# On the recent parametric determination of an asteroseismological model for the DBV star KIC 08626021

Francisco C. De Gerónimo<sup>1, 2</sup>, Tiara Battich<sup>1, 2</sup>, Marcelo M. Miller Bertolami<sup>1, 2</sup>, Leandro G. Althaus<sup>1, 2</sup> and Alejandro H. Córsico<sup>1, 2</sup>

<sup>1</sup>Grupo de Evolución Estelar y Pulsaciones. Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, (1900) La Plata, Argentina

<sup>2</sup>Instituto de Astrofísica La Plata, IALP (CCT La Plata), CONICET-UNLP

e-mail: fdegeronimo;tbattich;mmiller;althaus;acorsico@fcaglp.unlp.edu.ar

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#### ABSTRACT

*Context.* Asteroseismology of white dwarf stars is a powerful tool that allows to reveal the hidden chemical structure of white dwarfs and infer details about their present and past evolution by comparing the observed periods with those obtained from appropriate stellar models. A recent asteroseismological study has reproduced the period spectrum of the helium rich pulsating white dwarf KIC 08626021 with an unprecedented precision of  $(P_{obs} - P_{model})/P_{model} < 10^{-8}$ . The chemical structure derived from that asteroseismological analysis is notably different from that expected for a white dwarf according to currently accepted formation channels, thus posing a challenge to the theory of stellar evolution.

Aims. We explore the relevant micro- and macro-physics processes acting during the formation and evolution of KIC 08626021 that could lead to a chemical structure similar to that found through asteroseismology. We quantify to which extent is necessary to modify the physical processes that shapes the chemical structure, in order to reproduce the most important features of the asteroseismic model. *Methods.* We model the previous evolution of KIC 08626021 by exploring specific changes in the <sup>12</sup>C( $\alpha, \gamma$ )<sup>16</sup>O reaction rate, screening processes, microscopic diffusion, as well as convective boundary mixing during core-He burning.

*Results.* We find that, in order to reproduce the core chemical profile derived for KIC 0862602, the  ${}^{12}C+\alpha$  nuclear reaction rate has to be increased by a factor of ~ 10 during the helium-core burning, and reduced by a factor of ~ 1000 during the following helium-shell burning, as compared with the standard predictions for this rate. In addition, the main chemical structures derived for KIC 0862602, such as the very thin helium-pure envelope, the mass of the carbon-oxygen core, and the presence of a pure C buffer cannot be reconciled with our present knowledge of white dwarf formation.

*Conclusions.* We find that within our current understanding of white dwarf formation and evolution, it is difficult to reproduce the most important asteroseismologically-derived features of the chemical structure of KIC 08626021.

**Key words.** stars — pulsations — stars: interiors — stars: evolution — stars: white dwarfs

# 1. Introduction

White dwarf (WD) stars constitute the most common final evolutionary stage of low- and intermediate-mass (up to ~  $10.6 M_{\odot}$ , Woosley & Heger 2015) stars. In average-mass WDs, the chemical constitution of the core is mostly a mixture of <sup>12</sup>C and <sup>16</sup>O, plus trace elements, of which <sup>22</sup>Ne is expected to be the most abundant one. This chemical composition is the result of the core He-burning phase (CHeB) during progenitor evolution. At advanced stages of evolution, the WD progenitor is expected to evolve to the thermally pulsing asymptotic giant branch (TP-AGB), where the chemical composition of the outer layers of the WD is built up (Althaus et al. 2010a). This is a critical phase that will impact the evolution and pulsational properties of the emerging WD (De Gerónimo et al. 2017, 2018).

WDs exhibit pulsational instabilities at some point in their evolution. In particular, H-deficient (He-rich) pulsating WDs (or DBVs) are found to be unstable against pulsations in the effective-temperature range  $22\,000 \leq T_{\rm eff} \leq 30\,000$  K. Their multimode photometric variations are caused by non-radial, *g*-mode pulsations of low degree with periods between 100 and 1400 s. In the single-evolution scenario, DB WD stars are believed to be formed in the very late thermal pulse (VLTP),

where the progenitor star experiences its final thermal pulse on the early cooling branch, with the result that the remaining H envelope is consumed (Herwig et al. 1999; Iben et al. 1983; Miller Bertolami et al. 2006). Alternatively, some DB WDs can be formed by mergers of two WDs, either carbon-oxygen (CO)or helium (He)-core WDs (Saio & Jeffery 2000, 2002).

Details of the inner chemical structure of WDs can be inferred through the interpretation of their pulsational spectra by means of adequate representative models (asteroseismology). This procedure constitutes a key technique to understand the evolution of the WD progenitors (Córsico et al. 2019; Fontaine & Brassard 2008; Winget & Kepler 2008; Althaus et al. 2010b). In addition, asteroseismological analyses of WD stars provide strong constraints on the stellar mass, thickness of the outer envelopes, core-chemical composition, and stellar rotation rates (e.g., Bognár et al. 2014; Romero et al. 2012; Córsico et al. 2012; Bischoff-Kim & Østensen 2011), and allow to study physical processes such as crystallization (Montgomery & Winget 1999; Córsico et al. 2004; Romero et al. 2013; De Gerónimo et al. 2019).

Two main approaches have been adopted for the asteroseismology of pulsating WD stars. The first is based on static stellar structures with parameterized luminosity and chemical profiles (Bischoff-Kim & Østensen 2011; Bischoff-Kim et al. 2014, 2019; Giammichele et al. 2014, 2016, 2017). The second approach is based on stellar evolution models computed from the zero age main sequence (ZAMS) to the WD stage (see Romero et al. 2012, 2013; Córsico & Althaus 2006; Córsico et al. 2006, 2009, in the case of H-rich WD, DB, and PG1159 stars, respectively). In the first approach it is allowed for the construction of very dense grid of models and the exploration of chemical structures not necessarily expected from our current understanding of stellar evolution. The flexibility of this method allows for extremely high precision fits and asteroseismic models, albeit not necessarily accurate. Parameterized chemical profiles are usually mildly inspired by stellar evolution results. The second approach, on the other hand, relies on the accuracy of stellar evolution theory for a restriction of the parameter space but is usually based on coarser grids. This prevents high precision fits, but conversely, they are expected to be more accurate as they are informed by a mature theory like stellar evolution. This is particularly useful in the case of WD asteroseismology, where the number of observed independent periods is usually small. This asteroseismological approach is, however, affected by current uncertainties during the progenitor evolution. These uncertainties leave their signature on the predicted pulsation properties and asteroseismic inferences of pulsating WDs. As recently shown in De Gerónimo et al. (2017, 2018), the impact of these uncertainties can be quantified and bounded.

Based on the parametric approach, Giammichele et al. (2018) found an asteroseismic model with an unprecedented precision in their pulsation-period match for the DBV star KIC 08626021, being the derived stellar parameters  $M_{\rm WD} = 0.570 \pm$  $0.005 M_{\odot}, T_{\rm eff} = 29\,968 \pm 198$  K, log  $g = 7.92 \pm 0.01$  cm s<sup>-2</sup>. This pulsating star, located near the blue edge of the instability strip, has been extensively monitored by the Kepler mission, revealing eight independent modes with periods from 143.2 s to 376.1 s (Østensen et al. 2011). The precision of the fit is of less than  $1\mu$ s (i.e. a relative period difference of  $P_{\rm obs} - P_{\rm model})/P_{\rm model} < 10^{-8}$ ), well below the observational uncertainties of ~  $38\mu$ s. However, this finding has been put into question by Timmes et al. (2018), who showed that the inclusion of neutrino emission, expected in young WDs and not considered by Giammichele et al. (2018), impacts the low order g-mode frequencies up to ~  $70\mu$ Hz. Additionally, the derived structure parameters, such as a large CO core, a high central O abundance, a well defined C-pure mantle and a thin pure-He envelope pose a challenge to the stellar evolution predictions. This is particularly true for the homogeneous CO-core derived by Giammichele et al. (2018), which is much more massive  $(0.45M_{\odot})$  than theoretical expectations. This disagreement between stellar evolution theory and the asteroseismological model of Giammichele et al. (2018) is surprising in view of the previous studies by Van Grootel et al. (2010b,a); Charpinet et al. (2011) and Constantino et al. (2015) about the size of the He-burning core. These asteroseismological determinations found a good agreement between the size of the Heburning convective core  $(0.22-0.28M_{\odot})$ , that shapes the future homogeneous CO-core of the WD, with that coming from stellar evolution (see Constantino et al. 2015; Bossini et al. 2015).

In this paper, we will show that the main features of the chemical structure derived for KIC 08626021 from asteroseismology can not be reproduced in the frame of the standard evolutionary theory. We assess the impact of possible uncertainties during WD and progenitor evolution, by computing the full evolution of initial star models from the ZAMS through the CHeB and TP-AGB phases, and finally to the WD domain. We explore several physical processes that could lead to a chemical structure characterized by a large CO-core with high O abundance, a C-mantle on the top of the CO-core, and a C-rich intershell at the bottom of the very thin He envelope, as illustrated by the asteroseismic model for KIC 08626021. In particular, we explore the extra-mixing processes occurring at the border of the convective core as well as the dependence of the  ${}^{12}C(\alpha, \gamma){}^{16}O$  nuclear reaction rate on the temperature during the CHeB phase. In addition, we analyze to what extent the evolution during the TP-AGB could affects the CHe intershell on top of the C buffer. Finally, we assess the impact that element diffusion should inflict on the predicted chemical profile for KIC 08626021.

This paper is organized as follow: in Sect. 2 we describe the main features found in the chemical structure of a WD and their connection with the prior evolution. In Sect. 3 we present the results of our computations and finally in Sect. 4 we summary our results and conclusions.

#### 2. Formation of the chemical structure of a WD

Figure 1 shows the typical chemical structure of a DBV model with similar parameters to those found by Giammichele et al. (2018), namely  $M_{\rm WD} = 0.58 M_{\odot}$ ,  $T_{\rm eff} \sim 29\,000$  K and log g = 7.93 cm s<sup>-2</sup>, derived from the full computation of the progenitor evolution (upper panel) and the chemical-abundance profiles predicted by the asteroseismic model for the DBV KIC 08626021 (Giammichele et al. 2018, bottom panel). The abundance distribution of O, C and He from the core to the outer layers are shown in terms of the outer mass fraction coordinate. The chemical structure of the evolutionary model bears the clear signatures of distinct processes operative during stellar evolution such as the CHeB, He shell burning during the AGB, convective mixing during the TP-AGB, and element diffusion during the WD regime. Different regions of the WD chemical profile can be tracked down to individual processes and, consequently, related to specific uncertainties in stellar evolution. From center to surface, i.e. from left to right the upper panel of Fig. 1, in brief we can identify the following: The homogeneous central CO core  $[-q \leq 0.3, q = \log(1 - m_r/M_{\star})]$ , which is shaped during He-core burning and the very beginning of He-shell burning. As such, the size of the homogeneous core and the O mass fraction are affected by uncertainties in convective boundary mixing (CBM) and the  ${}^{12}C(\alpha, \gamma){}^{16}O$  rate (Straniero et al. 2003; Constantino et al. 2015; Bossini et al. 2015; Constantino et al. 2017). Then comes the region at  $0.3 \leq -q \leq 1.5$  which is built up during the early AGB and the TP-AGB as the He-burning shell progresses outwards (Salaris et al. 1997; Althaus et al. 2010a). The details of this region, in particular its C mass fraction and extension, are mostly affected by CBM during the thermal pulses and at the bottom of the convective envelope, that determine the efficiency of third dredge up and, in more massive stars, also the intensity of the second dredge up. This affects the height of the C peak at  $-q \sim 1.5$  which is higher when no CBM is included. Between 1.5  $\leq -q \leq 5$  come the He-C-O intershell produced during the last thermal pulse suffered by the progenitor star. The C and O abundances in this region are very dependent on the third dredge up history of the progenitor, and, as such on CBM during the TP-AGB. The more efficient CBM, the larger the final O abundance at the expense of C and He (Herwig 2000, 2005). The chemical transitions at  $-q \sim 1.5$  and  $-q \sim 5$  are shaped by gravitational settling, although the inner transition is far from diffusive equilibrium when reaching the DBV instability strip (Althaus et al. 2009). In addition, the total He content of the final WD is slightly affected by details on the AGB evolution but its order of magnitude is defined by the total mass of the final WD.

Figure 1 illustrates the profound contrast between the chemical structure predicted by stellar evolutionary theory and that predicted by the asteroseismic model for the DBV KIC 08626021. In fact, both the central O abundance and, more noticeable, the extension of the CO-core are larger than those predicted by stellar evolution for stars with final masses  $M_{\rm WD} \lesssim$  $0.6M_{\odot}$  (Salaris et al. 1997; Althaus et al. 2010a). Besides the properties of the CO core, other unconventional features are easily distinguishable in the asteroseismic model for the DBV KIC 08626021. The existence and location of the the almost pure C buffer located at 2.5  $\leq -q \leq 3$  is very different from that predicted by stellar evolution models. While stellar evolution models (e.g. Straniero et al. 2003; Miller Bertolami & Althaus 2006; Bossini et al. 2015) show a C peak formed during the late AGB evolution, its C mass fraction is always  $X_C < 0.8$  and it is located deeper inside the star. This last fact is connected to another unusual feature of the asteroseismic model for the DBV KIC 08626021 which is the low He content derived for that star  $(M_{\rm He} = 0.0001 M_{\rm WD})$ , about 2 orders of magnitude lower than that predicted for WDs of average mass ~  $0.6M\odot$  (Romero et al. 2012). Finally, the asteroseismologically derived pure He envelope is about 3 orders of magnitude less massive than that predicted by gravitational settling at the evolutionary stage at which KIC 08626021 is found.

#### 3. Results

The WD evolutionary models used in this work were computed with the LPCODE stellar evolution code (Althaus et al. 2005; Miller Bertolami 2016). LPCODE produces detailed WD models in a consistent way with the predictions of progenitor evolutionary history, based on an updated physical description. In the following we enumerate the most relevant physical parameters adopted in this work: i) Diffusive overhsooting during the evolutionary stages prior to the TP-AGB phase was allowed to occur following the description of Herwig et al. (1997). We adopted f = 0.0174 for all sequences, except when indicated. The occurrence of overshooting is relevant for the final chemical stratification of the WD (Prada Moroni & Straniero 2002; Straniero et al. 2003). ii) Gravitational settling and thermal and chemical diffusion were taken into account during the WD stage for <sup>1</sup>H, <sup>3</sup>He, <sup>4</sup>He, <sup>12</sup>C, <sup>13</sup>C, <sup>14</sup>N, and <sup>16</sup>O (Althaus et al. 2003). *iii*) During the WD phase, chemical rehomogenization of the inner C-O profile induced by Rayleigh-Taylor (RT) instabilities was implemented following Salaris et al. (1997).

In the next sections we will investigate the physical processes acting along the progenitor and WD evolution that could be responsible of shaping the most important features of the chemical structure of the asteroseismic model for KIC 08626021.

### 3.1. Convective boundary mixing during CHeB

The treatment of CBM is one of the major uncertainties affecting the stellar evolutionary models and has some influence in the chemical profile of the WD. In particular, the incorrect application of the Schwarzschild criterion during the He-core burning phase can have a strong impact on the final chemical profile of the white dwarf (Gabriel et al. 2014; Salaris & Cassisi 2017). The mass of the homogeneous central part of the CO core of WD models results from the interplay between convection and nucleosynthesis during CHeB, the ignition of the He shell at the very beginning of the early AGB and the late homogenization of the central parts driven by an inversion in the mean molecular weight of the stellar material (see Fig. 3 of Salaris et al. 1997).

Interestingly, the location of the outer boundary of the convective core is initially governed by a self-driving mechanism (Castellani et al. 1971). Any extension of the convective boundary beyond its formal value as given by the Schwarzschild criterion is expected to increase the C abundance of the neighbouring layers, thus leading to an increase in their opacity, and consequently  $\nabla_{rad}$ , and thus to a larger convective core. The increase of the size of the convective core moves the convective boundary, and CBM, even further. This process continues until the value of  $\nabla_{rad}$  equals the local value of the adiabatic gradient  $\nabla_{ad}$ . Due to the self-driving nature of this mechanism, as soon as some mixing is allowed beyond the He-burning convective core, the process develops until it reaches its stable value. In fact, Michaud et al. (2007) showed that even atomic diffusion is enough to trigger this instability, eventually increasing the size of the convective He core. Consequently, the adoption of a bare Schwarzschild criterion for the determination of the convective borders will lead to nonphysical convective He-burning cores, where neutral buoyancy is not attained at both sides of the convective border as a consequence of the chemical discontinuity. In our case, this problem can either be solved by a detailed analysis of convective stability at both sides of the convective border (Gabriel et al. 2014), or by allowing for some mixing beyond the ill-defined convective boundary. The inclusion of even a very tiny CBM already allows models to grow the convective core so that it reaches neutral buoyancy at its outer convective boundary. Due to the self-driving nature of the mechanism, it is expected that the final size of the convective core is similar irrespective of the nature of the additional mixing that occurs at the convective boundary. A detailed account of CBM during the He-core burning stage of low-mass stars can be found in Section 4.2 of Salaris & Cassisi (2017).

In addition to this self-driving mechanism, the latter He-core burning gives rise to the appearance of splittings in the formal (i.e. Schwarzschild criterion) convective core that can be modelled as a partially mixed region, where neutral buoyancy is attained (Castellani et al. 1985). This referred to as semiconvection by some authors<sup>1</sup>. Again, the inclusion of some minor CBM allows the convective zone to stay connected, and although details in the final chemical profiles keep a record of the exact method adopted for computing mixing beyond the formal convective boundary, all algorithms lead to similar sizes of the homogeneous central part of the CO core (Bossini et al. 2015; Constantino et al. 2015). As a consequence, different treatments of convective boundary mixing during the CHeB stage do not lead to significant discrepancies in the final chemical profiles of the WD, provided that some mixing is allowed beyond the formal Schwarzschild convective boundary.

The extent of the homogeneous central part of the core in the chemical profile derived by Giammichele et al. (2018), is about 0.45  $M_{\odot}$ , much higher than the predicted by evolutionary computations, ~  $0.32M_{\odot}$ . Giammichele et al. (2018) propose that this could be due to more extra mixing during the CHeB by semiconvection or overshooting. We explore then the impact of the extension of the convective core on the final size of the homogeneous central part of the WD core. In order to do this we performed simulations starting from the same initial model (Z = 0.01,  $M_i = 1M_{\odot}$ ) for different values of the CBM pa-

<sup>&</sup>lt;sup>1</sup> Not to be confused with the semiconvection mechanism described in textbooks (Kippenhahn et al. 2013) which is due to overstability as a consequence of non-adiabatic effects.



**Fig. 1.** Upper panel: Inner distribution of O, C an He in terms of the outer mass fraction corresponding to the expectations from a typical DBV model of mass ~ 0.58  $M_{\odot}$  resulting from the complete progenitor evolution. Bottom panel: same as above but for the asteroseismic model for the DBV KIC 08626021, Giammichele et al. (2018).



**Fig. 2.** Oxygen chemical profiles as a function of the mass coordinate for different assumptions of the overshooting parameter. Vertical dashed line corresponds to the extent of the homogeneous central part of the core predicted by the asteroseismic model of KIC 8626021.

rameter f during CHeB<sup>2</sup>. In particular, we explore values of f = 0.00174, 0.0087, 0.0174, 0.0348, 0.087, and 0.174 which

correspond to 1/10, 1/2, 1, 2, 5, and 10 times the standard value of  $f_0 = 0.0174$ , see Miller Bertolami (2016).

Fig. 2 shows the resulting chemical profiles of our models at the beginning of the thermally pulsing AGB phase, after the homogenization of the central parts driven by an inversion in the mean molecular weight of the stellar material (Salaris et al. 1997). As expected, as soon as some additional mixing is allowed at the convective boundary, the size of the homogeneous CO core is significantly enlarged. Even a very minor CBM efficiency  $(f = f_0/10)$  is already enough to start the self-driving mechanism mentioned at the beginning of this section, producing a homogeneous CO core of  $M_{\rm CO} \simeq 0.286 M_{\odot}$  (to be compared with the  $M_{\rm CO} \simeq 0.205 M_{\odot}$  resulting in the unrealistic case in which all CBM is prevented). In comparison, further increases in the value of f by factors of 5, 10, and 20 (i. e. f = 0.0087, 0.0174, 0.03) lead to relatively minor increases in the mass of the homogeneous CO core:  $M_{\rm CO} \simeq 0.292, 0.322$ , and 0.322  $M_{\odot}$  respectively. From our previous discussion, this is an expected trend, because the main process determining the size of the core only requires the existence of some additional mixing, provided that it is enough to alter the layers immediately outside the formal convective border (Castellani et al. 1971, 1985). Only when f = 0.087 is adopted, the extent of CBM leads to a larger homogeneous core of 0.354  $M_{\odot}$ . This value is still far below the value of 0.45  $M_{\odot}$  derived by Giammichele et al. (2018) for KIC 08626021. Considering that a value of  $f = 0.087 = 5 \times f_0$ 

<sup>&</sup>lt;sup>2</sup> The value of *f* relates the mixing coefficient of a layer outside the formal convective zone ( $D_{\text{CBM}}$ ) at given distance *d* from the formal convective boundary with the mixing coefficient close to the formal convective boundary ( $D_0$ ) via the relation  $D_{\text{CBM}} = D_0 \times \exp{-2d/fH_P}$ , where

 $H_P$  is the local pressure scale height at the formal convective boundary (Herwig et al. 1997).

is very high in comparison with any calibration of the overshooting parameter, this rules out the possibility of CBM as being the cause behind the large CO core inferred for KIC 08626021. Assuming a larger value of f, like f = 0.174, we find the evolution of the post-CHeB star to be completely altered, with thermal pulses developing only 800 000 yr after the end of CHeB, more than a factor 10 shorter than in a normal evolution, and thus effectively truncating the very existence of the early AGB phase. Such a model would be incompatible with the existence of the early AGB phase and should be already discarded on those grounds. And even with such inconsistently large value of f = 0.174, the mass of the homogeneous CO core is reduced by the first thermal pulse to  $0.386M_{\odot}$  (from a value of  $0.422M_{\odot}$ at the very end of the HeCB), well below the value of  $0.45 M_{\odot}$ derived by Giammichele et al. (2018).

The inability to produce homogeneous CO cores as large as those reported by Giammichele et al. (2018) is not a property of the exponentially diffusive overshooting prescription adopted here but of all studied CBM recipes. As already shown in Fig. 4 of Straniero et al. (2003) for standard sized WDs (~  $0.6M_{\odot}$ ) semiconvection and penetrative/mechanical overshooting, even under extreme assumptions, lead to homogeneous CO cores well below the value derived by Giammichele et al. (2018). A similar result is shown in Fig. 2 of Constantino et al. (2015), which in addition to penetrative overshooting and semiconvection also explore the CO-profiles left by a moderate exponentially decaying overshooting, and in Fig. A1 of Bossini et al. (2015) which shows the final CO-profiles under different assumptions of the temperature gradient for the mechanical overshooting approximation (called "overshooting" and "penetrative convection" in their work) under the extreme assumption of a  $1H_P$  overshooting zone. In addition to these experiments, Constantino et al. (2015) explored a "maximal-overshooting" scheme that avoids the splitting of the He-burning core at latter stages of the CHeB phase. This recipe leads to slightly smaller homogeneous COcores than the standard exponential and penetrative overshooting prescriptions. Finally, Constantino et al. (2017) also explored the incorporation of Spruit's core-growth rate (Spruit 2015). Spruit (2015) makes physically sounding arguments regarding the maximum rate at which a convective He-burning core can grow in a steady regime based on the higher buoyancy of the material ingested. This argument then sets an upper limit to the maximum size of a He-burning core and consequently to the size of the homogeneous CO region in the core of WDs. Fig 1 of Constantino et al. (2017) shows that Spruit's argument also leads to convective cores not larger than those obtained with the exponentially decaying overshooting approximation. All these works together show that the outer boundary of the homogeneous CO core of a low-mass star, like the progenitor of KIC 08626021, cannot exceed  $0.35M_{\odot}$  even under the most extreme situations.

We conclude that CBM cannot make the homogeneous part of the core grow up to  $0.45 M_{\odot}$  without changing drastically other parts of the stellar evolution that are well constrained such as the existence of the early AGB phase.

#### 3.2. Efficiency of diffusion processes

During the WD evolution several processes strongly modify the chemical structure of the progenitor star. Among them, gravitational settling is the primary shaper of WD chemical profiles, forming chemically-pure outer layers. Here, we explore to what extent element diffusion processes due to gravitational settling, thermal, and chemical diffusion could be responsible for the formation of a C-pure buffer at the top of the CO-core. We also



**Fig. 3.** Chemical profiles for He, C and O of our DBV evolutionary models (~ 29000 K) in terms of the outer mass fraction, resulting from different efficiency of element diffusion. The values of the quantity f indicates the multiplicative factor of the diffusion efficiency with respect to the standard value (f = 1).

explore for how long can a very thin He envelope survive the effects of diffusion in the absence of competing processes. Diffusion coefficients, that determine how efficient these processes are, have been calculated by various groups (e.g. Paquette et al. 1986; Baalrud & Daligault 2013). Differences in the diffusion coefficients are at most of one order of magnitude in the strong coupled plasma regime (Baalrud & Daligault 2013; Paxton et al. 2015).

To explore the impact of time-dependent diffusion on the chemical profile of a WD at the effective temperature and mass of KIC 8626021, we evolve a ~  $0.57M_{\odot}$  WD model from ~ 200000 K to ~ 29000 K and modify the efficiency of the diffusion processes by a multiplicative factor f, f = 0.01, 1 and 100, thus widely covering the actual uncertainties in these processes. Fig. 3 shows the chemical profiles resulting from our experiment. Clearly, changing the efficiency of the diffusion processes in any reasonable amount is not expected to reproduce the main remarkable features of the asteroseimological profile of KIC 8626021. In particular, we note that the peak of C at  $log(1 - m_r/M_{\star}) \sim -1.4$  does not change significantly, neither in the value of the peak nor in the position. This means that we cannot invoke diffusion as the responsible process to create an almost pure C buffer in the WD.

A difficulty also arises when trying to reproduce the thin pure He envelope derived by Giammichele et al. (2018). Thanks to the relatively low uncertainties in the diffusion physics in the outer regions of WDs (Baalrud & Daligault 2013; Paxton et al. 2015) we can estimate how long such a thin He-pure envelope can survive. To this end, we perform a set of numerical experiments with LPCODE by computing the speed of gravitational settling at the evolutionary stage and mass of KIC 8626021. Initial chemical profiles are those shown in Fig. 3 but with the outer He-pure envelope located at different initial depths of  $-\log(1 - m_r/M_{\star}) = 7.6, 8.6 \pmod{\text{A}}$  and B, respectively). Our computations show that in about 100000 - 200000 yr the envelope becomes already thicker than the value found for KIC  $8626021, -\log(1 - m_r/M_{\star}) = 7.4$  (see Fig. 4), falling outside of the range of the asteroseismical solutions. These timescales are only 1 to 2% of the time required by standard DB WD models to cool down to  $T_{\rm eff} \sim 30000$ K, which is of about 10 Myr for models in that mass range (Althaus et al. 2009). Hence, if



**Fig. 4.** Time evolution of the position of the bottom of the pure-He envelope (measured in terms of the outer mass fraction q) from  $T_{\text{eff}} \sim 30000 \text{ K}$ , for models with initial  $-\log(q) \sim 7.6$  and 8.6 (models A and B respectively). For model A (B), 0.08 (0.18) Myr is enough for diffusion processes to thicken the He envelope below  $\log(q) \sim 7.4$ .

KIC 8626021 is characterized by such thin He envelope, then the WD should have been formed by an evolutionary scenario that allowed it to cool down to its present state about 50 to 100 times faster than normal DB stars.

Competing processes such as strong winds or rotation could in principle delay the action of gravitational settling. However, the existence of strong winds in WDs is at variance with the observed action of radiative levitation in DO stars (Hoyer et al. 2018), which can only be effective if winds do not prevent the action of diffusion. Also the location of the DO-PG1159 transition (Werner et al. 2017) can be reproduced (Unglaub & Bues 2000) when WD winds decay strongly with decaying luminosity, as expected from radiation driven wind theory (e.g.  $\dot{M} \propto L^{1.86}$  as proposed by Bloecker 1995). In particular, stellar winds are expected to stop as soon as metals sink below the photosphere and are not available to absorb momentum from the radiation field (Unglaub & Bues 2000). In addition, the fast drop in mass loss with stellar luminosity proposed by Bloecker (1995) is needed to provide a coherent picture of the GW Vir red edge instability domain (Quirion et al. 2012). All these concerns are reinforced by the fact that such winds would require an extreme fine tuning of its intensity to remove almost all the initial He content but not all. Similarly, while rotational mixing could lead to a delay of gravitational settling, the slow solid body rotation measured in KIC 0826021 by Giammichele et al. (2018) strongly argues against this possibility.

# 3.3. The ${}^{12}C(\alpha, \gamma){}^{16}O$ nuclear reaction rate and Coulomb screening

The chemical abundances of the CO-core, as well as of those layers immediately above, are produced at the end of CHeB phase and the beginning of He-shell burning. In the previous section we show that diffusion is unable to create the C-pure buffer, even when diffusion coefficients beyond current uncertainties are adopted. Assuming that diffusion is the only process able to modify the chemical structure during WD stage, any chemical structure located so deep into the interior of the star should be a fossil record of the previous evolution. The O to C ratio left by He-burning is a consequence of the competition of the  $3\alpha$  reactions that creates  ${}^{12}C$  and the  ${}^{12}C+\alpha$  reaction that destroys  ${}^{12}C$  to create  ${}^{16}O$ . In particular, the  ${}^{12}C+\alpha$  reaction is among the most

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uncertain one in stellar evolution. In this section, we explore to which extent the temperature dependence of the  ${}^{12}C+\alpha$  nuclear reaction rate should be altered in order to produce the high central O abundances together with the previously discussed C buffer. Recently, De Gerónimo et al. (2017) explored the implications of the current uncertainties in the  ${}^{12}C + \alpha$  nuclear reaction rate during the CHeB phase over the chemical structure and pulsation periods of hydrogen-rich pulsating WDs. The authors found that these uncertainties have a non-negligible impact in the chemical structure, but as seen from their Fig. 7, it is clear that none of their models predict the most important features of the asteroseismic model found for KIC 08626021.

In view of these findings, we computed the evolution of a progenitor star from the ZAMS to the DB WD stage by altering significantly the nuclear reaction rate for the purpose of mimicking the chemical structure of KIC 08626021. Because of the different temperatures at which CHeB and He-shell burning proceed in the progenitor evolution, it is possible to alter the  ${}^{12}C+\alpha$  reaction rate to simultaneously reproduce the large central O abundance and the existence of a C buffer derived by Giammichele et al. (2018). Namely, we have been able to reproduce the high central abundance for  ${}^{16}O$  (~ 82% by mass) by enhancing the <sup>12</sup>C +  $\alpha$  reaction rate during the CHeB phase—up to 10 times larger than the highest value predicted by Kunz et al. (2002)—for  $T \leq 0.13 \times 10^9$  K. Beyond the core, we manage to form a C mantle in the top of the CO-core by reducing the generation of O in the outward moving He burning shell, during post-CHeB evolution. To do this, we find it necessary to decrease the reaction rate in the range  $0.13 \times 10^9 \leq T$  by about 100 to 1000 times from that predicted by Kunz et al. (2002). Only in this way, we find a C dominated buffer (~ 90%), with a small amount of O. In Fig. 5 we compare the standard  ${}^{12}C + \alpha$  reaction rate with its current uncertainties  $-\pm 30\%$  of relative uncertainty at the CHeB temperatures (red thick line) together with the altered reaction rate necessary for reproducing the asteroseismic model for KIC 8626021 (dashed line). It is clear that the uncertainty in the <sup>12</sup>C +  $\alpha$  reaction rate cannot be invoked to produce the high O abundance in the core and the almost C-pure buffer of the Giammichele et al. (2018) WD profile.

We also explore possible uncertainties in the Coulomb screening factors could lead to the formation of such features in the chemical structure. The screening corrections are applied as a multiplicative factor of the form exp f to the nuclear reaction rates, where the factor f depends upon the charge of the nucleus taking part in the reactions. Up to now, all the recipes of screening corrections are derived within certain assumptions (Dewitt et al. 1973; Graboske et al. 1973; Wallace et al. 1982). However, we need to keep in mind that any change in the screening correction of a particular reaction is not going to affect only that reaction, but possibly also every nuclear reaction where one of the same nucleus are involved. This inhibits us from doing extreme changes in the screening factors. In particular, as discussed in the previous paragraph, the  ${}^{12}C + \alpha$  reaction rate is the major responsible for setting the interior profile of a WD, both during the CHeB and the He-shell burning phases. If we interpret that this change is due to the uncertainty in the screening factor, we need exp f to be more than one order of magnitude higher than the one calculated by our code (taken from Graboske et al. 1973 and Wallace et al. 1982), for temperatures up to  $T_9 \sim 0.13$ and lower for temperatures  $T_9 \gtrsim 0.13$  (two order of magnitude lower for  $T_9 \gtrsim 0.16$ ). These extreme changes in the screening of the <sup>12</sup>C +  $\alpha$  reaction rate should affect other screening factors for reactions involving C, He, or both (or even other isotopes, due to the temperature dependence of the change), most proba-



**Fig. 5.**  $^{12}$ C +  $\alpha$  reaction rate at the CHeB temperatures, according to the work of Kunz et al. (2002) (red thick line) together with the altered reaction rate necessary for mimicking the asteroseismic model for KIC 8626021 (dashed line).



**Fig. 6.** Intershell abundances of  ${}^{4}$ He,  ${}^{12}$ C and  ${}^{16}$ O during the evolution on the thermally pulsing AGB phase. Dashed (solid) lines refers to the model in which (no) OV is considered in this stage.

bly changing drastically other parts of stellar evolution that are well constrained.

#### 3.4. Thermal pulses on the AGB

Three main features in the chemical structure of the asteroseismic model can be connected with physical processes occurring at the TP-AGB phase: the CHe-plateau located beyond the C buffer, the total content of He and the size of the degenerate core. The C-He plateau is the result of the short-lived convective episodes occurring at the He-burning shell, which dredge up C and shape the flattened profile. The amount of O, C and He left at this intershell region depends on the strength of the CBM at the border of the pulse-driven convection zone, where  $f \sim 0.0075$  reproduces reasonably well both the initial to final mass relation and the abundances of PG1159 stars (Miller Bertolami 2016). Particularly, the intershell abundances derived for the asteroseismic model (C ~ 80%, see lower panel of Fig.1) disagree with both the results from Herwig (2000) and our computations, as seen from Fig. 6. There we show the intershell abundances resulting from the computations of a  $M_{ZAMS} = 1.5M_{\odot}$  (final CO-core mass  $M_{CO} \sim 0.58M_{\odot}$ ) model adopting extreme values for the overshooting parameter f = 0 and f = 0.0174 (solid and dashed lines, respectively) in terms of the number of thermal pulses experienced by the star on the AGB. These extreme values of f widely cover the current overshooting uncertainties during the TP-AGB phase. We find that the maximum amount of <sup>12</sup>C in the intershell region (~ 50%) occurs at the very first thermal pulses of the model with f = 0.0174, and this abundance is still far below the <sup>12</sup>C abundances derived for KIC 08626021.

The low total content of He of the asteroseismological model could be explained if the star experiences a long lived TP-AGB phase, i.e., if the star experiences a large number of thermal pulses. We find that it is possible to reduce the total He content of the star from  $1.7 \times 10^{-1}$  to  $1 \times 10^{-2} M_{\odot}$  in the course of 10 thermal pulses. A total He content of  $10^{-4} M_{\odot}$ , as found for KIC 08626021, would be possible if the star experiences more than 30 thermal pulses. But in this case, the growth of the core would largely exceed the mass derived for the asteroseismic model. Therefore, it is not possible to find, in this context, a model with an extremely low content of He for an average mass WD. Such He content is found for ultra-massive WDs (Camisassa et al. 2019). Similar results are found by Lawlor & MacDonald (2006, see Figs. 9 and 10) where the authors find a final He content of  $\sim 6 \times 10^{-4} M_{\odot}$  for a WD of  $1.05 M_{\odot}$ .

A drawback arises when attempting to reproduce the intershell abundances and the low content of He for the same model. The inclusion of CBM during the TP-AGB phase favors the occurrence of third dredge up episodes that prevent the core from growing and leads to the C-enrichment of the surface layers. The pollution of the stellar surface with C drives strong winds, with the result of an earlier departure from the TP-AGB. This is in contrast with a long lived TP-AGB phase needed for the depletion of He to values close to ~  $1 \times 10^{-4} M_{\odot}$ .

In light of the previous discussion, it appears difficult that the physical processes operative at the TP-AGB phase within their respective uncertainties, could lead to the scenario in which an average-mass WD is formed with a C-rich intershell region simultaneously with a very low He content.

## 4. Summary and conclusions

Giammichele et al. (2018) have performed for the first time an extremely precise asteroseismological study of KIC 8626021, a DBV star extensively monitored by the Kepler mission. The authors have been able to find an asteroseismic model with an unprecedented precision in their pulsation period match. This pave the way to dig into the physical processes that lead to the formation of WD stars. The chemical structure derived from Giammichele et al. (2018) from their asteroseismological analysis for KIC 8626021 is not in agreement with what is expected for a DB white dwarf star in terms of the widely accepted formation channels, thus posing a challenge to the theory of whitedwarf formation. In this work, we have explored to what extent both microphysics (diffusion processes and nuclear reaction rates) and macrophysics (convective boundary mixing, semiconvection) processes should be modified in order to reproduce the chemical structure asteroseismologically derived for the DB pulsating WD KIC 8626021 by Giammichele et al. (2018). To this end, we computed the evolution of progenitor stars from the ZAMS to the DBV domain with final masses  $M_{\rm WD} \sim 0.58 M_{\odot}$ . As a first step we explored the extent of the convective boundaries during the CHeB phase in order to reproduce the mass of the large central homogeneous part of the core. Based on the ar-

guments presented by Giammichele et al. (2018), we explored the impact of the extension of the convective core on the final size of the homogeneous central part of the WD core by enhancing the overshooting up to 5 times the standard value. Even with such a large extension of the convective boundary, our models are unable to develop a homogeneous central part of the core of  $M \sim 0.45 M_{\odot}$ . We also explored the efficiency of the diffusion processes acting during the WD cooling path, in order to mimic the C buffer at the top of the core. We evolved a  $\sim 0.57 M_{\odot}$  WD model from  $\sim$  200000 K to the DB phase ( $\sim$  30000 K) in which we varied the efficiency of the diffusion processes from 0.01 to 100 times the standard value. We found that diffusion is unable to create the C buffer at the top of the core within a reasonable timescale. Additionally, we found that the thin He envelope that characterizes the asteroseismic model could take place if the star cool down 50 to 100 times faster than normal DB stars.

In view of these findings and assuming that diffusion is the only process able to modify the chemical structure during WD stage, these chemical features located so deep into the interior of the star, should be created during the evolution of the progenitor star, during the CHeB and AGB phases. We computed the complete evolution of a progenitor star in which we altered the  ${}^{12}C(\alpha,\gamma){}^{16}O$  nuclear reaction rate during the whole evolution. By modifying the nuclear reaction rate far beyond the extreme values predicted by Kunz et al. (2002), we have been able to reproduce a C buffer at top of an O-dominated core. In particular, these features are only achieved if we enhance the nuclear reaction rate up to 10 times for  $T < 0.13 \times 10^9$  K, and lowering down to 100–1000 times for  $T > 0.13 \times 10^9$  K, which clearly lies outside the values suggested by laboratory determinations, including their uncertainties. In addition, we discarded that such features in the chemical structure could be reproduced by altering the screening factors within their uncertainties. We discussed the presence of the C-rich CHe-plateau and the low He content in the whole asteroseismic model. We found that a long-lived TP-AGB phase could be a possible scenario for the formation of a low-He content star, but we envisage that such He content will be possible for WDs with  $M_{\star} \approx 1.05 M_{\odot}$ . This result is in contrast with the inclusion of CBM at the TP-AGB phase, a necessary ingredient to reproduce the intershell abundances.

The results found in this work suggest that the asteroseismic model for KIC 8626021 found by Giammichele et al. (2018) is difficult to reconcile with our current understanding of the standard evolutionary scenario for the formation of WDs. Further investigations are needed to understand the origin of this discrepancy.

In closing, it is appropriate to comment that Timmes et al. (2018) have shown that even the very feeble impact of neutrino emission on the mechanical structure of the WDs is enough to alter low-order g-mode frequencies by about  $70\mu$ Hz, having a sizeable impact on WD mass, radius, and central O mass fraction. Numerical experiments on our full evolutionary models show that the presence of small chemical details left by previous evolution (e.g. the small O bump at  $-q \sim 2$ , see the upper panel of Fig. 1) can alter low-order g-mode periods by  $\sim 0.1$  s  $(\sim 10^7 \mu \text{Hz}).$ 

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