PROGENITORS OF PLANETARY NEBULAE

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ABSTRACT. Over the past decade, we have come to realize that mass loss on the asymptotic giant branch (AGB) plays a significant role in the formation of planetary nebulae (PN). Mass ejected during the AGB can now be observed in haloes of PN and we believe that the main shell of PN is formed by the interaction of this material with a later-developed central-star wind. In this review, we show that the evolution from AGB to PN can be traced in a continuous infrared sequence. This sequence predicts properties of proto-PN which allow them to be identified.

1. INTRODUCTION

Since both the nebula and the central star of a planetary nebula (PN) originate from a progenitor star on the asymptotic giant branch (AGB), the study of the formation of PN cannot be isolated from the evolutionary stages immediately preceeding the PN. Figure 1 shows the evolutionary pathway leading to the formation of PN. As a star evolves up the AGB, it loses mass at an increasing rate until it is totally obscured by its own circumstellar dust envelope. At this time, the photosphere is no longer visible and the star will appear as an infrared object. It is useful to designate this stage as the late AGB (LAGB). When mass loss reduces the mass of the hydrogen envelope (M_e) to a certain value ($M_e \sim 10^{-2}$ $M_\odot$ for a core mass [M_c] of 0.60 $M_\odot$, Schönberner 1983), the star will turn to the left and evolve towards the blue side of the H-R diagram. When M_e is down to 10^{-3} $M_\odot$ (again for M_c=0.6 $M_\odot$), the envelope is so disrupted that large-scale mass loss is no longer possible to continue. We will define this point as the end of the LAGB and the beginning of the proto-planetary nebula (PPN) phase. The effective temperature of the star will continue to increase due to the loss of envelope mass as the result of hydrogen shell burning. The PPN phase will last ~1500 yr until the central star is hot ($T_* \sim 30{,}000$K) enough to ionize the circumstellar nebula. Recombination line of hydrogen and forbidden lines of metals will make the nebula easily observable in the visible. In this talk, I will discuss the physical processes in the LAGB and PPN phases and their effects on the formation of PN.

S. Torres-Peimbert (ed.), Planetary Nebulae, 401–410.

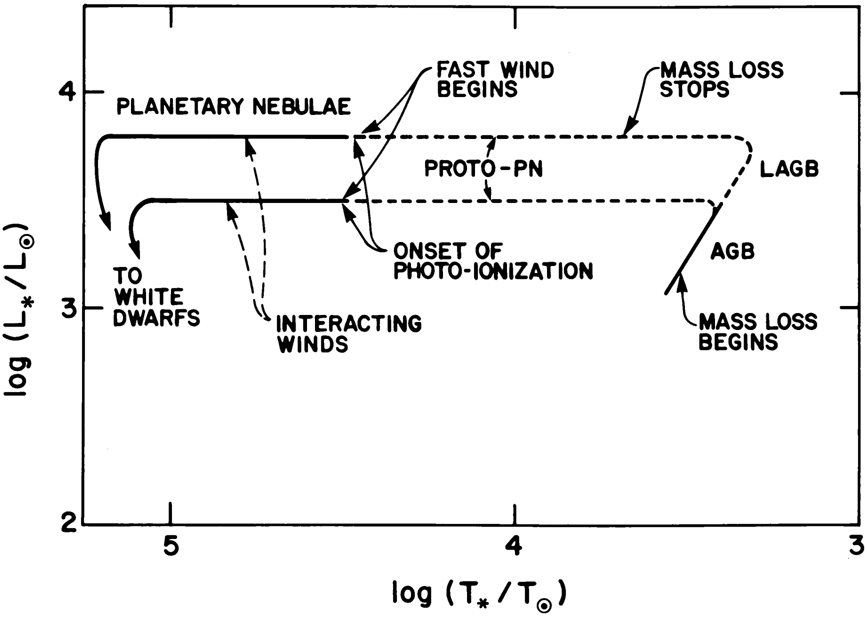

Figure 1. Evolutionary paths from AGB to PN in the H-R diagram.

2. ASCEND OF THE ASYMPTOTIC GIANT BRANCH

While conventional spectral classification schemes stop at about spectral class M10 for evolved stars, it is now recognized that there exist AGB stars that have evolved beyond this limit. The *IRC*, *AFGL*, and *IRAS* infrared sky surveys have discovered many heavily reddened stars which have luminosities higher than Mira Variables and are likely to be LAGB stars. Since the stellar photosphere of LAGB stars are obscured by dust ejected during the mass loss process, one has to rely on radio and infrared techniques as probes of their properties. For oxygen-rich stars, the circumstellar envelope (CSE) generally shows the 9.7 μm silicate feature either in emission or absorption (Merrill and Stein 1976) in the infrared and OH maser emission in the radio (Herman and Habing 1985). For carbon-rich stars, the 11.3 μm SiC feature is usually present and the structure of CSE can be studied by rotation transition of CO in the radio (Knapp and Morris 1985).

Among these four diagnostic tools, the 9.7 μm silicate feature is particularly useful. It is observed in over 2000 stars by the *IRAS* Low Resolution Spectrometer (LRS) and shows a variation in strength from strong emission to strong absorption (Volk and Kwok 1987a). The inferred optical depth in the feature ranges from 0.1 to >100, implying a change in mass loss rate of over 3 order of magnitudes among AGB stars. Since the transition from emission to absorption occurs at $\tau(9.7\ \mu m)\sim4$, almost all stars showing silicate absorption features are without optical counterparts (Kwok, Hrivnak, and Boreiko 1987), and are therefore members of LAGB stars. While precise locations of LAGB stars on the H-R diagram are difficult to determine due to uncertainties in both L_* and T_*, the distribution of the silicate absorption objects in a colour-colour diagram shows that they lie on a well-defined band (Olnon *et al.* 1984; Bedijn 1988; Kwok, Hrivnak, and Boreiko 1987). In comparison, stars which show the silicate feature in emission (e.g. Mira variables) occupy part of the colour-colour diagram to the left of the absorption objects (Figure 2). If we interpret this band as an evolutionary sequence, then we have a picture of AGB stars evolving from the colour temperatures of >600 K for Mira variables to ~250 K for extreme LAGB stars.

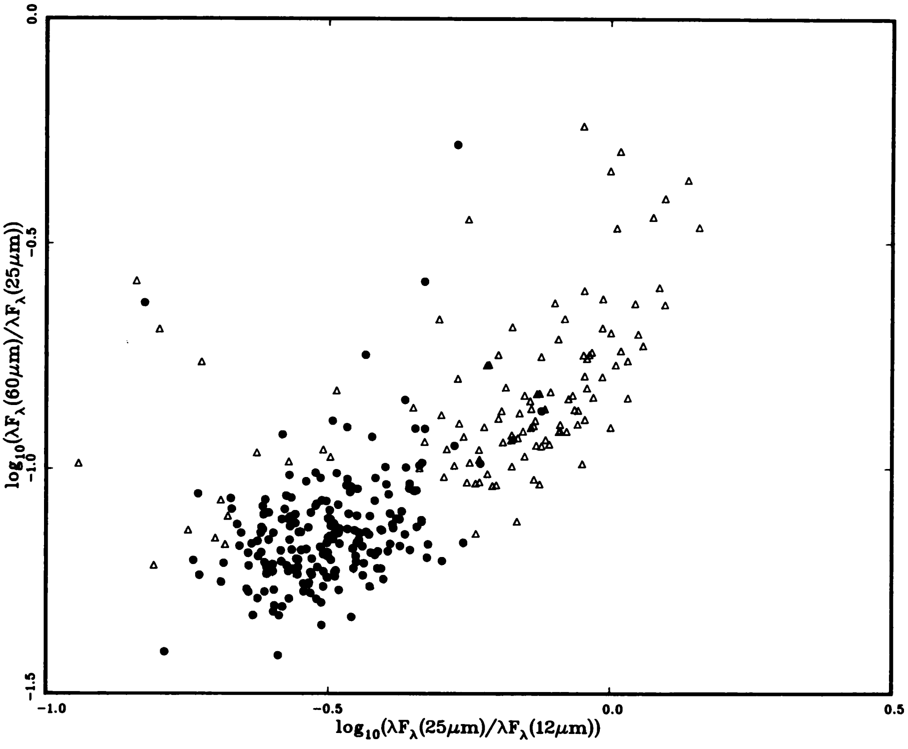

Figure 2. Colour-colour diagram of AGB and LAGB stars. The filled circles are LRS class 25-29 sources with good fluxes at all four bands and the triangles are LRS class 31-39 sources with good fluxes at 12,25 and 60 μm bands. A number of class 30 sources with possible confusion with HII regions are not plotted.

3. INFRARED LINK BETWEEN THE AGB AND PN

For a number of years, I have argued that the CSEs created by mass loss on the AGB should be observable in PN and their presence may have significant effects on the formation of PN (Kwok 1980, 1982). The recent *IRAS* sky survey has revealed that PN have cool dust components, and Pottasch *et al.* (1984) have found that the colour temperatures of evolved PN lie in the range of 40-100 K. An analysis of young PN by Kwok, Hrivnak, and Milone (1986) shows that the near infrared emission from PN is due to thermal free-free emission from the ionized gas whereas dust emission is responsible for the far infrared emission. They also found that the colour temperatures of young PN are higher than those of evolved PN, with typical values in the range of 100-200 K.

The fact that the colour temperatures of young PN are in between the colour temperatures of LAGB and evolved PN strongly suggests that the infrared emission in these objects all originates from the dust CSEs which are ejected during the LAGB phase but have cooled during the PN stage. Figure 3 shows a plot of the radio brightness temperature against 60 μm optical depth for 266 PN. These two parameters are used because they both are distance-independent and are gauges of the dynamical ages of the gas and dust components respectively. The strong correlation found is evidence that the gas and dust components of PN are both expanding with time and the location of individual PN in Figure 3 is a measure of its relative age.

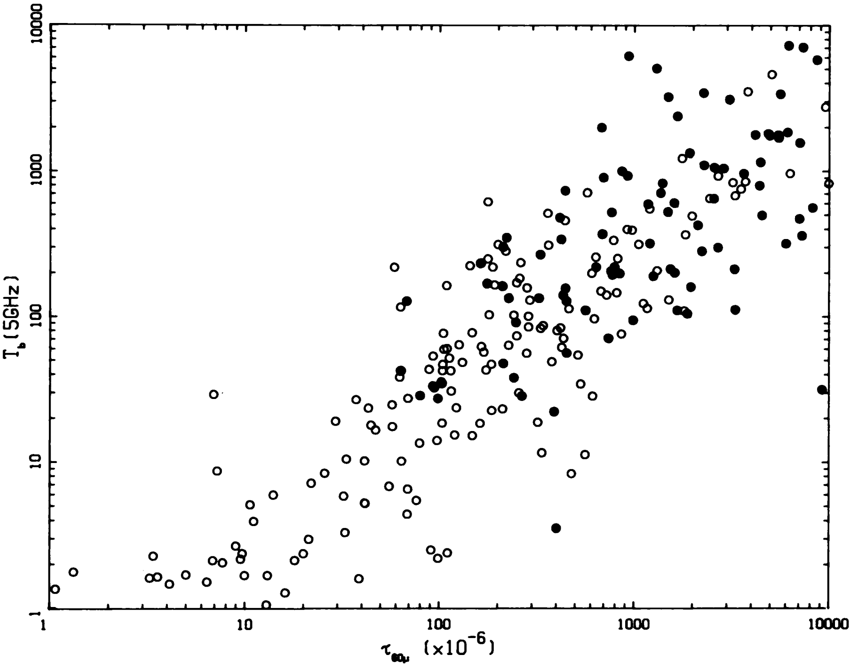

Figure 3. The 5 GHz radio brightness temperature plotted against 60 μm optical depth for 266 PN. The filled and open circles are respectively VLA and single-dish measurements.

From the above discussions, it has become obvious that there exists an continuous infrared sequence connecting the evolutionary stages of AGB and PN. The colour temperature decreases monotonically from >600 K for Mira Variables to 250-600 K for LAGB stars, to 100-200 K for young PN and then to 40-100 K for evolved PN. It is important to note that while the change in colour temperature is monotonic and reflects the evolution of the dust CSE, the physical reason for the decrease is different in the AGB and PN phases. During the AGB and LAGB when mass is continuously ejected from the star, the lowering of colour temperature is the result of increasing optical depth in the CSE. However, beyond the LAGB, optical depth of the envelope begins to decrease and the change in colour temperature is the result of geometric dilution.

4. THE PROTO-PLANETARY NEBULA PHASE

Renzini (1983) has suggested that many PN may remain undetected if the central stars evolve too slowly. The common occurrence of PN therefore implies that the PPN stage cannot be more than a few thousand years in duration, otherwise the nebula would have been dispersed before it is ionized. If we adopt the transition time of ~1500 yr calculated by Schönberner (1983) then the ratio of PPN to PN is approximately the ratio of their respective lifetimes, or 5-15%. From the number of PN in the *IRAS* Point Source Catalogue (>1000) we therefore expect that there should be 50-150 PPN detected by the *IRAS* survey.

If we accept the existence of the infrared sequence discussed in §3, then the infrared properties of PPN can be interpolated from those of LAGB and young PN. This suggests an intermediate colour temperature of 150-250 K. As a PPN has very little hydrogen atmosphere, we also do not expect it to be a strong pulsator (Habing, van der Veen, and Geballe 1987). A search of PPN using these criteria were carried out by Kwok and Hrivnak at the Canada-France-Hawaii Telescope (CFHT). A number of *IRAS* sources of low colour temperatures were found with blackbody-like energy distributions and with no optical counterparts.

As the remnant dust CSE continues to expand and the envelope optical depth continues to drop, the star will eventually become visible again. By extending the radiative transfer models for AGB stars to beyond the AGB, Volk and Kwok (1987b) find a distinct spectral shape for PPN. A search of the LRS catalog resulted in a number of sources showing agreement with the model prediction, one of them being 18095+2704. This *IRAS* source was identified at the CFHT with a relatively bright star of 11 mag. Optical spectroscopy at the Dominion Astrophysical Observatory shows that it has a spectral type of F3 Ib (Hrivnak, Kwok, and Volk 1988). A combined visual and infrared spectrum from 0.36 to 100 μm for 18095+2704 is shown in Figure 4. Assuming $L_*=10^4$ $L_\odot$ and $T_*=6000$ K, a model fit to the spectrum suggests that the inner radius of the dust shell is located at 7×10^{15} cm. Using the expansion velocity of 7 km s^{-1} derived from OH observations (Lewis, Eder, and Terzian 1985), it is estimated that the star had a mass loss rate of 2×10^{-5} $M_\odot$ yr^{-1} at the AGB and the shell was detached from the star ~325 yr ago.

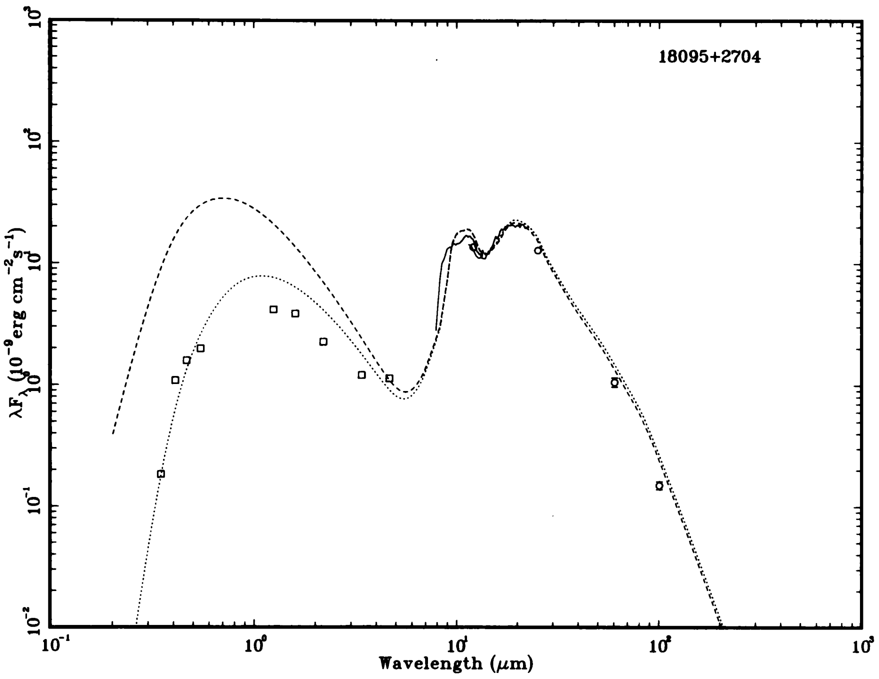

Figure 4. The IRAS LRS spectrum of 18095+2704 combined with the ground-based and IRAS photometry, and plotted together with a PPN model. The temperature and luminosity are assumed to be 6000K and 10^4 $L_\odot$ respectively. The dotted line shows the resultant spectrum after the addition of an extinction component of the form $\exp[-1.406/\lambda(\mu m)]$.

The dual-peak spectral behaviour of this PPN candidate is similar to the PPN candidates found from non-variable OH/IR stars (van der Veen, Habing, and Geballe, these proceedings). As PPN evolve into the early stages of PN, part of the nebulae will begin to be ionized. The OH sources with radio continuum emission found by Zijlstra *et al.* (these proceedings) could represent some of the youngest PN observed.

5. TERMINATION OF THE AGB

An important question on the origin of PN is the time scale of the ejection of the nebula. This ranges from the traditional theories of sudden ejection where the process occurs in a few years (cf Roxburgh 1978), to ~10^3 yr (Tuchman, Sack, and Barkat, 1979) and ~10^4 yr (Herman and Habing 1985) in the "superwind" models. The term "superwind" has its origin in that the mass loss rate during this phase is high in comparison to the Reimers' formula (Reimers 1975). However, infrared and radio (CO) observations show that mass loss rates of AGB stars with spectral types later than M3 are already much higher than that given by the Reimers' formula. Since the mass loss rates of AGB stars increase with luminosity (or time), one could refer to the very last stage ($<10^4$ yr) of mass loss as a "superwind" phase, although the distinction is strictly semantic. In my opinion, it is not appropriate to refer to the OH/IR phase as the "superwind" phase because the LAGB phase, which coincides with the observation of OH/IR stars with no optical counterparts, certainly lasts more than 10^5 yr. Furthermore, a mass loss rate of only few times 10^{-6} $M_\odot$ yr^{-1} will completely obscure the photosphere of the star and such mass loss rates cannot in any sense be considered "super".

If the AGB is indeed terminated by the complete removal of the hydrogen envelope through steady mass loss, then can PN be nothing more than ionized CSEs? This possibility was first raised by Paczynski (1971) and has since been re-discussed by other authors (Harpaz and Kovetz 1981), and most recently by Taylor, Pottasch, and Zhang (1987). This scenario of PN formation was considered by Kwok (1981) to be inadequate for three reasons:

1. Densities of PN shell are higher than the observed densities in AGB CSEs.
2. Expansion velocities of PN shell (~20-50 km s^{-1}) are higher than expansion velocities of AGB star winds (~3-20 km s^{-1}).
3. Many PN have well-defined shell-like morphologies whereas AGB winds have smooth density distributions.

All these three points are still relevant today. Direct comparisons of the densities of shell and halo of PN also suggest a difference in density of a factor ~10 (Jewitt, Danielson, and Kupferman 1986; Bässgen *et al.*, these proceedings). Expansion of AGB stellar winds are well determined by CO and OH measurements and the discrepancy between these values and PN velocities are still significant. Brightness distributions of CO in IRC+10°216 shows an inverse square density law with no definite shell structure (Kwan and Link 1982). These problems indicate that another physical process is needed to adequately explain the formation of PN.

6. THE INTERACTING WINDS MODEL

The Interacting Stellar Winds model of Kwok, Purton, and FitzGerald (1978, hereafter KPF) was an attempt to address the problems mentioned in §5. This model postulates the presence of a fast wind which shapes, accelerates, and compresses the remnant AGB wind material into PN. If this model represents the universal formation mechanism of PN, then three conditions must be satisfied:

1. Remnants of CSE of AGB progenitor are still present in PN;
2. high velocity wind from the central star is a common phenomenon;

and 3. masses of PN increase with age as the remnant CSE is swept up by the central-star wind.

While the existence of central-star winds and haloes around PN has been known for some time (Smith and Aller 1969; Duncan 1937), their common occurrence in PN was not confirmed until recently. The *IUE* satellite found P Cygni profiles in resonance lines of central stars of many PN (Heap *et al.* 1978) with velocities ranging from 1400 to 5000 km s^{-1}, and mass loss rates between 10^{-9} to 10^{-7} $M_\odot$ yr^{-1} (Grewing, these proceedings; Perinotto, these proceedings). Faint haloes are now believed to be present in over 50% of all PN (Jewitt, Danielson, and Kupferman, 1986; Chu, Jacoby, and Arendt 1987; Balick 1987). Maps of H_2 molecules show that the molecules are distributed outside of the main shell (Zuckerman and Gatley 1987). OH and CO molecules which are common in AGB CSEs are found in increasing number of PN (OH: Seaquist and Davis 1983; Payne, Phillips, and Terzian, these proceedings; Zijlstra *et al.* these proceedings; CO: Thronson 1983; Healy and Huggins, these proceedings; Walsh, Clegg, and Ukita, these proceedings). Atomic hydrogen has also been detected (Rodriguez and Moran 1982; Taylor and Pottasch 1987). The presence of dust continuum emission from the remnant CSE has already been discussed in §3.

The masses of PN remain a controversial issue. There is, however, good evidence that the ionized masses of PN range over three order of magnitude (Pottasch 1980). Ionized masses determined from the radio survey of compact PN also point to similar conclusions (Kwok 1987). It is possible that some of this variation in mass is due to ionization effects, but the interacting winds process may also contribute toward the large observed mass range.

The above summary of recent observations suggests that the qualitative predictions of KPF have been largely confirmed. It is, however, important to test the quantitative predictions of the model as well. It has been shown that at least in the energy conserving case, the observed central-star wind mass loss rates and velocities are adequate to explain the observed masses and velocities of the PN shell (Volk and Kwok 1985). With kinematic information of the halo now available through spectroscopic observations (Chu, these proceedings; Bässgen *et al.*, these proceedings), it is possible not only to test the validity of the dynamical models but also to determine whether the wind interactions are energy or momentum conserving.

Previous dynamical calculations usually assume an *ad hoc* mass loss formula for the central star (e.g. Volk and Kwok 1985). The theoretical formula reported by Kudritzki (these proceedings) may allow the incorporation of a realistic formula in dynamical calculations. With the improved models of central star evolution (Schönberner, these proceedings) and models of nebular dynamics, calculation of the evolution of the nebular spectrum has become possible (Schmidt-Voigt and Köppen 1987a,b). Comparison of the theoretical results and observations may become one of the most fruitful area of research in this subject.

7. CONCLUSIONS

In this conference, Chu raised the question "What is the definition of planetary nebula?" This is a very valid question. My response is that we should consider the term "the PN system" which consists of a central-star wind, a shell, and a halo, in addition to the central star. The traditional meaning of PN refers only to the shell component, which may have densities, velocities, or compositions which are different from the other two components.

Significant progresses have been made in the understanding of the transition phases between AGB and PN since the last IAU symposium. Observations in the far infrared from the *IRAS* satellite have led to the identification of a continuous infrared sequence connecting the AGB, LAGB, PPN and PN phases. This proposed sequence of evolution is summarized in Table 1.

A number of candidates of PPN have now been identified. Further identification and observations of PPN in the next few years will hopefully settle the question of the origin of planetary nebulae.

TABLE 1
EVOLUTION FROM AGB TO PLANETARY NEBULAE

evolutionary phase	example	optical image	period (days)	colour temperature (K)	silicate dust	OH
AGB	Mira Variables	bright	300-600	>600K	emission	yes
LAGB	OH/IR stars	no optical counterpart	600-2000	250-600K	absorption	strong
post-AGB	19454+2920	no	non-variable	150-250	?	weak
proto-PN	18095+2704	yes	non-variable	150-250	emission	weak
young PN	Vy2-2 Hb 12	bright	non-variable	100-200	emission	single peak
PN	many	bright	non-variable	<100	no	no

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