

The formation of DA white dwarfs with thin hydrogen envelopes

L. G. Althaus^{1,*}, M. M. Miller Bertolami^{2,**}, A. H. Córscico^{2,3,*}, E. García-Berro^{1,4}, and P. Gil-Pons¹

¹ Departament de Física Aplicada, Universitat Politècnica de Catalunya, Av. del Canal Olímpic s/n, 08860 Castelldefels, Barcelona, Spain

e-mail: althaus@fcaglp.unlp.edu.ar

² Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, (B1900FWA) La Plata, Argentina

³ Instituto de Astrofísica La Plata, IALP, CONICET-UNLP, Argentina

⁴ Institut d'Estudis Espacials de Catalunya, Ed. Nexus, c/Gran Capità 2, 08034 Barcelona, Spain

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Abstract. We study the formation and evolution of DA white dwarfs, the progenitors of which have experienced a late thermal pulse (LTP) shortly after the departure from the thermally pulsing AGB. To this end, we compute the complete evolution of an initially $2.7 M_{\odot}$ star all the way from the zero-age main sequence to the white dwarf stage. We find that most of the original H-rich material of the post-AGB remnant is burnt during the post-LTP evolution, with the result that, at entering its white dwarf cooling track, the remaining H envelope becomes $10^{-6} M_{\odot}$ in agreement with asteroseismological inferences for some ZZ Ceti stars.

Key words. stars: evolution – stars: abundances – stars: AGB stars: interiors – stars: white dwarfs – stars: oscillations

1. Introduction

White-dwarf stars constitute the end-point of the evolution of low- and intermediate-mass stars. Hence, they play a key role in our quest for understanding the structure and history of our Galaxy. The vast majority of white dwarfs are the remnants of Asymptotic Giant Branch (AGB) stars and are characterized by H-rich atmospheres (usually referred to as DAs). Indeed, white dwarfs with H surface layers represent about 80% of the spectroscopically identified white dwarfs.

Considerable progress in the study of these stars has been possible partially because some of these stars pulsate. The study of the pulsational pattern of variable DA white dwarfs (or ZZ Ceti stars) through asteroseismology has provided valuable constraints to their fundamental properties, such as the core composition, the outer layer chemical stratification or the stellar mass. In particular, the mass of the outer H layer is an important issue regarding the spectral evolution theory. Most of the asteroseismological fittings to individual pulsators predict the thickness of the almost pure H envelope to be about 10^{-4} of the total stellar mass, M_{*} , in agreement with the expectations from the standard stellar evolution theory. However, H envelopes substantially thinner than the quoted value have been inferred for some ZZ Ceti stars (Bradley 2001), suggesting that there is likely a *range* of H content possible for

DA white dwarfs, a suggestion that is in line with evidence from spectroscopy (Fontaine & Wesemael 1997). The existence of DA white dwarfs with such thin H envelopes is difficult to reconcile with the accepted view of the post-AGB evolution theory that predicts the thickness of the H envelope to be about $10^{-4} M_{*}$. Indeed, the existence of such white dwarfs poses a real challenge to the theory of stellar evolution.

We undertake the current investigation with the aim of exploring the possibility that a fraction of the DA white dwarf population with thin H envelopes could be the descendants of post-AGB PG 1159 stars with surface layers rich in H, helium, carbon and oxygen (Werner 2001). According to Blöcker (2001), these hybrid-PG 1159 could be the result of a final helium shell flash experienced by a star shortly after the departure from the AGB – the so-called AGB final thermal pulse, AFTP scenario, or late thermal pulse, LTP. During an AFTP or LTP, H is not burnt, in contrast to post-AGB stars that experience a *very* late thermal pulse (a born-again episode, see Althaus et al. 2005, for a recent calculation), but it is diluted by surface convection and mixed inwards with the underlying intershell region formerly enriched in helium, carbon and oxygen. We speculate that H burning during the following PG 1159 stage will reduce most of the H content of the remnant to a level compatible with the asteroseismological predictions for some DA white dwarfs with relatively thin H envelopes. Specifically, we present complete evolutionary calculations that simulate the formation and evolution of H-rich white dwarfs through a late helium shell flash starting from the main sequence.

* Member of the Carrera del Investigador Científico y Tecnológico and IALP, CONICET / FCAG-UNLP, Argentina.

** Fellow of CONICET, Argentina.

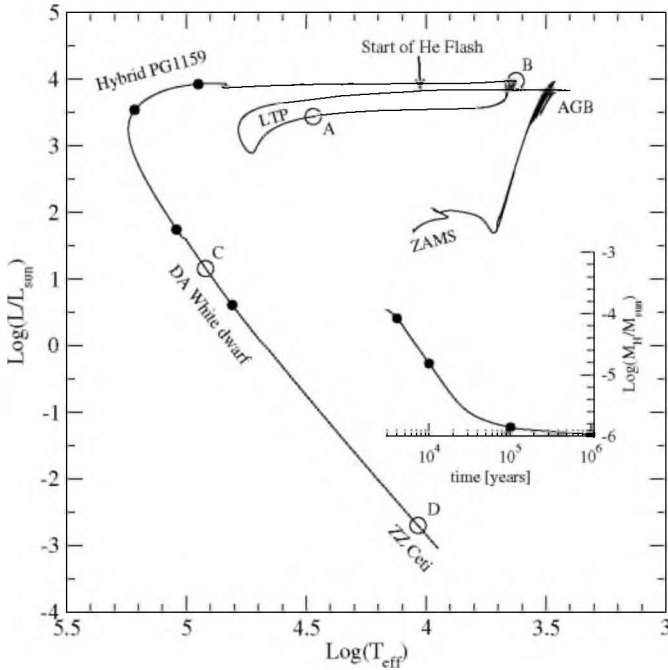


Fig. 1. H-R diagram for the complete evolution of the initially $2.7 M_{\odot}$ stellar model from the ZAMS to the ZZ Ceti domain. In this simulation, the star undergoes a LTP shortly after leaving the AGB at $\log T_{\text{eff}} = 4$. As a result, further evolution proceeds to the blue and then to the red-giant domain where the H envelope is diluted by surface convection. Inset: temporal evolution of H mass in solar units. Filled dots correspond to those stages indicated along the evolutionary track. Most of H is processed by nuclear burning during the PG 1159 stage.

2. Input physics and computational details

The calculations presented in this work have been done with the same stellar evolutionary code we employed in our previous study of the formation of H-deficient white dwarfs via a born-again episode (Althaus et al. 2005). The code is based on a detailed description of the main physical processes involved in the formation of post-AGB stars. Abundance changes are described by means of a time-dependent scheme for the simultaneous treatment of nuclear evolution and mixing processes (Althaus et al. 2003). This is particularly relevant during some short-lived phases of evolution for which the instantaneous mixing approximation becomes inadequate for addressing chemical mixing. In addition, we have included time-dependent overshoot mixing above and below any convective region during all evolutionary stages. As shown by Herwig (2001), convective overshoot during the post-AGB stage is required to obtain efficient dredge-up for very low envelope masses and dilution of H¹. Gravitational settling, chemical and thermal diffusion have been considered during the whole white dwarf regime. The evolutionary stages for the progenitor star are described in Althaus et al. (2005). Briefly, the evolution of an initially $2.7 M_{\odot}$ stellar model has been computed from the zero-age main sequence all the way from the stages of H and helium burning in the core up to the tip of the AGB where

¹ An additional process that could contribute to the dredge-up is the rotationally induced mixing, see Langer et al. (1999).

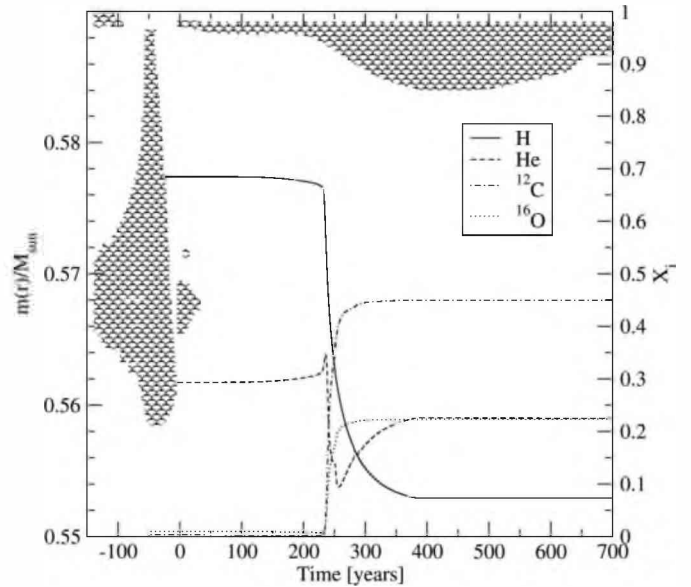


Fig. 2. Temporal evolution of the convective regions and surface abundances of ^1H , ^4He , ^{12}C and ^{16}O during the LTP. Note the development of the surface convection zone and the dilution of surface H.

helium thermal pulses occur. A solar-like initial composition (Y, Z) = (0.275, 0.02) has been adopted. After experiencing 10 thermal pulses, the progenitor departs from the AGB with a stellar mass of $0.5885 M_{\odot}$ and evolves towards high effective temperature (T_{eff}) values. Departure from the AGB takes place at such an advanced phase of the helium shell flash cycle that the post-AGB remnant undergoes a LTP at about $T_{\text{eff}} = 10\,000$ K. In order to get the last flash at the appropriate location, we forced the model to depart from the thermally pulsing AGB somewhat later than it was done in Althaus et al. (2005). As a result of the flash, the remnant evolves back to the AGB, and eventually to the domain of the PG 1159 stars.

3. Evolutionary results

A complete coverage of the evolutionary stages in the H-R diagram of our sequence is displayed in Fig. 1. Relevant episodes are shown at specific points along the curve. In particular, note that after the occurrence of the thermal pulses at the tip of the AGB, the remnant star evolves through a LTP, which starts at about $\log T_{\text{eff}} = 4$. As a result, the star evolves rapidly to high T_{eff} values and then back to the red-giant region, where the remaining H-rich material is diluted by surface convection and mixed inwards with the underlying intershell region (see Fig. 2). After the short-lived dredge-up episodes, the remnant is left with an envelope composition rich in H, helium, carbon and oxygen. In particular, H is diluted to very low abundances and it extends downwards as deep as $5.6 \times 10^{-3} M_{\odot}$ below the stellar surface. Dredge-up sets in at the minimum effective temperature ($T_{\text{eff}} \approx 4600$ K) and develops during a short redward excursion. Specifically, the final surface abundances by mass of H, helium, carbon and oxygen amounts, respectively, to 0.073, 0.323, 0.382 and 0.19. After H dilution, evolution proceeds into the domain of the central stars of planetary nebulae at high T_{eff} to become a hybrid PG 1159 star.

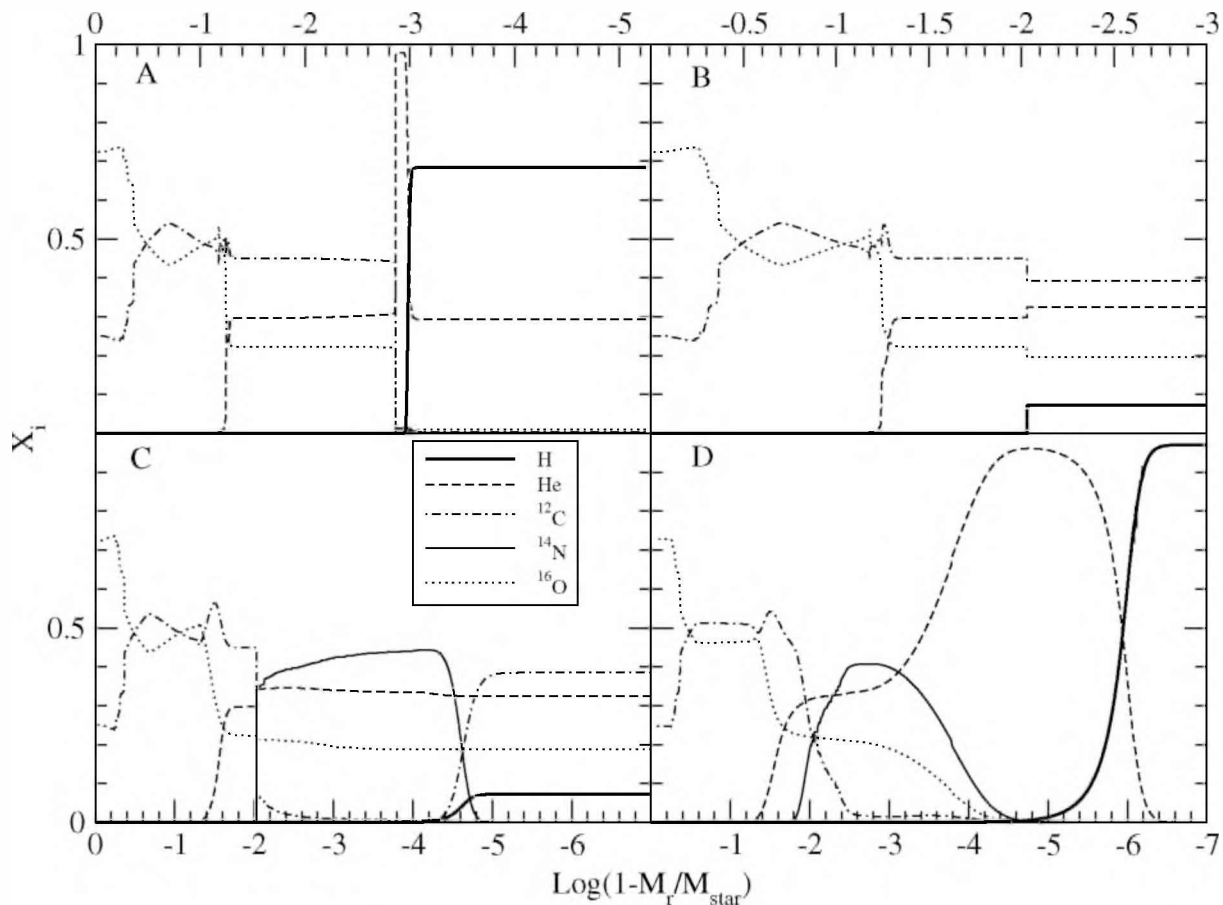


Fig. 3. Internal abundance distribution of ^1H , ^4He , ^{12}C , ^{14}N and ^{16}O as a function of the outer mass fraction for the $0.5885 M_{\odot}$ remnant at various selected epochs comprising the LTP and the white dwarf stages. Panels A, B, C and D correspond to stages labeled by letters along the curve in Fig. 1. Because of nuclear burning occurring during the PG 1159 stage at high effective temperatures, the remnant star is left with a small H content at entering the white dwarf cooling track. Gravitational settling ultimately leads to the formation of a DA white dwarf with a thin H envelope.

In the meantime, H is reignited and after the point of maximum effective temperature is reached on the early white dwarf cooling track, the H content is reduced to about $8 \times 10^{-7} M_{\odot}$, that is, by more than two orders of magnitude as compared with the amount of H that is left after the remnant departs from the AGB. This value is the amount of H with which the star enters the white dwarf domain. The temporal evolution of the H content is illustrated in the inset of Fig. 1. Most of the residual H material is burnt over a period of roughly 100 000 yr during the PG 1159 stage. It is noteworthy that H burning takes place in a carbon-enriched medium, with the consequent nitrogen enrichment in the H-burning layers. On the cooling track, H diffuses outwards, turning the white dwarf into one of the DA type with a thin pure H envelope of a few $10^{-7} M_{\odot}$.

An example of the main inner chemistry variations that take place after the remnant star leaves the AGB is provided in Fig. 3. Specifically, the abundances by mass of ^1H , ^4He , ^{12}C , ^{14}N and ^{16}O are displayed in terms of the outer mass fraction. Panel A shows the chemical stratification shortly after the occurrence of the LTP (marked as A in Fig. 1). In the outermost layers the chemical profile corresponds essentially to that emerging from the dredge-up events and nuclear burning during the thermally pulsing AGB phase. As the star

becomes cooler, the inward-growing surface convection zone eventually mixes downwards protons from the original H-rich envelope with the underlying intershell region rich in helium, carbon and oxygen. The resulting abundance distribution after this dredge-up episode is illustrated in panel B (corresponding to point B in Fig. 1). Note that H has been diluted to surface abundances of about 0.073 and mixed down to regions as deep as $5.6 \times 10^{-3} M_{\odot}$ below the stellar surface. Most of this deep-lying H is burnt as the star evolves towards high effective temperatures, as documented in panel C (labeled as C in Fig. 1). After nuclear processing is completed, the remaining H mass amounts to only $8 \times 10^{-7} M_{\odot}$. Because H burning occurs in a carbon-enriched medium, an overwhelming abundance of nitrogen is expected. Finally, panel D (which corresponds to point D in Fig. 1) illustrates the situation by the time the domain of the ZZ Ceti stars is reached. The signatures left by the various diffusion processes acting during white dwarf evolution are easily recognizable. In particular, note the formation of a pure H envelope of $4 \times 10^{-7} M_{\odot}$ as a result of gravitational settling. That is, a DA white dwarf with a thin H envelope is formed. Gravitationally-induced diffusion gives also rise to the development of a triple-layered chemical structure characterized by a pure H envelope atop a pure helium buffer

and an underlying intermediate remnant shell rich in helium, carbon, nitrogen and oxygen. Note also the mixing episode that takes place in the region below the intershell zone around $1 - M_r/M_* = 0.1$. This region is characterized by an inward-decreasing mean molecular weight induced by the occurrence of overshooting during the AGB thermally pulsing phase. The resulting Rayleigh-Taylor rehomogenization is responsible for the redistribution of the chemical species in that region.

4. Discussion and conclusions

The present work has been specifically designed to explore the possibility that post-AGB stars that undergo a LTP could evolve into the white dwarf regime with thin H envelopes. The results are based on evolutionary calculations starting on the ZAMS that cover all the stages involved in the formation of hybrid (H-rich) PG 1159 stars via a LTP. Our results show that most of the original H-rich material of the post-AGB remnant is burnt during the post-LTP evolution. We have found that when the star enters its terminal white dwarf cooling track, the H content is reduced to about $10^{-6} M_\odot$ after nuclear burning has virtually ceased, that is, by more than two orders of magnitude as compared with the amount of H that is left after the remnant departs from the AGB. Because we have not invoked possible mass-loss episodes during the PG 1159 stage, the quoted value for the H mass should be considered as an upper limit.

Roughly 25% of stars leaving the AGB are expected to suffer from a born-again episode (with the complete burning of protons) or a LTP when H burning is still active (Blöcker 2001; Iben 1984). In particular, stars leaving the AGB with a thermal-pulse cycle phase larger than about 0.90 are expected to undergo a LTP. Hence, in view of our results, it is conceivable that a non-negligible fraction of the DA white dwarf population could harbour thin H envelopes. This result is in line with asteroseismological and spectroscopic predictions that suggest that there is likely a range of H thicknesses possible for DA white dwarfs (Fontaine & Wesemael 1997; Bradley 1998, 2001). Indeed, H envelopes substantially thinner than the canonical value of $10^{-4} M_*$ have been inferred for some ZZ Ceti stars.

In particular, Bradley & Kleinman (1997) found from seismological data a H envelope thickness of $5 \times 10^{-7} M_*$ for the ZZ Ceti star G 29–38. In addition, seismologically-inferred H envelopes ranging from $\sim 10^{-6}$ to $\sim 10^{-7} M_*$ have been reported by Bradley (1998) for G 117-B15A and R 548 if the period of the 215 s mode corresponds to an $\ell = 1, k = 1$ mode. Coupled with previous inferences, Bradley (1998) concluded that the H layer masses of several ZZ Ceti pulsators should lie between 10^{-4} and $10^{-7} M_*$. The results presented here place on a solid evolutionary basis these predictions about the existence of some DA white dwarfs with thin H envelopes.

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