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Stellar paleontology using planetary nebulae

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Abstract. Photoionization and winds interactions cause a complete redistribution of the circumstellar density in the brightest, innermost regions of planetary nebulae, cancelling all the information about the mass loss history of the AGB progenitors. On the contrary, the faint extended haloes that are observed around planetary nebulae can still be used to trace back the AGB mass loss history. In particular, the edges of these haloes are the imprint of the last AGB thermal pulse, and can be used to derive timescales and mass loss rates for the latest AGB evolution. I describe below the recent advances on this topic.

Key words. Planetary nebulae – AGB stars – hydro-modelling

1. Introduction

That planetary nebulae (PNe) have varied morphologies it is known since long time ago (I have in mind, for instance, some beautiful drawings by Padre Angelo Secchi). However, there is no doubt that most of the advances in the field were achieved in the last 15 years, when the highly articulated structure of PNe was revealed by a large number of high quality images taken from the ground (Balick 1987; Schwarz et al. 1992; Manchado et al. 1996) or with the Hubble Space Telescope (see e.g. Balick et al. 1998).

The morphological components of PNe can be divided into two groups: *i)* large-scale components, like spherical shells, haloes or bipolar lobes, and *ii)* small-scale structures, like jets, low-ionization knots, filaments, cometary globules, etc. (see e.g. Gonçalves et al. 2001).

In this contribution, I do not discuss the small-scale components of PNe, although they might hide important information about the mass loss mechanisms working in evolved stars. Nor do I discuss large-scale components that deviate significantly from the spherical symmetry, like PNe with bipolar lobes, which although extremely interesting by themselves represent a minor fraction (some 15%) of the total sample of known Galactic PNe. The main topic covered here is the interpretation of the observations of spherical (or slightly ellipsoidal) *multiple* shells in PNe, as understanding the spherical case is the first crucial step toward a comprehension of the basic mass loss and radiative phenomena which occur during the late asymptotic giant branch phase (AGB) and beyond. A more extensive discussion can be found in Corradi et al. (2003, hereinafter CSSP03). This work is done in collaboration with Detlef Schönberner and Matthias Steffen in Potsdam, and Mario Perinotto in Firenze.

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2. Key processes in the formation of planetary nebulae

Three main physical processes are at work in shaping PNe.

The first one is the AGB wind. Being characterised by a heavy mass loss rate, up to 10^{-4} $M_{\odot}$ yr^{-1}, and a low expansion velocity, of the order of the escape velocity from the surface of AGB stars (say between 5 and 25 $km\,s^{-1}$), it is usually named as the "slow massive AGB wind". This wind is driven by a combination of mechanical input from stellar pulsations and radiation pressure on dust grains, which in turn transfer moment to the gas by collisions. The mass loss rate and outflow velocity is modulated all along the AGB by the long-term increase in stellar luminosity and, on shorter timescales but with a larger magnitude, by the luminosity peaks and dips during and after helium shell flashes (thermal pulses). In our models, we used the semi-empirical AGB mass loss history from Blöcker (1995). In order to follow the evolution of such outflows till the end of the AGB and beyond, proper time-dependent hydrodynamical calculations need to be ran. This was done by Steffen et al. (1998) who also realised the importance of the dust composition (oxygen or carbon based), owing to the different radiative absorption efficiency, and thus acceleration properties, of the two types of dust.

The other important processes take place in the post-AGB phase. At this stage, a wind driven by radiation pressure on lines is produced by the compact stellar remnant. It has a high velocity of several thousand $km\,s^{-1}$ (the escape velocity from the core), but it is much more tenuous than the AGB wind, having a mass loss rate around 10^{-8} $M_{\odot}$ yr^{-1} (Pauldrach et al. 1998).

This highly supersonic wind rapidly reaches the regions occupied by the slowly expanding, previous AGB wind and causes a strong shock to propagate through it. The shock compresses matter in a thin shell that appears as the bright portion of the PN when is photoionized by the central star. This two-wind process is a formidable physical problem, as the momentum and energy ratio between the two winds is enormous; it is like blowing with your own breath on a high density wall! Again, proper hydrodynamical modelling is necessary to follow the evolution of the circumstellar matter under such circumstances.

The third process playing an important role in the dynamical evolution of PNe is the energetic radiation from the hot stellar remnant. This is clearly responsible of making the nebulae bright via photodissociation first and then photoionization and reprocessing of the stellar ionizing continuum into specific emission lines from the atomic gas. But it also has important dynamical effects, as the temperature and pressure discontinuities between the ionized and neutral regions (ionization fronts) also cause the formation of expanding/contracting shock waves that redistribute matter around the star.

State-of-the-art radiative/hydrodynamical simulations of the post-AGB evolution of the nebulae with time-dependent stellar evolution parameters are presented by Schönberner & Steffen (2003) and Steffen & Schönberner (2003), and form our theoretical base for the comparison with the observational dataset.

3. Interpreting the multiple shells of planetary nebulae

Many spherical and elliptical PNe are known to display *multiple* distinct shells around their central stars (e.g. Chu et al. 1987), although the nomenclature used in the literature to indicate the various shells is varied (to say it nicely) and horrendously inhomogeneous.

The modern radiation-hydrodynamical simulation mentioned above provide us with the tool to understand the formation of these multiple shells. According to the models, we can draw a sketch of a 'standard' PN, that is illustrated in Fig. 1 by the case of NGC 6826. Around the central star, that is evolving to high temperatures at an approximately constant luminosity, the combined action of photoionization and wind interaction causes the formation of a nebula composed of two shells. The bright inner one, the so-called **rim**, is the result of the interaction of the fast post-AGB wind with the slow AGB one. Outside the rim, an outer fainter **shell** is set-up

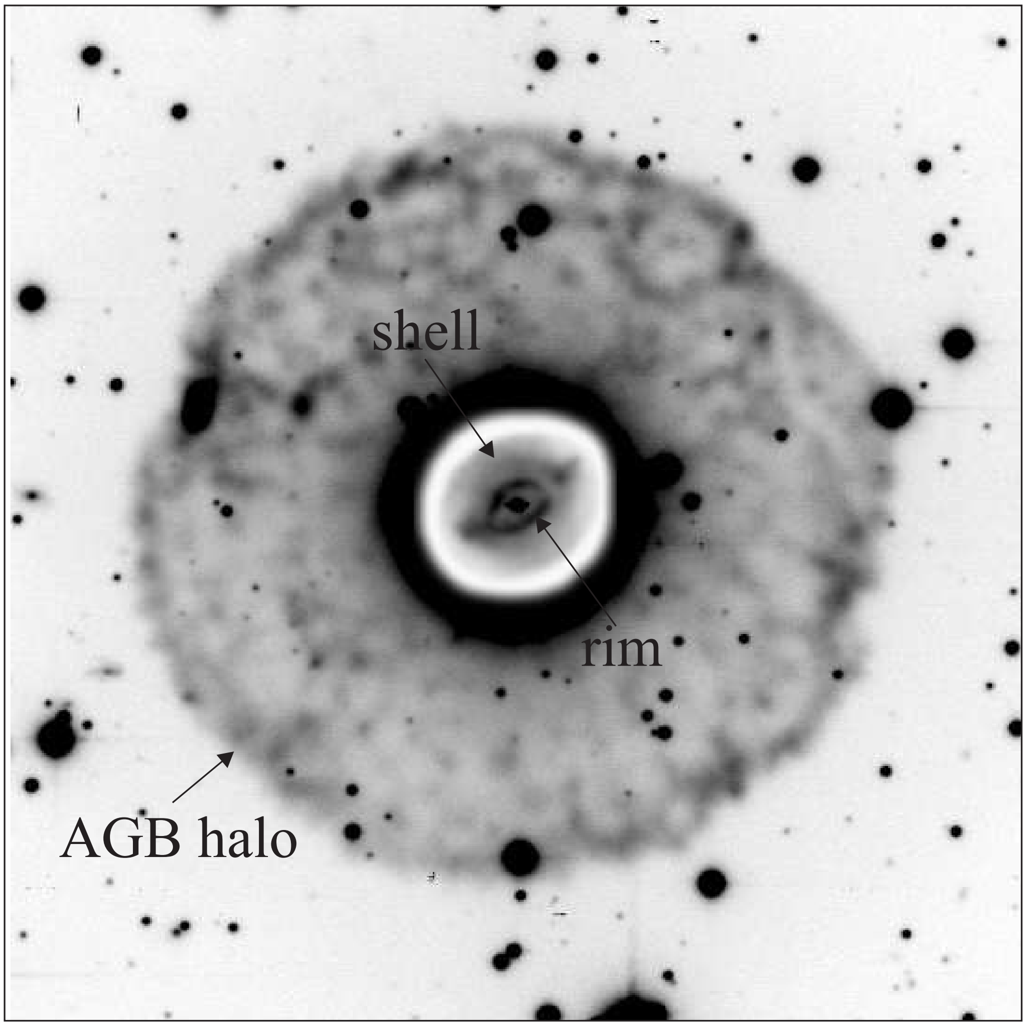

Fig. 1. [OIII] image of NGC 6826, obtained at the 2.5m Isaac Newton Telescope, on a log intensity scale. The picture is a combination of a short (inner inset image) and a deep (full picture) exposures.

by photoionization during the early stages of evolution. The shell has a typical linearly decreasing surface brightness profile.

Around the inner double-shell bright nebula, a large photoionized halo is expected to be found. This halo has a surface brightness some 10^3 times fainter than the inner rim+shell, and its (usually limb-brightened) edge is the signature of the last thermal pulse on the AGB. For this reason, we call this extended shell as an **AGB halo**.

This simplified picture applies to a large fraction of the life of a PN, except for its earliest and latest evolutionary phases. In the early phases, the power of the fast wind from the relatively cold central star is still small, and the PN consists only of one shell set-up by photoionization (Schönberner & Steffen 2003). In the latest stages, another important dynamical effect occurs when hydrogen burning on the central star ceases and its surface luminosity drops by about one order of magnitude within a short lapse of time of 1 000 years. Due to the lack of ionizing photons, recombination sets in the outer regions, and the loss of pressure in the recombined zone makes the region to collapse into a thin, high-density shell that might be confused, on a pure morphological basis, with a real AGB halo. These are called **recombination haloes**, and clearly do not trace any AGB mass loss event. The existence of such recombination haloes has been convincingly (hopefully) demonstrated by Corradi et al. (2000) in the case of NGC 2438.

Thus, while the regions of the inner rim and shell have completely lost the memory of the AGB mass loss history, their density structure being completely determined by wind interactions and photoionization, AGB haloes (but not recombination ones) still contain information about the AGB mass loss history and can be used to derive some important properties of the latter. For instance, the halo kinematical age is a measure of the time elapsed since the last AGB thermal pulse.

4. The observational database

With this picture in mind, we have completed an imaging search for haloes around PNe using several telescope at ESO La Silla (like the 3.5m NTT and the 1.54m DAN) and at La Palma (the 1m JKT, the 2.5m INT and the 2.6m NOT). Deep [O III]λ5007 and/or Hα+[N II] images have been obtained, aimed at getting as faint as at least 10^{-3} the surface brightness of the rims of the target PNe. An extensive bibliographical search was also produced. The whole dataset (new data + literature) is presented in CSSP03, and the original images are available at http://www.ing.iac.es/~rcorradi.

The various shells observed in the PNe were then classified according to the predictions of the models, and an updated, comprehensive sample of AGB haloes was drawn out. The final sample consists of:

- 21 PNe with *circular or slightly elliptical AGB haloes*. These are fairly circular, allowing a straightforward measure of their size and surface brightness profile.
- 6 PNe with *highly asymmetrical AGB haloes*. Haloes that otherwise would be classified as genuine AGB haloes were put into this separate category because have a significantly aspherical morphology. Their shape might be determined by "internal" factors, like stellar rotation, magnetic fields or binary interactions in their AGB progenitors, or more likely by "external" ones, such as interaction with the interstellar medium for fast moving progenitors (Villaver et al. 2003).
- 5 PNe with *candidate recombination haloes*. They contain low luminosity stars, i.e. are in an evolutionary status in which recombination haloes are expected to form.
- 17 PNe with *uncertain or peculiar cases*.
- 11 PNe with *non-detections*, i.e. no halo is found to a level of $\lesssim 10^{-3}$ the peak surface brightness of the inner nebula.

Our survey roughly doubles the number of genuine AGB haloes previously known. Examples of the haloes are illustrated in Fig. 2. Note that a common characteristic of all ionized haloes observed is that they have a rather sharp edge and display substructures like knots, filaments, ridges, or azimuthal fluctuations of the surface brightness. Some of them are particularly knotty or filamentary (see e.g. CN 1-5 in Fig. 2).

5. Main results

So far, we have attempted a detailed comparison of the halo surface brightness profiles with our hydrodynamical models for two PNe, NGC 6826 and NGC 2022. The structure of the halo of NGC 6826 is nicely fitted by the set of models that consider a carbon-rich dusty AGB wind (Corradi et al. 2003b), as illustrated in Fig. 3. This is consistent with the finding that the central star of NGC 6826 is a carbon star (C/O=4.5 by number). The modelling also shows that mass loss increased substantially towards the end of the AGB, that the outer edge of the halo of NGC 6826 is defined by the final helium-shell flash on the AGB,

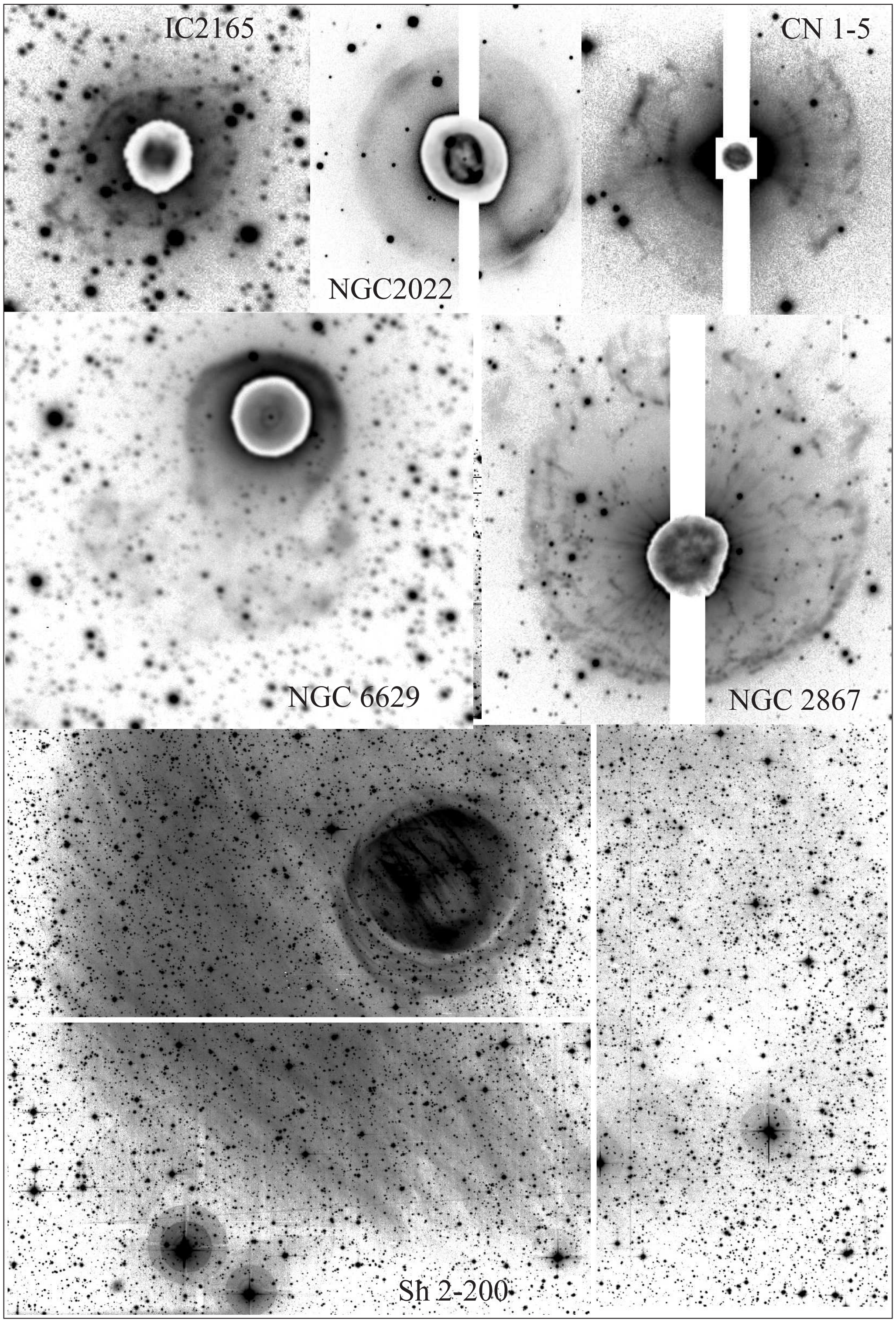

Fig. 2. Examples of haloes around PNe (from CSSP03). As in Fig. 1, pictures are combinations of short (inner insets) and deep exposures. The white bands in some images correspond to the gap between CCDs in mosaic cameras like SUSI2 at the NTT or the INT WFC.

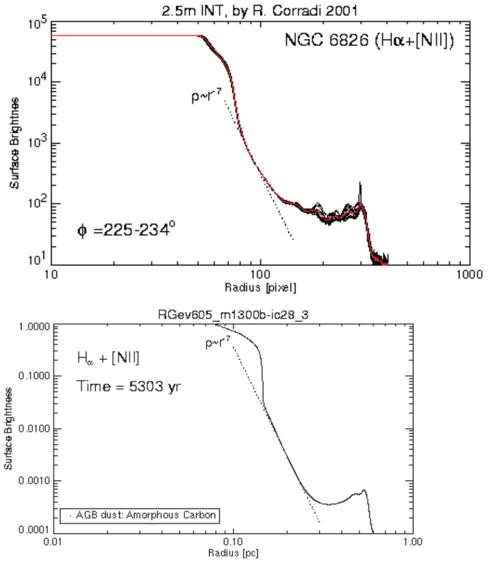

Fig. 3. Top: surface brightness profile along several directions of the halo of NGC 6826 (see also Fig. 1). Bottom: model predictions for a carbon-rich dusty AGB wind. Note the excellent agreement with the observations.

that the time elapsed since the last helium-shell flash – i.e. the kinematical age of the halo – is of ~33 000 yr, and that the central star of NGC 6826 is most likely still powered by hydrogen burning. The halo of NGC 2022 is instead better modelled by the models with oxygen-rich dust. Thus this kind of modelling proves to be an excellent tool to recover the mass loss rate and timescales at the tip of the AGB, and with this objective a thorough analysis of other individual PNe is in progress.

The largely improved sample of PNe with haloes also allowed us to investigate basic statistical properties (CSSP03). It is found that, as predicted by models, ionized AGB haloes are a quite common phenomenon in PNe, having been found in 60% of elliptical PNe for which adequately deep images exist. Another 10% shows possible recombination haloes. Non-detections are also very interesting, as some of the PNe in this category are in an evolutionary stage where an ionized halo *must* (of course according to the models) be observable. We are planning to take even deeper images to see whether the halo is fainter than expected, otherwise these non-detections would reveal a significantly different mass loss history for their AGB progenitors, possibly related to a different stellar initial mass.

To check this latter point, we have also tried to locate our observed PNe in the H-R diagram, a task that is always difficult to do owing to the general uncertainty in the distances to PNe. In spite of this limitation, we found that PNe possessing AGB haloes seem to follow the standard mass distribution of the global sample of Galactic PNe, with most masses being clumped around 0.6 $M_\odot$. Recombination haloes correspond to objects located in the fading part of their post-AGB evolutionary track (but this is just one of our criteria to select recombination haloes). The central stars of PNe with highly asymmetrical haloes do not show any peculiar behaviour in the H-R diagram compared to round AGB haloes, supporting the idea that the asymmetry in these haloes might be primarily of external origin (like interaction with the ISM). As with non-detections, there is some faint evidence that their central stars might be located at higher average luminosities (implying larger masses) than PNe with detected haloes, but the sample is small and errors on the luminosity large. Understanding this point is clearly a main task for the future.

As far as sizes and luminosities are concerned, most AGB haloes have a radius between 0.2 pc and 1.3 pc, with record sizes of several parsecs for the huge halo-like structures around NGC 2867, NGC 3242 and Sh 2-200, whose nature as genuine AGB haloes must however be confirmed. Note that the halo sizes are much larger than the typical radii for the inner rims of one-two tenths of a parsec or less for non-evolved PNe, and up to almost 0.3 pc for very evolved objects. Note also that the candidate recombination haloes are on the average smaller than the AGB haloes, as expected from the models. Most circular AGB haloes have a surface brightness $\leq 4 \times 10^{-3}$ that of the peak in the inner nebular regions. On the average, highly asymmetrical AGB haloes are brighter, up to nearly 10^{-2} the brightness of their inner rims. Compression by the interac-

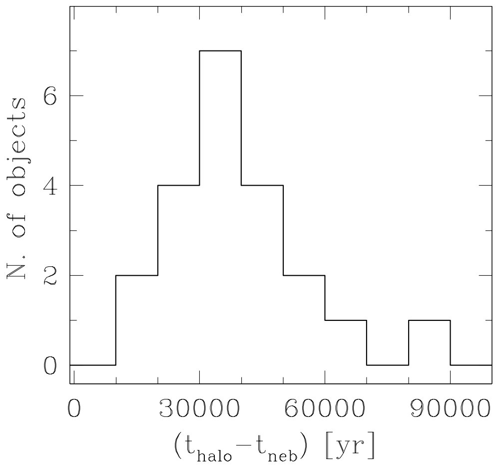

Fig. 4. The time interval between the last AGB thermal pulse and the end of the AGB (from CSSP03).

tion with the ISM is the most likely explanation for this enhanced emission. Recombination haloes are even brighter, having a relative surface brightness between 0.5×10^{-2} and 10^{-1}.

But the most interesting property to investigate is the kinematical age of the haloes. As mentioned above, the kinematical age of the halo edge (t_{halo}) tells us how many years ago the last AGB thermal pulse occurred. If we also determine the kinematical age of the inner nebula (t_{neb}), that represents the post-AGB age of the PN, we can then estimate the time ($t_{halo} - t_{neb}$) elapsed between the last AGB thermal pulse and the end of the AGB. This is presented in the histogram of Fig. 4, which shows that for AGB haloes the quantity ($t_{halo} - t_{neb}$) ranges between 15 000 and 60 000 yr, with a peak between 30 000 and 40 000 yr. Considering that most central stars have masses around 0.6 $M_\odot$ (see discussion above), and that the interpulse timescale for such a core mass is ~90 000 yr (Blöcker 1995), the observed ages of the AGB haloes confirm the conclusion of Schönberner (1981) that *most of the PNe have left the AGB far from a thermal pulse, at a phase at which hydrogen burning is the dominant energy source*. Thus, most PNe in our sample have hydrogen burning central stars, except for the hydrogen-deficient central star of of NGC 6543 which must be burning helium, and whose halo kinematical age is in fact ≈ 85 000 yrs (rightmost bar in the histogram), indicating that it would have left the AGB during or very close to a helium-shell flash.

Our results are substantially different from those of other authors. The main reason is that, in the past, attempts were made to link directly the kinematical ages of multiple shells in PNe with the occurrence of distinct AGB mass loss episodes, without a proper understanding of the origin of each individual shell. We know now that this is not correct, but still the method is very valuable when relies on detailed radiation-hydrodynamical modelling, as we are doing.

This is clearly a rich field of research for the next years. Detailed modelling of individual PNe, together with the determination of dynamical and chemical properties of their haloes, would reveal a wealth of information about the very late AGB evolution – such as the wind dynamics, timescales, mass loss rate, and chemical composition – that can be hardly obtained in other ways.

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