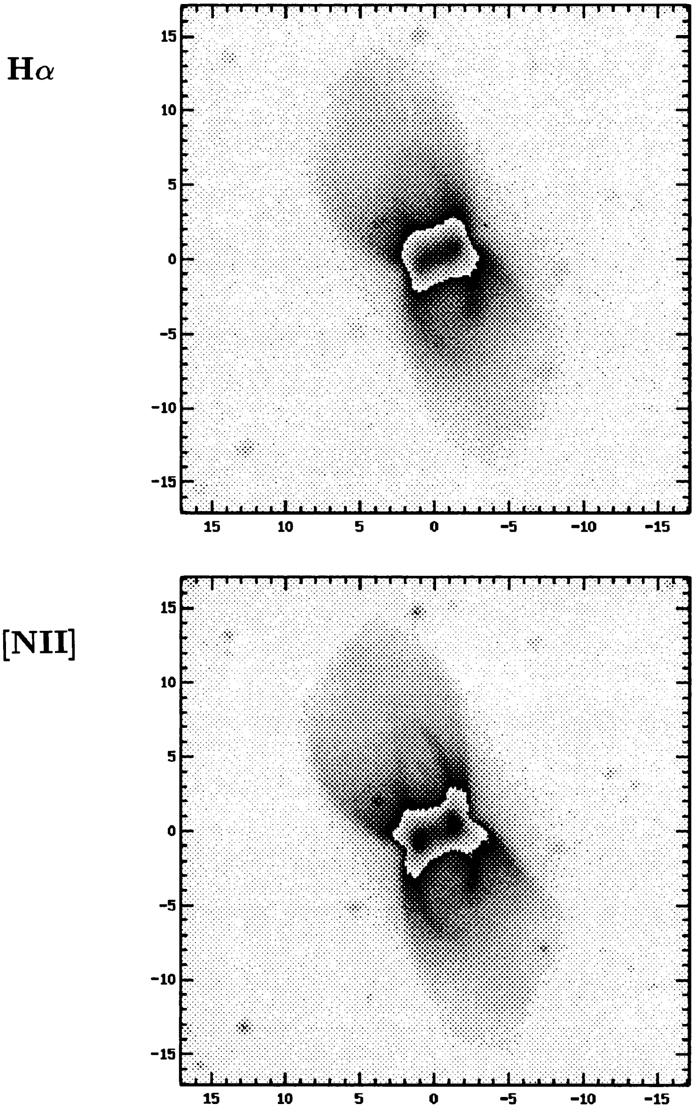
VI. FROM PLANETARY NEBULAE TO WHITE DWARFS



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STRUCTURE AND EVOLUTION OF CENTRAL STARS OF PLANETARY NEBULAE

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Abstract. In this review a critical examination of our present knowledge about the structure and evolution of central stars of planetary nebulae is presented. In particular, the still enigmatic origin of the Wolf-Rayet central stars is addressed, too. Some directions for future work are given at the end.

1. Introduction

When I was asked to present a review lecture on structure and evolution of the central stars, I was a little bit embarrassed since this would be the fourth time that I got invited to speak about the same topic on an IAU symposium devoted to planetaries (Schönberner and Weidemann, 1983; Schönberner, 1989; Schönberner, 1993). The less so since our knowledge on central-star evolution hasn't really improved since the last symposium in Innsbruck four years ago. This is contrasted by the tremendous wealth of high-quality observational data that have been accumulated during the same time and which demands appropriate interpretation.

Because I expect many new colleagues in the audience, I will start with a short introduction of the subject before I will turn to still existing problems. More details concerning evolutionary aspects about planetaries, central stars and their progenitors and successors can be found in the very extensive review article of Iben (1995).

Observationally there are two distinct populations of central stars known, as manifested by their spectral signatures: most central stars have a normal. i.e. solar, helium-to-hydrogen ratio, a significant but not yet to specify fraction of them, however, appears to be hydrogen-deficient and carbon-rich (cf. Hamann, these proceedings). Whereas we believe to understand the structure and evolution of the former with normal surface abundances

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reasonably well, the evolution of the so-called Wolf-Rayet central stars is still enigmatic. The main part of this review is thus devoted to the theory of central-star evolution applicable to objects with normal surface helium-to-hydrogen ratio. The question about formation and evolution of Wolf-Rayet central stars will be addressed at the end.

There is no doubt today that planetary nebulae (PN) represent in the Hertzsprung Russell diagram the short-lived evolutionary link between the tip of the asymptotic giant branch (AGB) and the regime of the white dwarfs. The internal constitution of the central stars (CSPN) and hence their evolutionary behavior is determined by the transition from a state in which one of the two possible nuclear-burning shells, either the hydrogen or helium shell source, provides the surface luminosity until a state is reached in which the star has run out of nuclear fuel and is radiating away only energy from gravo-thermal energy release. Whereas the beginning of the central-star phase is well defined by the turn-on of its planetary because of ionization, there exists no sharp transition to the white-dwarf regime: many central stars of the oldest planetaries (as judged from their kinematical ages) are obviously among the hottest white dwarfs (Napiwotzki and Schönberner, 1995).

Since the last symposium new complete evolutionary calculations from the main sequence until the final white-dwarf stage have been published by Vassiliadis and Wood (1993, 1994) and Blöcker (1995a, 1995b). The most important ingredient for such calculations is the inclusion of mass loss which then results in an unique combination of initial (main sequence) and final (white dwarf) mass. Since a rigorous theory of mass loss is still lacking, one has to resort to semi-empirical expressions that relate the stellar parameters to a mass-loss rate. Both sets of calculations used different approaches, the resulting initial-final mass relations, however, are within the observational uncertainties consistent with the empirical relation of Weidemann (1987). Vassiliadis and Wood considered also lower metallicities in order to cover Magellanic Cloud data.

An example of a complete evolutionary calculation of an initially $3\,M_\odot$ star from the main sequence through all following stages is shown in Fig. 1. Mass loss occurs mainly during the thermal pulses (not well resolved in the figure), terminates abruptly the AGB evolution and determines the final mass, $0.605\,M_\odot$ of the central star (and white dwarf). The mass loss prescription is that of Blöcker (1995a).

Regardless what kind of specific mass-loss description has been used, at the upper AGB the corresponding rate is always much larger than the burning rate and determines final mass and internal structure of the AGB remnant. On the AGB the stellar structure is briefly characterized by two burning shells surrounding the electron-degenerated carbon-oxygen core

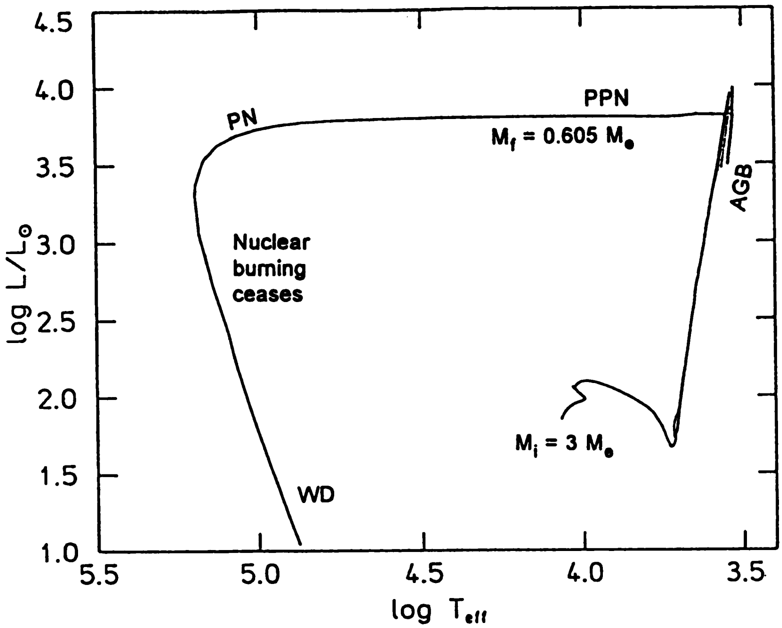

Figure 1. Evolutionary path of an initially 3 $M_{\odot}$ star from the main sequence to the white-dwarf stage. The main evolutionary phases are indicated (AGB = asymptotic giant branch, PPN = proto-planetary nebulae, PN = planetaries, WD = white dwarfs), and the last thermal pulses (from a total of 17) at the tip of the AGB are clearly visible. The model is burning hydrogen until the shell source gets extinct ($\Phi_i \approx 0.5$). The final mass is 0.605 $M_{\odot}$.

which represents nothing else than a very hot white dwarf. Normally the hydrogen-burning shell source provides the surface luminosity, and helium burning contributes only insignificantly. The helium shell source is, however, thermally instable and runs repeatedly into short-lived luminosity spikes, the so-called thermal pulses or helium shell flashes. Most of this extra energy generation is being converted into potential energy, leading to a rearrangement of the internal structure and to corresponding surface-luminosity variations (cf. Iben, 1995). Right after the pulse, for instance, the hydrogen-rich layers are lifted and cooled until the shell source gets practically extinct. Helium burning is now the dominant energy source until contraction heats up the hydrogen-rich layers hydrogen burning takes over again.

These thermal pulses appear with a regular period that increases slowly with the core mass, a relation originally found by Paczyński (1975). For a typical core mass of about 0.6 $M_{\odot}$ this period is of the order of 10^5 years. It is useful to characterize the internal stellar structure by a thermal-pulse cycle phase angle, Φ, where $\Phi = 0$ is naturally set at the maximum of the helium-shell luminosity. Since during one complete thermal-pulse cycle, i.e. from one pulse to the next one, the luminosity contributions of the two burning shells and the gravo-thermal part to the total surface luminosity are slowly changing with time, the internal constitution of an AGB star is conveniently characterized by Φ. For small phase angles ($0 \leq \Phi \lesssim 0.15$) the star is said to be helium burning, for larger angles hydrogen burning (cf. Fig. 2). These two main internal structures (i.e. helium or hydrogen burning) that develop at the upper AGB transform into different shapes and speeds of the evolutionary paths in the HRD diagram (Härm and Schwarzschild, 1975; Schönberner, 1979; Iben, 1984). Each individual evolutionary path is characterized by the initial phase angle Φ_i when the star left the AGB driven by mass loss.

The model shown in Fig. 1 has $\Phi_\mathrm{i} \approx 0.5$ and is burning hydrogen until the shell source ceases at the entrance to the white-dwarf regime. Two things, however, are to be noted. Firstly, even during hydrogen-burning the power of the hydrogen shell source is steadily increasing, while helium burning and gravo-thermal energy release are decreasing to unimportance until the next helium shell flash occurs. Correspondingly, *the* well-defined hydrogen-burning post-AGB evolutionary track does not exist (cf. discussion in Wood and Faulkner, 1986). The typical variations of the different energy producing processes during a complete thermal-pulse cycle are illustrated in Fig. 2.

Secondly, and even more important, the phase angle Φ characterizing the internal constitution advances during the post-AGB evolution and may even reach unity before hydrogen burning ceases. This means that a so-called "late" thermal pulse occurs during the remnant's transition to a white-dwarf configuration (Schönberner, 1979). Driven by the excess energy liberated in the helium shell the model turns rapidly back to its Hayashi limit, stays there for a while, and repeats again its course to a white-dwarf configuration, now burning helium. This kind of evolution is often referred to as the "born again" scenario. Note, however, that the assignment of such an evolutionary state to one particular object is only a matter of indirect reasoning since the (hydrogen-rich) surface composition is not altered at all! The only bona fide born-again object known so far is the central star FG Sge (Blöcker and Schönberner, 1995; Blöcker and Schönberner, 1997).

With a small probability the helium shell flash is triggered right after the hydrogen shell gets extinct, and in this case the flash driven convective tongue cuts into hydrogen-rich matter and mixes protons down to burning temperatures (Schönberner, 1979). To follow the evolution further is numerically tricky since proton burning and convective turn-over time scales become equal (Iben et al., 1983). A first more exploratory computation through such a very late pulse has been presented by Iben and MacDonald

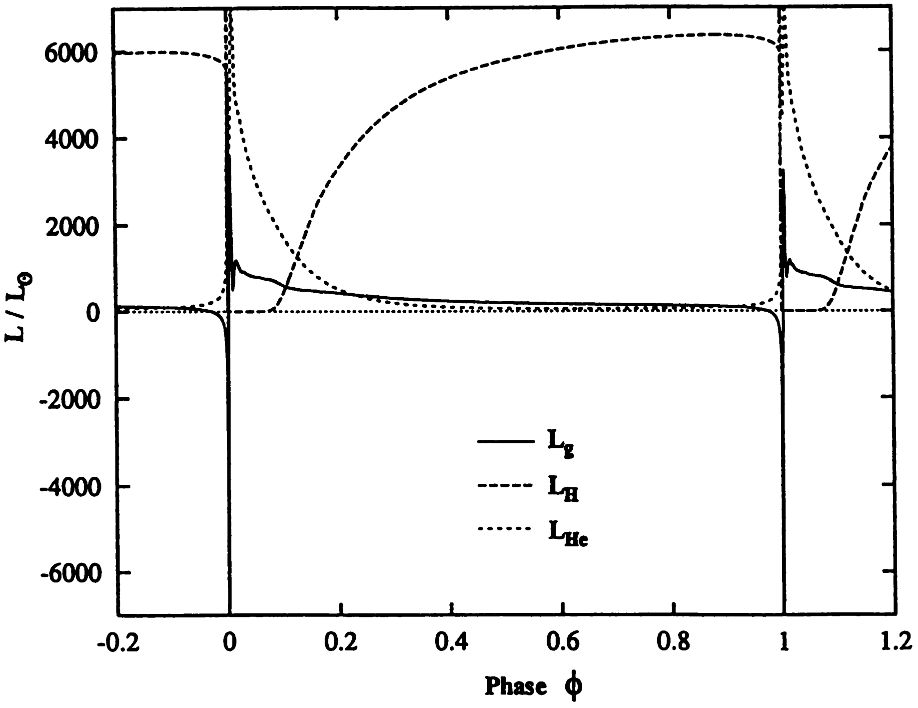

Figure 2. The contribution of hydrogen burning ($L_{\rm H}$), helium burning ($L_{\rm He}$) and gravo-thermal energy release ($L_{\rm g}$) to the surface luminosity as function of the thermal-pulse phase angle Φ. The seventh thermal pulse cycle of the sequence from Fig. 1 is shown, and the corresponding mass of the hydrogen-exhausted core is 0.578 $M_{\odot}$.

(1995). It appears that the stellar surface becomes hydrogen poor by rapid burning and mixing, the evolution across the Hertzsprung Russell diagram is, however, so quick that it may prove difficult to find observational counterparts to the models. It is believed that two objects suffered, or are just suffering, from a such very late pulse, viz. V605 Aql, the central star of A 58 (Seitter, 1987), and Sakurai's object (Duerbeck and Benetti, 1996).

2. Evolution off the AGB, across the Hertzsprung-Russell diagram and down to the white-dwarf regime

2.1. EVOLUTION OFF THE AGB

It has been emphasized above that mass loss determines the final evolution along the upper AGB and hence also the transition into the PN region where the evolution is controlled by nuclear burning. The modeling of mass loss fixes then the evolutionary speed of any AGB remnant and the time in

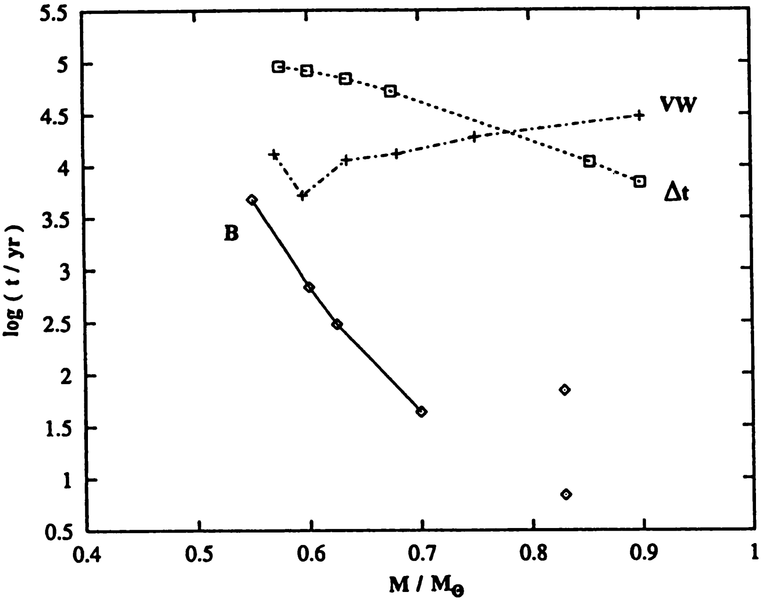

Figure 3. Post-AGB ages at $T_{\rm eff}$ = 10 000 K of remnants with different masses as they follow from the calculations of Vassiliadis and Wood (VW) and Blöcker (B). The thermal-pulse cycle periods are also given for comparison (Δt).

which a cool dusty wind envelope is being transformed into an observable planetary. At present two different semi-empirical approaches have been performed (Vassiliadis and Wood, 1993; Blöcker, 1995b). Vassiliadis and Wood decided to switch off the large AGB mass loss relatively close to the Hayashi limit, whereas Blöcker kept the high AGB rate until the star's fundamental radial pulsation period has fallen below 50 days. This latter approach leads to rather high starting temperatures for the post-AGB evolution, viz. 6000 K for 0.6 $M_\odot$ up to 7900 K for 0.94 $M_\odot$. In the Vassiliadis and Wood approach the situation is different: the post-AGB evolution starts at 5000 K for low remnant masses and at 3500 K for 0.9 $M_\odot$.

Correspondingly, the transition times from the tip of the AGB into the PN regime behave quite differently as illustrated in Fig. 3. The Blöcker models show a very rapid *decrease* of the transition time with mass by two orders of magnitude, whereas the Vassiliadis and Wood models indicate a slight *increase* with mass. At lower remnant masses both sets of calculations give similar answers. The important difference is that the transition times of the Vassiliadis and Wood models compare well with the thermal-pulse cycle periods, a fact which favors, according our discussion above, the occurrence of a late helium flash already during the transition to the

PN region. This explains the relatively large number of helium-burning, "born-again" models found by Vassiliadis and Wood (1993).

It appears to us that the rather large transition times found for the Vassiliadis and Wood mass-loss modeling are somewhat in variance with observations: the coolest post-AGB stars known have about 5000 K effective temperature (Schönberner and Blöcker, 1993), and kinematical ages of the youngest planetaries are only of the order of 1 000 years. As long as there is no consistent theory available that describes mass loss on and in the vicinity of the AGB, the models of Blöcker (1995b) are to be preferred.

2.2. EVOLUTION ACROSS THE HERTZSPRUNG-RUSSELL DIAGRAM

In the PN region proper (cf. Fig. 1) mass loss based on radiation pressure on lines is always too small as to compete with hydrogen burning (Pauldrach et al., 1988). The total crossing time is then uniquely given by the available fuel (i.e. the envelope mass) divided by the hydrogen luminosity. Because the envelope mass decreases and the luminosity increases with remnant mass, one arrives at the following figures for typical crossing times from 10 000 K to the turn-around point in the Hertzsprung-Russell diagram: about 100 000 years for $0.55\,M_\odot$, 4 000 years for $0.6\,M_\odot$, and 50 years for $0.94\,M_\odot$. Small differences for a given mass are due to the dependence of envelope mass and hydrogen luminosity from the phase angle Φ_i, as discussed above. Also a metallicity dependence has been noted (Iben and MacDonald, 1986).

2.3. FADING TO THE WHITE-DWARF REGIME

When hydrogen burning cannot be sustained any longer because the envelope mass becomes too small, the surface luminosity must drop very fast by at least one order of magnitude until the gravo-thermal contribution is reached. Helium burning is unimportant for most phase angles and dies away as well. The fading time of AGB remnants down to, for instance, 100 $L_\odot$ is thus controlled by the gravo-thermal energy release (and by neutrino energy losses as well). Both processes depend on the thermo-mechanical structure of the core, and thus on the the *complete* evolutionary history!

Fig. 3 of Blöcker (1995b) demonstrate clearly how the gravo-thermal and neutrino luminosity along the AGB develop with increasing core mass (i.e. with each thermal pulse or with time) and how both depend on the parent masses. The general trend is that both luminosities increase with core mass, with the important modification that they first decrease for larger initial masses until the cores converge into common structures. This evolutionary phase, however, may not be reached because of mass loss. Considering only the gravo-thermal energy, the fading time down to the white-dwarf regime would actually *increase* with core mass. Only the increasing neutrino luminosity leads to accelerated dimming of the more massive remnants (cf. Fig. 11 in Blöcker, 1995b). Note also that because the gravo-thermal energy release that can be radiated away is restricted by the degree of electron degeneracy, the larger cores from more massive parent stars (less dense, hotter and hence less degenerated) fade more slowly than corresponding cores from lighter parent stars (Blöcker and Schönberner 1990).

The lowest luminosity that can be reached by a central star within the typical lifetime of its planetary ($\approx$ 10 000 years) depends also on the crossing time discussed above, which is largest for the lowest masses. Considering crossing and fading time together with a reasonable assumption of the parent star's mass it turned out that the least luminous central stars should have about 0.65 $M_\odot$ (Blöcker and Schönberner, 1990). A similar result emerges from Vassiliadis and Wood's (1994) calculations.

3. Hydrogen or helium burning?

We discussed already how the mass loss in the vicinity of the AGB may influence the internal structure and evolutionary pace of post-AGB remnants. Of special importance for the interpretation of observations is the question about the ratio between hydrogen and helium-burning CSPN. To proceed in this direction, it is customary to determine evolutionary rates for a sample of well-placed central stars from the corresponding nebular ages as defined by nebular radii divided by expansion velocities. This method has, however, severe inherent defects:

- nebular radii depend on the distances assumed, which then limits the method to galactic bulge or Magellanic Cloud objects;
- because of stratification the expansion velocity may depend on the ion used;
- the nebular rim is a shock front whose propagation speed is in most cases larger than that of any material inside the PN and not accessible to spectroscopic observations.

We conclude that observed nebular ages are of very limited use to deduct the internal structure of the corresponding central stars and that any results based on them should be treated with caution. At the moment we can only state that the present used mass-loss prescriptions favor post-AGB models with $\Phi_\mathrm{i} \gtrsim 0.5$. The helium-burning models of Vassiliadis and Wood (1994) are practically all born-again objects, i.e. they left the AGB when still burning hydrogen! Models with $\Phi_\mathrm{i} = 0$ would require an extreme fine tuning between evolution and mass loss which appears to us very unlikely.

4. The Wolf-Rayet central stars

The Wolf-Rayet central stars constitute a significant fraction of the whole central-star population and seem to form a complete evolutionary sequence from the coolest very luminous down to faint but very hot objects. Further details of their properties are given by Hamann (these proceedings), and they can briefly be summarized as follows:

- the stellar surface is virtually hydrogen-free, but extremely carbon-rich with $C/He \approx 1 \ldots 0.5$, $C/O \approx 3 \ldots 10$ (mass fractions);
- relatively large mass-loss rates, varying between 10^{-7} and 10^{-5} $M_\odot/yr$;
- the main body of the nebular shells show, however, in all cases a normal, i.e. hydrogen-rich elemental composition. Also other nebular properties are in line with those that are found in planetaries around hydrogen-rich central stars (cf. Górny and Stasińska, 1995).

From these observational constraints one may conclude that the formation of hydrogen-deficient CSPN must occur near the tip of the AGB within a time span of the order of 1 000 years by an as yet not specified mechanism.

The only scenarios proposed so far rely on a late thermal pulse in connection with mass loss or a very late pulse with incomplete envelope burning and mixing. Both scenarios have obvious defects and are so far only in a very rudimentary stage (cf. discussion in Schönberner, 1996). For instance, mass loss cannot expose the hydrogen-free layers before temperatures of 100 000 K are reached (Iben, 1984; Blöcker and Schönberner, 1990), and if both burning and mixing occurs, the times scales become too short (Iben and MacDonald, 1995). Both scenarios suffer also from the fact that the present stellar models cannot even principally account for the observed surface abundances of the Wolf-Rayet central stars: the composition of the intershell region, containing the products of partial helium burning, is in variance with the observations, $C/He \approx 1$, $C/O \approx 3 \ldots 10$!

In this context I would strongly advise not to compare observed properties of Wolf-Rayet CSPN with existing evolutionary calculations. Inferred conclusions may be completely misleading!

5. Concluding remarks

At this stage I would like conclude my review with the following remarks: The theory of central stars as being mainly hydrogen-burning post-AGB objects with normal surface composition is fairly elaborate and quite successful in interpreting the observations. We don't know yet, however, the fraction of helium-burning CSPN (with normal surface compositions), and how it is possible for some of them to turn into hydrogen-free objects.

What is needed in the future is a theory of mass loss on the AGB and beyond, a better treatment of very-late shell flashes with burning, mixing and mass loss, and new stellar models that include optically-thick wind envelopes. More attention should also be given to model the whole physical system, central star with its expanding wind envelope, from the AGB down to the white-dwarf region.

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