The Diffusion Induced Nova Scenario

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Abstract

We propose a scenario for the formation of DA white dwarfs with very thin Helium buffers. For these stars we explore the possible occurrence of diffusion-induced CNO-flashes, during their early cooling stage. In order to obtain very thin helium buffers, we simulate the formation of low mass remnants through an AGB final/late thermal pulse (AFTP/LTP scenario). Then we calculate the consequent white dwarf cooling evolution by means of a consistent treatment of element diffusion and nuclear burning. Based on physically sounding white dwarf models, we find that the range of helium buffer masses for these diffusion-induced novas to occur is significantly smaller than that predicted by the only previous study of this scenario. As a matter of fact, we find that these flashes do occur only in some low-mass ($M < 0.6 M_\odot$) and low metallicity ($Z_{ZAMS} < 0.001$) remnants about $10^6 - 10^7$ yr after departing from the AGB. For these objects, we expect the luminosity to increase by about 4 orders of magnitude in less than a decade. We also show that diffusion-induced novas should display a very typical eruption lightcurve, with an increase of about 1 magnitude per year before reaching a maximum of $M_V \sim -5$ to -6. Our simulations show that surface abundances after the outburst are characterized by $\log N_H/N_{He} \sim 0.15...0.6$ and N>C>O by mass fractions. Contrary to previous speculations we show that these events are not recurrent and do not change substantially the final H-content of the cool (DA) white dwarf.

Introduction

Since the first simulations of white dwarf evolution that included a simultaneous treatment of diffusion and cooling (i.e. Iben & MacDonald 1985, 1986) it was noticed that diffusion could trigger thermonuclear CNO-flashes. In fact, the inward diffusion of H and the outward diffusion of C within the pure He zone (usually named "He-buffer", see Fig. 1) left after the last thermal pulse can lead to a runaway CNO-burning. This produces a very rapid expansion, of the order of years, of the outer layers of the white dwarf pushing the star back to a giant configuration and increasing its visual magnitude from $M_V \sim 9$ to $M_V \sim -6$ in a few years. We term this eruptive event as "diffusion-induced nova" (DIN) although it leads to a much slower brightening than classical novas. Iben & MacDonald (1986) showed that after such events the stars will become, in a few years, yellow giants with mildly He enriched surface compositions. In a more speculative mood they also suggested that DINs may be recurrent, finally leading to H-deficient compositions. Later, prompted by this speculation, D'Antona & Mazzitelli (1990) suggested that the H-rich envelope could be strongly reduced during these events, leading to DA white dwarfs with thin H-envelopes, as inferred in some DA white dwarfs (Castanheira & Kepler2009).

The main purpose of the present work is to study the possibility that DINs could take place in physically sounding white dwarf models with a realistic evolutionary history. We will also identify a detailed scenario for the creation of white dwarfs with thin enough He-buffers for DIN events to occur. Specifically, to perform this study we compute realistic white dwarf models by means of "cradle to grave" stellar evolution simulations. Then we compute white dwarf cooling sequences by considering a simultaneous treatment of element diffusion and evolution.

Brief description of the stellar evolution code

White dwarf models are obtained as the result of computing the evolution of low mass stars from the ZAMS through the helium core flash and through the thermal pulses on the AGB (TP-AGB) and, then, to the white dwarfs stage. LPCODE considers a simultaneous treatment of non-instantaneous mixing and burning of elements, by means of a diffusion picture of convection coupled to nuclear burning —see Althaus et al. (2005) for numerical procedures. The nuclear network considered in the present work accounts explicitly for the following 16 elements: ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{7}Li, ^{7}Be, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{18}O, ^{19}F, ^{20}Ne and ^{22}Ne, together with 34 thermonuclear reaction rates corresponding to the pp-chains, the CNO bi-cycle, He-burning and C-ignition as described in Miller Bertolami et al. (2006).

The treatment of diffusion is similar to that of Iben & MacDonald (1985, 1986) but we consider, in addition gravitational settling and chemical diffusion, the process of thermal diffusion. We do not take into account radiative levitation, as it is only relevant for determining surface chemical abundances and, thus, is irrelevant for the purpose of the present work. Our treatment of time dependent element diffusion is based on the multicomponent gas picture of Burgers (1969). Specifically, we solved the diffusion equations within the numerical scheme described in Althaus et al. (2003).

The proposed evolutionary scenario

Whether white dwarfs with thin He-buffer can be actually formed relies on identifying a scenario in which they could be formed under standard assumptions. As shown in Fig. 1, after a He-shell flash on the TP-AGB, the mass of the He-buffer region becomes strongly reduced by intershell convection. Such thin He-buffer survives until the reignition of the H-burning shell.

In particular, the first thermal pulses of low-mass stars ($M \sim < 1.5 M_\odot$) are not very strong and, thus, no third dredge up takes place in numerical models. Hence, it is not unreasonable to accept that low-mass stars experiencing an AGB final thermal pulse (AFTP) or a Late Thermal Pulse (LTP) will end as DA white dwarfs with thin He-buffers. In those cases, as no third dredge up happens, the very thin He-buffer survives the last helium shell flash (either AFTP or LTP). Then, during the He-burning phase that follows the flash, AGB winds will erode an important fraction of the remaining (already depleted) H-rich envelope, preventing a reignition of the H-burning shell and an increase in the He buffer mass. As a result, the He-buffer is still very thin when the star finally reaches the white dwarf phase. Then, when the star enters the white dwarf cooling phase, the inward diffusion of H and the outward diffusion of C within the He-buffer leads to the ignition of a CNO-burning shell and ultimately to a CNO-flash (see Fig. 2).

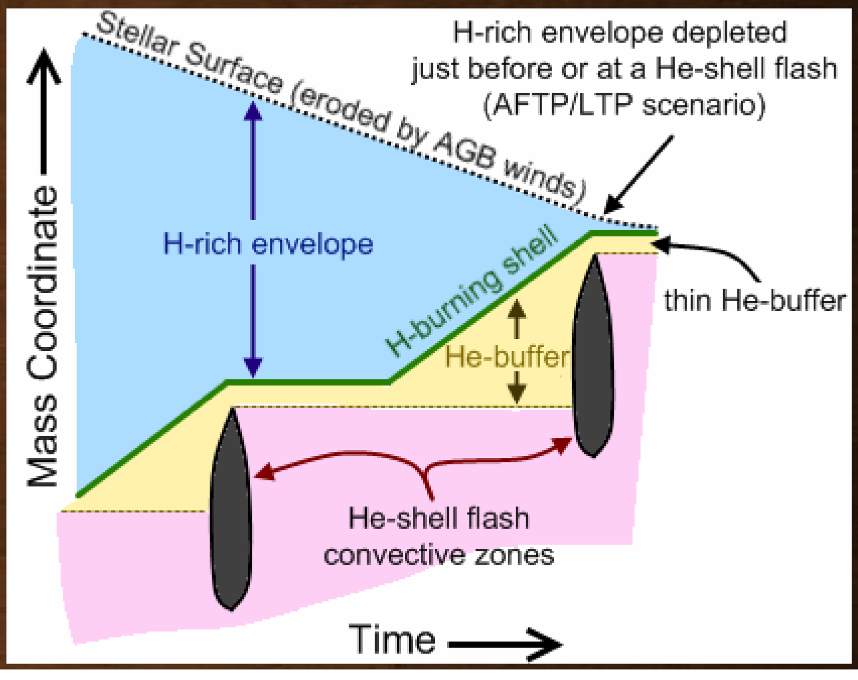

Figure 1. Sketch of a Kippenhahn diagram of the proposed sce nario for the formation of DA white dwarfs with thin He-buffers.

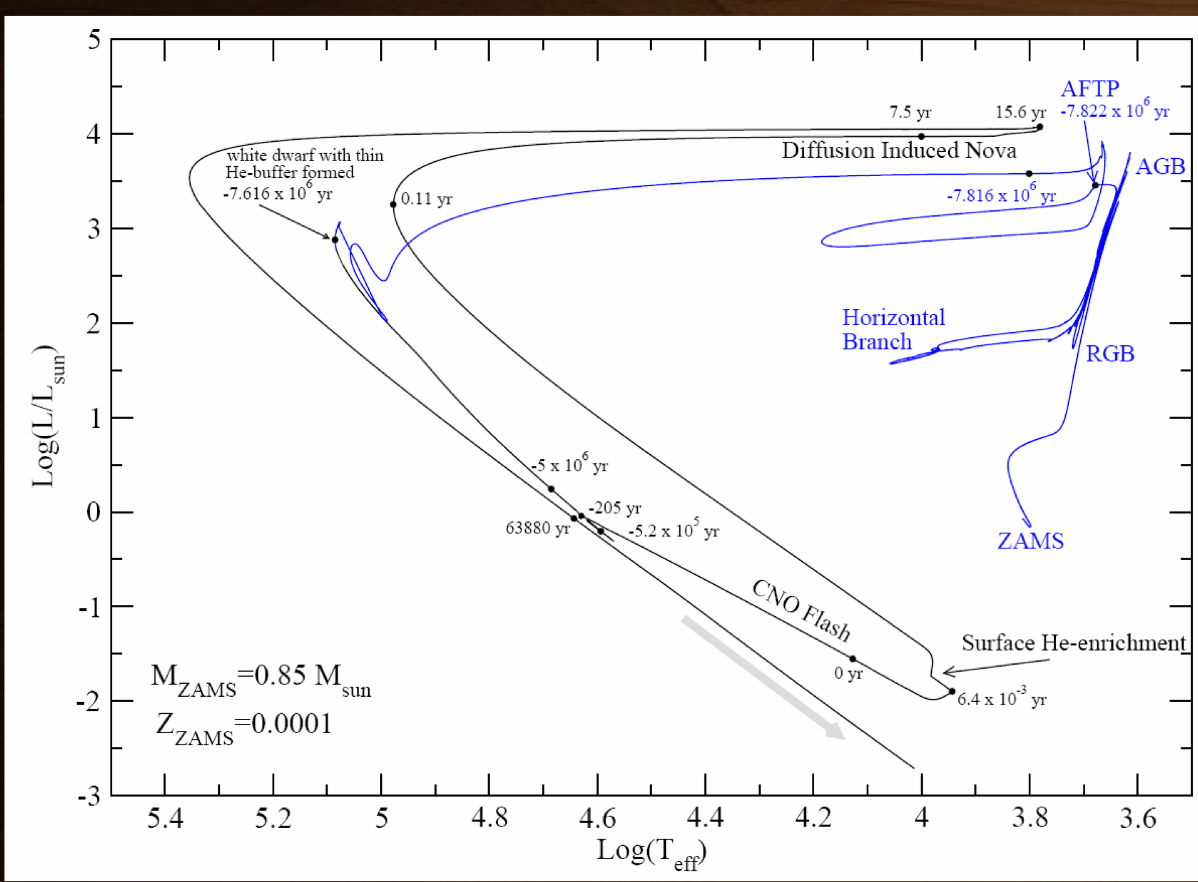

Figure 2. Evolutionary track in the HR-diagram of one of our DIN-sequences (M_{WD}=0.53946 $M_\odot$, see Table for more details). The blue part of the curve describes the pre-white dwarf evolution. Note the last thermal pulse during the departure from the AGB (AFTP, blue loop) which leads to the formation of a thin He-buffer in the white dwarf as described in Fig. 1. The black curve shows the evolution during the white dwarf stage and the diffusion induced nova event. Black dots indicate the time before and after the maximum energy release during the CNO-flash. Note that, after the CNO-flash the star acquires a giant configuration in only 15 yr. This violent change in the luminosity and temperature of the star leads to a very characteristic visual lightcurve for these objects (see Fig. 3).

As a consequence of convective mixing of the pure H envelope with material from the He-buffer the surface abundances of the star during the outburst are strongly enriched in He and N (see Table).

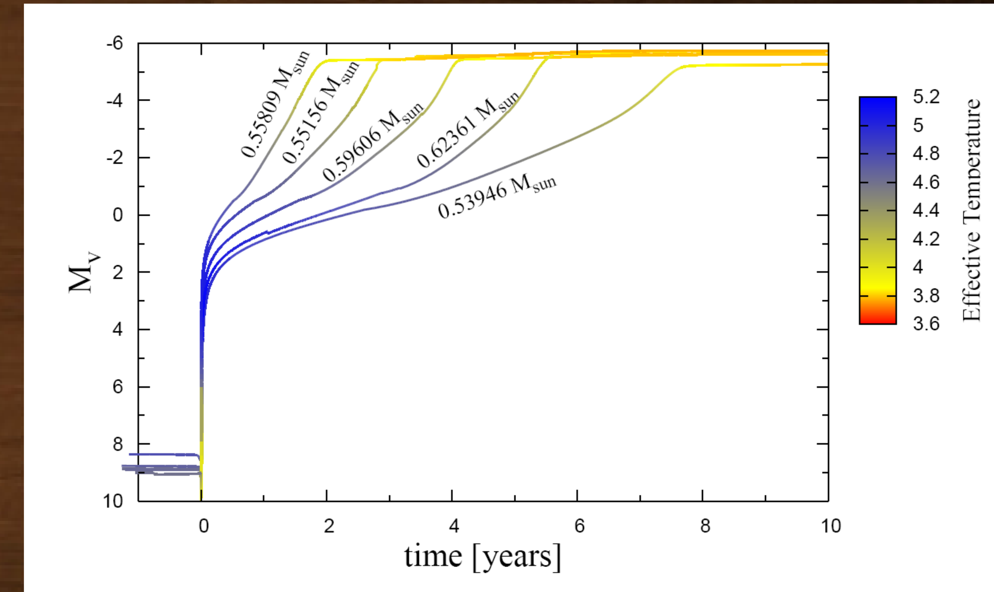

Figure 3. Predicted lightcurves and temperatures for our DIN simulated sequences during the outburst.

Progenitor Mass	White Dwarf Mass	$\log L_{pre}/L_\odot$	$\log T_{eff}^{pre}$	τ_1 [yr]	τ_2 [yr]	$\lvert dM_V/dt \rvert$	τ_3 [yr]	τ_4 [yr]	H	He	C	N	O
$0.85 M_\odot$	$0.53946 M_\odot$	-0.31	4.57	7.6×10^6	7.9	1.6	260	$\lesssim 1.6\times10^5$	0.39	0.61	10^{-5}	2.2×10^{-4}	1.1×10^{-6}
$0.85 M_\odot$	$0.54006 M_\odot$†	-0.46	4.54	1.2×10^7	10.2	1.3	-	-	0.28	0.72	4×10^{-6}	6.1×10^{-5}	3.6×10^{-7}
$0.85 M_\odot$	$0.54076 M_\odot$†	-0.96	4.42	4×10^7	4.9	1.6	-	-	0.19	0.81	10^{-5}	1.4×10^{-4}	10^{-6}
$0.85 M_\odot$	$0.54115 M_\odot$†	-1.19	4.37	7.7×10^7	2.7	2.4	-	-	0.15	0.85	4×10^{-5}	3.3×10^{-4}	3.2×10^{-6}
$1 M_\odot$	$0.55156 M_\odot$	-0.33	4.57	6.5×10^6	3	3.3	270	9.7×10^4	0.38	0.62	2×10^{-4}	4.2×10^{-3}	10^{-6}
$1.25 M_\odot$	$0.59606 M_\odot$	-0.05	4.65	3.4×10^6	4.2	2.9	216	5.5×10^4	0.49	0.51	5×10^{-5}	1.3×10^{-3}	10^{-5}
$1.8 M_\odot$	$0.62361 M_\odot$‡	0.25	4.73	2.2×10^6	5.7	2.7	49	3.1×10^4	0.46	0.54	2×10^{-5}	4.6×10^{-3}	3×10^{-6}
$1. M_\odot (Z=0.001)$	$0.55809 M_\odot$	-0.47	4.54	8.9×10^6	2.1	3.9	456	1.1×10^5	0.30	0.70	1×10^{-4}	1.9×10^{-3}	4×10^{-6}
$0.85 M_\odot$	$0.53946 M_\odot$ (w/OV)≀	-0.31	4.57	7.6×10^6	0.66	6.2	1367	5.2×10^4	0.22	0.73	6.6×10^{-3}	0.038	1.1×10^{-3}
$0.85 M_\odot$	$0.53946 M_\odot$ (w/OV, CO-rich)≀,∗	-0.03	4.63	4.1×10^6	0.42	3.1	1628	5.8×10^4	0.23	0.62	0.033	0.081	0.033
IM86 $(Z=0.001)$	$0.6 M_\odot$	-0.54	4.52	$\sim 10^7$	~ 7.5	-	-	-	0.29	0.71	6.6×10^{-4}	7.5×10^{-4}	8.1×10^{-6}

Table Outburst properties of the DINs studied in this work. With exception of the last sequence all sequences come from ZAMS progenitos with $Z = 0.0001$. Timescales are defined as follows; cooling time at the moment of the CNO-flash (τ_1), expansion time from the maximum energy release to the giant stage at $\log T_{eff} = 3.9$ (τ_2), duration of the cool ($\log T_{eff} < 4$) giant stage (τ_3) and contraction time needed to reach the pre-outburst luminosity (τ_4). †These remnants were obtained by reducing the mass lost during the final AGB thermal pulse from that predicted by standard AGB wind prescriptions. ‡This remnant was obtained by applying an artificially high wind during the fifth thermal pulse.≀ These DINs were obtained form the $0.53946 M_\odot$ sequence by including OV in the convective zone generated during the CNO-flash. ∗ In this case the intershell composition of the remnant was modified to resemble the C- and O- rich surface abundances of PG1159 stars.

Results

- We have identified a definite scenario leading to the formation of DA white dwarfs with thin He-buffers. Such white dwarfs are naturally formed in low-mass stars, that do not experience third dredge up during the TP-AGB, and suffer from either an AFTP or a LTP.
- We have explored the parameter space of the DIN scenario and shown that there is a range of values of $M_\star$, Z_{ZAMS} and He-buffer masses for which DIN occur in physically sounding white dwarf models. Our results suggest that DINs take place in white dwarfs with $M_\star < 0.6$ and $Z_{ZAMS} < 0.001$ and thin He-buffers —as those provided by the scenario described above.
- Our simulations provide a very detailed description of the events before, during and after the DIN event. In particular, our results show that DIN events are not recurrent as previously speculated. Thus, DINs do not form H-deficient white dwarfs, nor DA white dwarfs with thin H-envelopes.
- We have qualitatively described the mechanism by which the CNO-shell becomes unstable. Our analysis shows that the occurrence of CNO-flashes depends strongly on the intensity of the CNO-burning shell (as compared to the core luminosity), and its temperature. This seems to be in agreement with the fact that only our sequences with $M_\star < 0.6$ and $Z_{ZAMS} < 0.001$ and thin He-buffers experienced DIN events.
- Regarding the criterion presented by Iben & MacDonald (1986) for the occurrence of DIN events, we find that such criterion is misleading as the He-buffer mass is not the only parameter that determines whether a DIN event will take place or not. In particular, for more massive remnants our simulations do not predict DIN for any possible He-buffer masses.
- Our simulations provide a very detailed description of the expected surface abundances and lightcurves during the outbursts. In particular we find that typical lightcurves display a maximum of $M_V \sim -5.5$, a brightness speed of a few magnitudes per year, and a mild He- and N- enrichment; with $N \sim 10^{-4} - 10^{-3}$ by mass fraction and $\log N_H/N_{He} \sim -0.15...0.6$. Also, in all our sequences we find surfaces abundances with N > C > O by mass fraction.
- We find that the inclusion of extramixing events at the boundaries of the CNO-flash driven convective zone leads to higher He, N, C and O abundances than in the case in which no extramixing is considered. Relative surface CNO abundances in these cases are N > C > O (by mass fractions), although the precise values will be strongly dependent on the C and O composition of the He-, C- and O- rich intershell.