ambient (neutral or ionized) matter and creates an expanding *shell*[2], where the radial position of the shock front, $R_{\rm pn}$, which also constitutes the outer physical boundary of the whole structure, is mainly determined by the balance of the shell's thermal pressure, $P_{\rm shell}$, with the ram pressure, $V_{\rm agb}^2\,\rho_{\rm agb}$, exerted by the ambient medium,

$$P_{\rm shell} \simeq (\dot{R}_{\rm pn} - V_{\rm agb})^2\,\rho_{\rm agb}.$$

The speed and position of the outer PN boundary depends thus also on the mass-loss history along the AGB. The mass embraced within $R_{\rm pn}$ is steadily

[2]We follow the notation of Balick et al. (1998).

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growing with time at the expense of the still dynamically undisturbed AGB wind.

• The fast central-star wind with $\dot{M}_{\rm pagb}$ and $V_{\rm pagb}$ does not interact directly with the AGB matter. Instead the wind's kinetic energy thermalizes through a shock and adds to the energy and matter content of hot, shocked wind material emitted at earlier times. The thermal pressure, $P_{\rm hb}$, of this *hot bubble* of very tenuous gas drives the inner edge of the planetary, giving rise to a shell of compressed gas, the *rim*. Since the bubble's temperature, $T_{\rm hb}$, is controlled by the kinetic energy flux of the central-star's wind,

$$P_{\rm hb} \propto \rho_{\rm hb}\, T_{\rm hb} \propto \int \dot{M}_{\rm pagb}\, V_{\rm pagb}\, dt,$$

the evolution of the central star determines the kinematics of the inner parts of middle-aged PNe.

• Ionization in conjunction with wind interaction leads unavoidably to a typical double-shell structure where the (outer) shell is much fainter than the rim. Since rim and shell are driven by different physical processes their expansion properties are distinct such that the shell expands faster than the rim, as is observed in most PNe (cf. Sect. 1). The whole PN structure has no resemblance with the original density and velocity distribution of the former AGB envelope, i.e. planetaries *do not* contain direct information on the details of previous mass-loss phases (cf. poster by Perinotto et al., these proceedings)! Only the halo, i.e. the region ahead of the shell contains information on previous mass-loss episodes (see the contributions of Steffen and Corradi, this volume). The observed radial brightness distributions of shells and haloes suggest, when compared with the model predictions, that the mass loss has increased towards the end of the AGB evolution (Plait & Soker 1990; Mellema 1994).

All attempts to model the evolution of planetary nebulae face the problem of selecting the proper initial configuration of the AGB envelope, i.e. its density distribution and velocity field. Since practically nothing is known, usually rather simple conditions are assumed, viz. mass outflow with constant speed and rate. Stellar evolution theory, however, predicts on the AGB large luminosity variations (up to a factor three) during a thermal pulse, followed by a more gradual luminosity increase towards the next pulse instability (cf. Blöcker, these proceedings). Since according to Arndt, Fleischer, & Sedlmayr (1997) the winds depend on the stellar parameters one expects corresponding changes of outflow rates and speeds during a thermal pulse cycle. Thus gasdynamical simulations of AGB wind envelopes along the upper AGB could certainly give very useful informations about initial conditions for the PN formation.

A first step into this direction has been reported by Schönberner et al. (1997). The stellar outflow is assumed to be spherically symmetric and is computed for time-dependent values of stellar mass, luminosity, effective temperature *and* mass loss utilizing the stellar evolutionary models of Blöcker (1995). The equations of hydrodynamics are solved for the gas and the dust component, coupled by momentum exchange due to dust-gas collisions. A more detailed description of this fully implicit radiation hydrodynamics code, including comparisons with solutions for stationary outflows, has been given by Steffen et al. (1997) and Steffen et al. (1998).

4. Typical Evolutionary Stages

The models of Steffen et al. (1998) are based on the 3 $M_\odot$ sequence of Blöcker (1995), computed through all evolutionary phases with mass loss towards the white dwarf configuration (Fig. 1). The final models are used as input for an

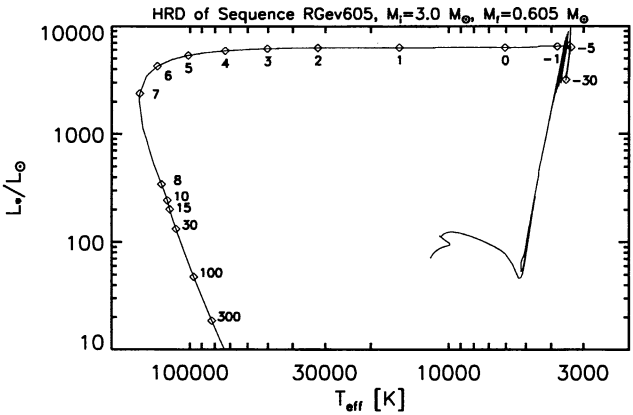

Figure 1. The complete evolutionary path for a main-sequence star of 3 $M_\odot$ until it ends up as a (hydrogen burning) 0.605 $M_\odot$ central star (or white dwarf, respectively). Tick marks correspond to ages in 10^3 years, and the post-AGB phase starts at time zero, defined by a rapid decrease of the AGB mass-loss rate (Blöcker 1995).

explicit radiation hydrodynamics code based on a second-order Godunov-type advection scheme in order to follow their evolution into the domain of planetaries. The radiation part of this code considers time-dependent ionization, recombination, heating and cooling of six elements (H, He, C, N, O, Ne) with all of their ionization stages. More details are given in Perinotto et al. (1998). The treatment of the central-star wind followed that of Marten & Schönberner (1991) and is based on the theory of Pauldrach et al. (1988).

As an example we show in Fig. 2 a model in the so-called transition or *proto planetary-nebula* stage (PPN). The structure of the detached envelope is determined by the mass-loss history at the tip of the AGB: a large density minimum ($r \simeq 10 \cdot 10^{17}$ cm) caused by the last thermal puls about 40 000 years before the end of the AGB, and inwards a density increase with $r^{-3 \dots -4}$ due to the strong mass-loss increase towards the end of the AGB (see Steffen et al. 1998) This envelope structure is of relevance for interpreting the haloes found in many PNe (cf. Steffen & Schönberner, these proceedings). At the particular time depicted in the Fig. 2, 779 yrs after the end of the AGB, the central-star wind is already fully ionized, whereas the original AGB envelope is still neutral, except for its innermost regions where both flows interact. The image of a PPN (or very young PN) in such a stage would show only the central-star wind with a sharp outer edge, possibly shaped by any existing density irregularities of the inner AGB material generated while the AGB wind ceased.

Fig. 3 illustrates how the morphology of our models change with time along the evolution towards the white-dwarf domain. At age = 1 837 yrs (upper left) ionization has already created a small but bright shell limited by a D-shock

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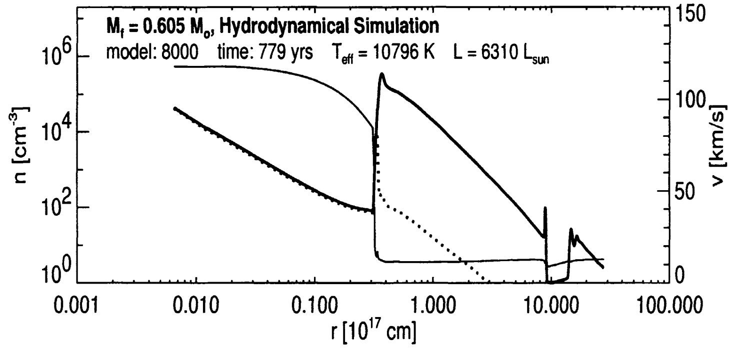

Figure 2. Radial structure of a typical PPN from our hydrodynamical simulations. Given are the heavy particle density (thick), the electron density (dotted), and the velocity (thin). The interaction zone between AGB and central-star wind is at $r = 0.3 \cdot 10^{17}$ cm, but the *hot bubble* has not yet formed because of the still too slow central-star wind ($\simeq$ 100 km/s). At $r = 9 \cdot 10^{17}$ cm the AGB wind is interacting with the low density material emitted during and after the last thermal pulse, leading to a thin shell of compressed gas.

wave that keeps the photons trapped. About 1 900 years later (upper right), the ionization has broken through the shock, the *shell* develops, expands and gets further accelerated (up to $\approx$ 40 km/s) due to the steeper than ρ^{-2} density slope. At about this time, the structure becomes dominated by the central-star wind: it compresses the inner edge of the shell into a bright *rim* giving rise to a double shell structure, as is typical for many round and elliptical PNe (Chu, Jacoby, & Arendt 1987; Stanghellini & Pasquali 1995). At age = 6 365 yrs (lower left), the brightness contrast between rim and shell has further increased by the combined action of the shell's expansion into the AGB wind and compression by the hot bubble. Because of the particular density profile of the AGB envelope, the shell's surface brightness decreases linearly with radius.

When the central star's luminosity has dropped rapidly to only a few 100 $L_\odot$, recombination within the shell reduces its brightness to about halo values (age = 8 716 yrs, lower right) and ends the double shell phase that lasted for about 4 800 yrs, i.e. for a quite substantial fraction of a typical PN life time. Though the shell looks like a halo, it is of course not a (real) halo: the matter within the recombined shell continues to expand and compresses the AGB gas into a dense but thin shell, leading to substantial limb brightening. Tylenda (1986) coined the term *recombination halo*, and Corradi et al. (2000) showed that the halo of NGC 2438 is indeed due to recombination.

In general, our radiation-hydrodynamics models have a very close resemblance to reality: morphologies and kinematical properties of the models match very well those of individual objects. In Fig. 4 we compare the morphologies of three well known PNe with models from our hydrodynamics simulations. Relative sizes and intensities of the rims and shells are astonishingly well reproduced, and the three displayed planetaries represent obviously an evolution of their morphology where the ratio between the mean rim and shell brightnesses steadily increases, and where the shell develops into one with a linear radial intensity decrease. The evolution of the morphology complies with the central-star prop-

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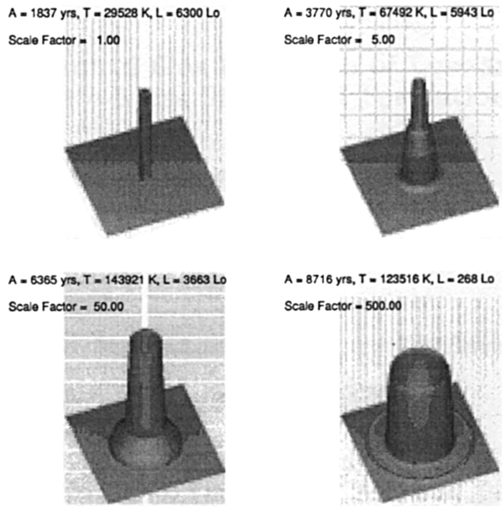

Figure 3. 3D representation of the surface-brightness distributions in Hα of selected models along the post-AGB track displayed in Fig. 1. The models are labeled by their post-AGB age, and the effective temperature and luminosity of their central stars. The scale factor indicates the decrease of the surface brightness with time.

erties: NGC 6826 has a rather cool central star ($T_{\rm eff} = 50\,000$ K), whereas those of NGC 3242 and NGC 1535 are much hotter ($T_{\rm eff} = 70\,000 \ldots 75\,000$ K).

From the existing simulations it appears now that we understand the basic principles of the formation and evolution of round/elliptical PNe. PNe are definitely not formed by a sudden mass-loss ejection, maybe triggered by a thermal pulse, instead they are created smoothly by the action of stellar winds with different properties, supported by the radiation field of an evolving central star. The PN morphology develops with time, and the detailed behavior of the surface brightness demands that the mass-loss rate *increases* substantially towards the tip of the AGB. For any modeling, it is absolutely necessary to consider the whole physical system, i.e. the circumstellar envelope as generated by stellar winds *and* the central star, consistently and fully time-dependent.

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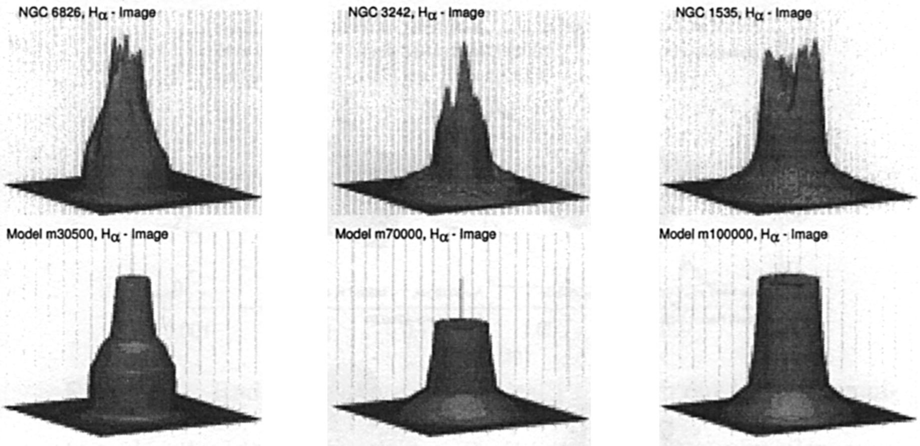

Figure 4. Hα surface-brightness profiles of NGC 6826 (left), NGC 3242 (middle), and NGC 1535 (right) compared with appropriate models taken at ages 3770, 5590, and 6366 yrs of the post AGB sequence from Fig. 1. These models are *not* fits to the observations!

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