



<b>Title</b>	<b>Stellar evolution from AGB to planetary nebulae</b>
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<b>Citation</b>	<b>The International Astronomical Union Symposia and Colloquia S252: The Art of Modeling Stars in the 21st Century, Hainan, China, 6-11 April 2008.</b>
<b>Issued Date</b>	<b>2008</b>
<b>URL</b>	<b><a href="http://hdl.handle.net/10722/128482">http://hdl.handle.net/10722/128482</a></b>
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# Stellar Evolution from AGB to Planetary Nebulae

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**Abstract.** Planetary nebulae are formed by an interacting winds process where the remnant of the AGB wind is compressed and accelerated by a later-developed fast wind from the central star. One-dimensional dynamical models have successfully explained the multi-shell (bubble, shell, crown, haloes) structures and the kinematics of planetary nebulae. However, the origin of the diverse asymmetric morphology of planetary nebulae is still not understood. Recent observations in the visible, infrared, and the submillimeter have suggested that the AGB mass loss becomes aspherical in the very late stages, forming an expanding torus around the star. A fast, highly collimated wind then emerges in the polar directions and carves out a cavity in the AGB envelope to form a bipolar nebula. Newly discovered structures such as concentric arcs, 2-D rings, multiple lobes, and point-symmetric structures suggest that both the slow and fast winds may have temporal and directional variations, and precession can play a role in the shaping of planetary nebulae. In this paper, we review the latest observations of planetary nebulae and proto-planetary nebulae and discuss the various physical mechanisms (rotation, binary, magnetic field, etc) that could lead to the observed morphologies.

**Keywords.** Stars: AGB and post-AGB, Planetary nebulae: general, Stars: evolution

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## 1. Introduction

Planetary nebulae (PNe) represent a short ( $\sim 10^4$  yr) phase of stellar evolution between the asymptotic giant branch (AGB) and white dwarfs. The central stars of PNe are remnants of the electron-degenerate C-O cores of their AGB progenitors, having lost most of their H envelopes due to mass loss on the AGB. They maintain their energy output through H-shell burning and evolve with constant luminosity from low to high temperature across the H-R diagram. When their entire H envelope is consumed by a combination of nuclear burning and mass loss, their luminosities begin to decrease and the central star gradually cool to become white dwarfs. This basic scenario was outlined by Paczyński (1971), and was confirmed by detailed evolutionary tracks calculations by Schönberner (1979) and Wood & Faulkner (1986).

## 2. What is a planetary nebula?

Traditionally, PNe are observationally defined as optical nebulae with a central star with some degree of symmetry and a strong emission-line spectrum with no or very weak continuum. This definition does not take into account modern observational properties such as dust emission in the infrared, X-ray continuum from hot gas, emission lines from molecules, etc. However, even an expanded observational definition is not enough because symbiotic stars share many of these same properties and there is significant confusion between PNe and symbiotic stars in the literature (Kwok 2003). It is clear that we need to incorporate a theoretical element into our definition. For example, we can define PNe as ionized circumstellar shells showing some degree of symmetry surrounding

a hot, compact star evolving from the AGB to the white dwarf phase (Kwok 2000). This definition will distinguish PNe from symbiotic stars or novae, which are binary systems undergoing mass exchange. While the hydrogen envelope mass of a PN central star is being depleted by nuclear burning and mass loss, and therefore constantly evolving, a symbiotic star maintains its energy source through accretion, and is therefore stationary in evolution. It should be noted, however, a post-outburst nova or symbiotic nova also evolves to the blue similar to a PN. Unless the outburst (H ignition) is observed, it may also be difficult to distinguish a symbiotic nova from a PN.

### 3. The existence of planetary nebulae

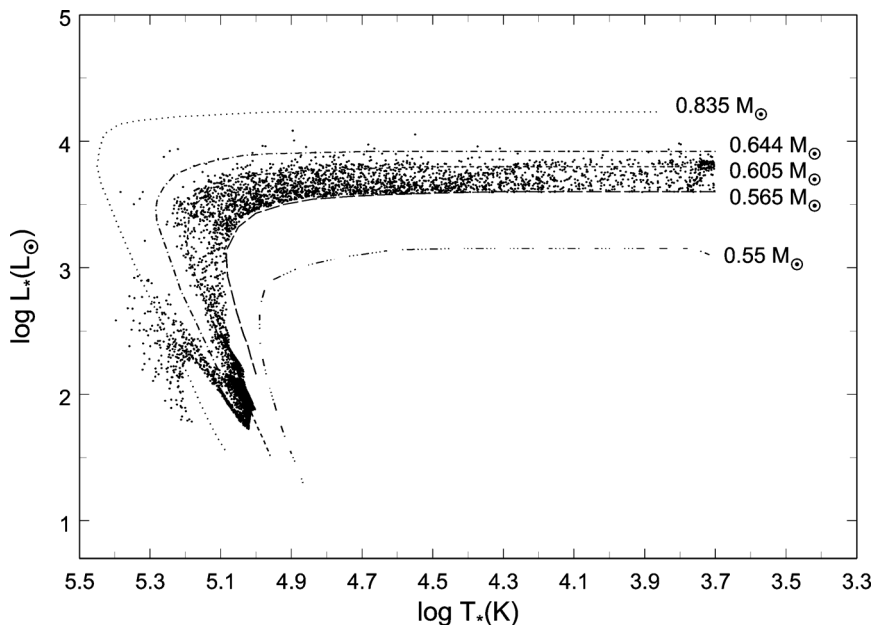
Since PNe represent material ejected during the AGB phase and later ionized by the increasingly hot central star, the existence of PNe requires that the dynamical (expansion) age of the nebula be comparable to the evolutionary age of the central star. A star with higher core mass leaves the AGB with a smaller H envelope but burns at a higher rate. As a result, the transition time between the AGB and PN stage is highly dependent on the core mass. While a high-mass star will evolve so fast that it only illuminates the nebula for a very short time, a star with low core mass will evolve too slowly to ionize the circumstellar nebula before it dissipates into the ISM. Consequently, not all stars that evolve past the AGB will become PNe.

Due to strong mass loss on the AGB, stars with main-sequence masses as high as  $8 M_{\odot}$  can lose their entire H envelope before the core mass reaches the Chandrasekhar limit of  $1.4 M_{\odot}$ . From the initial mass function, one can estimate that 95% of all stars that have evolved from the main sequence during the lifetime of the Galaxy will end their lives as white dwarfs. A majority (30-90%, Drilling and Schönberner 1985) of these stars will have passed through the PN stage. Figure 1 shows a simulated distribution of post-AGB stars on the H-R diagram. We can see that all the high core-mass stars are on the cooling track, and the horizontal parts of the evolutionary tracks are mostly populated by PNe with core masses around  $0.6 M_{\odot}$ .

### 4. Planetary nebulae as an evolving dynamical system

While an impulsive ejection appears intuitively obvious for the formation of PNe, the discovery of large-scale mass loss on the AGB led to the realization of the importance of AGB mass loss on the origin of PNe and the formulation of the interacting stellar winds (ISW) model (Kwok *et al.* 1978, Kwok 1982). In addition to the well-observed shell, the ISW model predicts the following components: a fast wind from the central star, a low-density halo representing the unshocked AGB wind, and a high-temperature bubble representing the shocked fast wind. The *IUE* satellite has observed P Cygni profiles corresponding to wind velocities of several thousands  $\text{km s}^{-1}$  in many central stars of PNe, confirming that fast winds are indeed common in PNe. Evidence for the existence of haloes outside the PN shells were found by CCD imaging and by the detections of dust and molecular envelopes by infrared and millimeter-wave observations. Extended diffuse X-ray emission from the hot bubble was detected by *ROSAT* and by *CHANDRA* observations.

A PN is a dynamical system whose evolution is tightly coupled to the evolution of the central star through a changing rate of stellar Lyman continuum output and photoionization, and by a changing mass loss rate and wind velocity from the central star and wind interaction. The appearance and the structure of PN therefore reflect the coupled dynamical and ionizational evolution of the nebula. The time-dependent nature of PN



**Figure 1.** A simulated distribution of post-AGB stars in the H-R diagram. A random sample of 9951 stars with initial masses between 0.95 and 8  $M_{\odot}$  are generated using the Salpeter initial mass function and the initial mass-final mass relationship of Weidemann (2000). They are distributed in equal time intervals between  $t = 0$  (set at  $T_e = 3.7$ ) and 40,000 yr along H-shell burning evolutionary tracks. Tracks with masses between the five core masses calculated by Schönberner (1981, 1983) are derived from interpolation. Stars on the left of  $\log T_e = 4.5$  are PNe and those on the right are PPNe.

evolution was incorporated into many of the 1-D spherically symmetric treatments of the ISW model (e.g., Marten & Schönberner 1991; Frank 1994; Mellema 1994). High dynamical range imaging observations of PNe with CCD detectors have revealed a much more complicated structure of PN than the classical picture of a shell plus central star. In addition to a bright shell, a low-surface brightness outer structure (“crown”) and an extensive faint halo can be seen (Guerrero *et al.* 2000, Frank *et al.* 1990). While such multiple shell structures are difficult to understand in the classical model, they can be reproduced when the evolution of the central star is incorporated in the ISW model (Mellema 1994, Steffen *et al.* 1998, Corradi *et al.* 2000). In a 1-D model, the “shell” can be identified as the high-density shell compressed by the hot bubble, the “crown” as the extent of the ionization front, and the halo as the remnant of the AGB wind (Schönberner *et al.* 2005). It is important to note that these structures can change with time as the star evolves.

## 5. The intrinsic 3-D structure of PNe

Beginning with the work of Curtis (1918), there have been many attempts in classifying the morphologies of PNe (e.g., Stanghellini *et al.* 1993, Machado *et al.* 1996). However, all classification schemes suffer from the problem of sensitivity dependence where a deeper exposure can reveal fainter structures which change the classification of the PNe. For example, the waist of a bipolar nebula could be classified as elliptical if the bipolar lobes are too faint to be detected. NGC 650-1, Sh 1-89, and SaWe 3 are some of the cases where their bipolar nature were discovered as the result of deep CCD imaging.

The apparent morphology is also dependent on the lines of different ions observed due to ionization structures and stratification effects. Furthermore, projection effects due to viewing orientation may affect the morphological classification. It is clear that the examination of the apparent morphology alone is not sufficient to obtain the true intrinsic structure of PN. Kinematic data are necessary to separate various components projected on the same positions in the sky.

When the above factors are taken into consideration, it becomes clear that the fraction of bipolar nebulae is much higher than the fraction given in classification schemes based on apparent morphology. As a first order approximation, we may consider that the 2-D structure of a PN consists of the following components:

- A low-density spherical halo representing a remnant of the AGB wind.
- An ionization-bounded, dust-obscured torus representing an equatorial outflow during the late stages of AGB evolution.
- Two density-bounded polar lobes representing cavities created by fast outflows and the subsequent photoionization of the circumstellar material.

Under this model, a PN viewed near pole on will appear elliptical, with the torus seen as a shell and the lobes seen as envelopes surrounding the shell. Detailed kinematic studies have shown that several of the well-observed ring-like PN are in fact bipolar (NGC 6720, Bryce *et al.* 1994, Steffen *et al.* 2008; NGC 7027, Latter *et al.* 2000; NGC 3132, Monteiro *et al.* 2000). When viewed near edge on, the PN will appear to have a bipolar or butterfly shape. Although the fraction of bipolar PNe based on apparent morphology is relatively small ( $\sim 15\%$ ), the true fraction could be much higher.

Beyond this torus-bipolar lobes basic structure, recent high-resolution images obtained with the *HST*, have discovered a number of additional microstructures:

- FLIERS: FLIERS (fast low-ionization emission regions) are pairs of small, bright knots of low excitation gas found along the major axes of PNe (Balick *et al.* 1998). Examples of well-defined FLIERS can be found in NGC 3242, NGC 6826, and NGC 7009.

- Collimated outflows: some PNe and PPNe (e.g. Hen 3-401, Sahai *et al.* 1999a) have extreme bipolar (cylindrical) shapes, suggesting that their morphology is shaped by a collimated outflow. The direct imaging of bipolar lobes emerging from a circumstellar disk in the PPN IRAS 17106–3046 (Kwok *et al.* 2000) suggests that disks could play a role in the collimation of the bipolar flows.

- Multipolar and point-symmetric structures: point-symmetric pairs of knots in an S-shape structure, or sometimes referred to as bipolar, rotating, episodic jets (BRET), have been seen in a number of PNe (e.g. KJPn8, López *et al.* 1995; NGC 6884, Miranda *et al.* 1999). Some PNe have been found to have more than one polar axis, suggesting that the outflow direction has changed with time (e.g. NGC 2440, López *et al.* 1998; M1-37 and He2-47, Sahai 2000). High-resolution mid-infrared imaging has found that the dust torus in the PPN IRAS 17441–2411 is in fact mis-aligned by  $23^\circ$  with the optical bipolar axis, suggesting that the torus may have precessed over time (Volk *et al.* 2007).

- Concentric arcs: concentric circular arcs have been observed in both PNe (e.g. Hb 5, NGC 6543, NGC 7027) and PPNe (e.g. AFGL 2688, IRAS 17150–3224). These arcs are of almost perfectly circular in shape, and have relatively uniform separations of  $\sim 10^2$  yr (Kwok *et al.* 2001). Such time intervals are too short for thermal pulses ( $\sim 10^4$  yr) and too long for pulsations ( $\sim 10^0$  yr). Similar arcs have been detected in the carbon star IRC+10216, suggesting that these features originate in the AGB phase. The coexistence of these perfectly circular features with bipolar lobes suggests that the arcs are projections of undisturbed spherical shells on the sky. Possible mechanisms for the creation of such arcs include dynamical instability in the gas-dust coupling in the AGB outflow (Deguchi

1997), perturbation by a binary companion (Mastrodemos & Morris 1999), and magnetic cycle (Soker 2000, Garia-Segura *et al.* 2001).

- Two-dimensional co-axial rings: multiple rings perpendicular to the bipolar axis have been found in several PNe, including MyCn18 (Sahai *et al.* 1999b) and NGC 6881 (Kwok & Su 2005) and Hb 12 (Kwok & Hsia 2007). Such rings may be created by a periodic or episodic fast wind interacting with the circumstellar medium.

## 6. Shaping of PNe and the origin of the asymmetry

The fact that AGB circumstellar envelopes are generally spherically symmetric and PNe are highly asymmetric suggests that a drastic morphological transformation must have occurred in the post-AGB evolution. The discovery of PPNe (Kwok 1993) offers the opportunity to pinpoint the earliest stage of this transformation. Early models of PN shaping relied on the asymmetry of the AGB and the ISW process to amplify such asymmetry to create bipolar morphology observed in PNe (Balick 1987, Mellema & Frank 1995). According to this scenario, PNe morphology should be age-dependent with the most evolved objects being most extreme in bipolar form and the youngest members being much less so. However, imaging of PPNe have found many PPNe to possess bipolar morphology, implying that the shaping process occurs during the PPN phase, well before the photoionization of the nebulae (Kwok *et al.* 1996, 1998). Some PPNe and young PNe have highly focused lobes, suggesting that the fast wind is being collimated by a disk. The misalignment between the infrared dust torus and the optical bipolar lobes seen in the PPN IRAS 17441–2411 suggests that some of such collimating disks may be precessing. Hydrodynamic models have shown that FLIERs and BRETs could be naturally produced by the ISW process if the mass loss rate and velocity of the fast wind are functions of both time and direction (Steffen *et al.* 2001). The change in outflow direction could be the result of rotation and magnetic fields (Garcia-Segura *et al.* 1999).

## 7. Conclusions

From the above discussions, it is clear that the study of circumstellar matter such as PNe can reveal a great deal about the physical processes within stars. The detection of concentric arcs suggests that the AGB wind may have discrete shell structures. The fact that many PPNe possess highly bipolar structures suggest that the morphological transformation is by a highly collimated fast wind. The observations of multiple co-axial 2-D rings suggest that this fast wind may be episodic. The existence of point-symmetric structure suggests that the fast wind may be precessing. These observations raised a number of questions on their physical origins, e.g., what roles do binary evolution, magnetic fields, or rotation play in the launching, collimation, and precession of the fast outflow? Are these circumstellar asymmetry in any way related to the asymmetry generated by convection, turbulence, and magnetic fields in the interiors of AGB stars? All these questions are relevant to the development of realistic models of the structure and evolution of stars.

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**Discussion**

G. HENSLER: What are spectra telling us about kinematics and excitation mechanisms of the PNe substructures?

S. KWOK: While it is now possible to do spectroscopy on the shell, crown and even the haloes (and therefore able to obtain kinematic information on these structures), the arcs and the rings are too faint to do spectroscopy.

P. WOITKE: Could you comment on the possibility that the rings around PNe are actually not concentric, but narrowly wiggled spirals? A companion star that wobbles the mass losing star could then provide an explanation. With the exception of IRC+10216, the rings of all PNe seem to be exactly concentric.

S. KWOK: The only AGB star that has been found to have arcs is IRC+10216. There are some suggestions that the arcs in this object is part of a spiral pattern. However, the PPN, and PNs, the arcs are highly concentric. Binary perturbations have indeed been suggested as a cause of the existence of these uniformly spaced concentric arcs.

J. VINK: I have two questions: (1) Could you put some number on the incidence of bipolarity among the class of PNe, and (2) you mentioned the asphericity stars during the p-AGB phase. Would you be able to say at which  $T_{eff}$  this happens?

S. KWOK: In early morphological classification schemes, the fraction of bipolar nebulae is estimated to be  $\sim 15\%$ . However, when sensitivity and orientation factors are taken into account, its fraction is considerably higher.

From the existence of highly bipolar pre-planetary nebulae, the initiation of a fast, collimated wind must be very early, may be right at the end of the AGB. Pre-planetary nebulae are typically of special type F or G, so the fast wind could begin as early as  $T_e \simeq 5000$  K.