White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
Proceedings IAU Symposium No. 357, 2019
M. A. Barstow, S. J. Kleinman, J. L. Provencal & L. Ferrario, eds.
doi:10.1017/S1743921320001362

Evolution and asteroseismology of ultra-massive DA white dwarfs

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Abstract. Ultra-massive ($\geqslant 1M_{\odot}$) oxygen/neon (ONe) core white dwarfs (WDs) are the result of the evolution of isolated progenitor stars with masses above $6-9M_{\odot}$. It is expected that hydrogen-rich (DA) ultra-massive WDs harbor crystallized cores at the typical temperatures of the ZZ Ceti instability strip. These stars offer a unique opportunity to study the processes of crystallization and to infer their core chemical composition. We present a study of the evolution and asteroseismology of ultra-massive DA WDs. We found that all pulsating WDs known to date with $M_{\star} \geqslant 1.1M_{\odot}$ should have more than 80% of their mass crystallized, if a ONe-core is assumed. Finally, we present a complete asteroseismological analysis to the well known ZZ Ceti BPM 37093 and a preliminary analysis to GD 518 and SDSS J0840+5222.

Keywords. White Dwarfs, Oscillations

1. Introduction

Ultra-massive ($\geqslant 1M_{\odot}$) ONe-core WDs stars are the final evolutionary stage of progenitor stars with masses above $6-9M_{\odot}$. These progenitors are expected to reach the necessary conditions in their interiors to ignite carbon in semi-degenerate conditions during the evolution through the super asymptotic giant branch (SAGB) phase, leaving as a result a very dense ONe core. In particular, ultra-massive DA WDs are expected to harbor highly crystallized ONe cores by the time that they reach the ZZ Ceti instability strip.

Through detailed asteroseismological analysis it is possible to obtain details of the chemical composition, in particular, the degree of crystallization.

We present a study of the evolution and asteroseismology of ultra-massive DA WDs based on the development of updated and realistic chemical profiles, reliable to perform detailed asteroseismological analysis.

2. Input physics

Our WD evolutionary sequences were computed by adopting the initial realistic chemical profiles from Siess (2010), resulting from the complete evolution of the progenitor stars through the SAGB phase. Our evolutionary sequences are characterized by stellar masses $M_{\star} = 1.10, 1.16, 1.22,$ and $1.29M_{\odot}$.

All the evolutionary models were computed with the `LPCODE` evolutionary code (Althaus *et al.* 2005). This numerical code considers all the physical ingredients necessary for the description of WD evolution. Energy release and chemical redistribution induced by the process of phase separation during crystallization are included by adopting the oxygen/neon phase diagram of Medin & Cumming (2010).

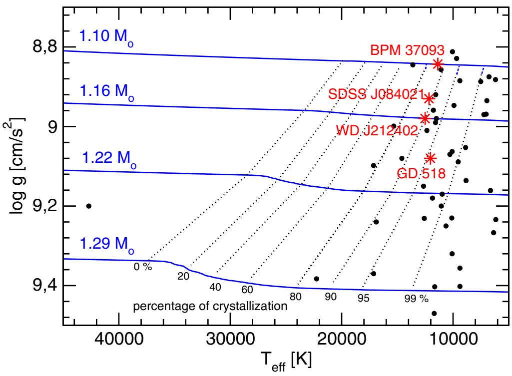

Figure 1. Evolutionary sequences for the ultra-massive DA WDs.

The pulsational properties of the nonradial g(gravity)-modes were computed by using the adiabatic version of the `LP-PUL` pulsation code (Córsico *et al.* 2005). Of particular interest, for the treatment of crystallization and its effect on the pulsation spectrum of g modes, we adopted the "hard sphere" boundary conditions which assume that the amplitude of the eigenfunctions of g modes is reduced substantially below the solid/liquid interface (see Montgomery & Winget 1999).

3. Results

The main properties of our evolutionary sequences are shown on Fig. 1. There we show the spectroscopic Hertzsprung-Russell diagram (the $\log g - T_{\rm eff}$ plane) together with the crystallized mass fraction. The position of the ultra-massive DA WDs known at date are plotted with black star symbols while the ZZ Ceti stars are plotted with black dots. As can be seen from the figure, ZZ Ceti stars with $M_\star \geqslant 1.1 M_\odot$ should have more than 80% of their mass crystallized.

Diffusion processes and gravitational settling play a key role in the development of a pure H envelope and eroding the chemical profiles all along the WD cooling. Due that the crystallization temperature of ^{20}Ne is larger that the crystallization temperature of ^{16}O, a phase separation is induced by the crystallization process. These changes in the chemical profiles are translated into no-negligible changes on the period spectrum. The signatures of the phase separation and the induced chemical redistribution are seen as peaks in the Brunt-Väisälä frequency. These features are completely irrelevant for the pulsation properties of the more massive models due to they are within the crystallized region.

4. Asteroseismological analyses

4.1. *BPM 37093*

This white dwarf was the first ultra-massive ZZ Ceti star discovered (Kanaan *et al.* 1992). Recently, Nitta *et al.* (2016) determined $T_{\rm eff} = 11370$ K $\log g = 8.843$. While the asteroseismological study performed for this star by Metcalfe *et al.* (2004) indicates a crystallized mass fraction $\sim 90\%$, Brassard & Fontaine (2005) questioned this result and argued that the crystallized region should be between 32% and 82%. In the following we present our detailed asteroseismological analysis based on an updated and realistic set of ONe-core ultra-massive white dwarf models, by considering the set of eight pulsation modes (511.7, 531.1, 548.4, 564.1, 582.0, 600.7, 613.5, 635.1) from Metcalfe *et al.* (2004).

https://doi.org/10.1017/S1743921320001362 Published online by Cambridge University Press

Table 1. References: (a) Nitta *et al.* (2016). (b) Camisassa *et al.* (2019)

Quantity	Spectroscopy	Asteroseismology
$T_{\rm eff}$ [K]	$11\,370 \pm 500^{(a)}$	$11\,650 \pm 40$
$M_\star/M_\odot$	$1.098 \pm 0.1^{(b)}$	1.16 ± 0.014
$\log g$ [cm/s^2]	$8.843 \pm 0.05^{(a)}$	8.970 ± 0.025
$M_{\rm cr}/M_\star$	$0.935^{(b)}$	0.923

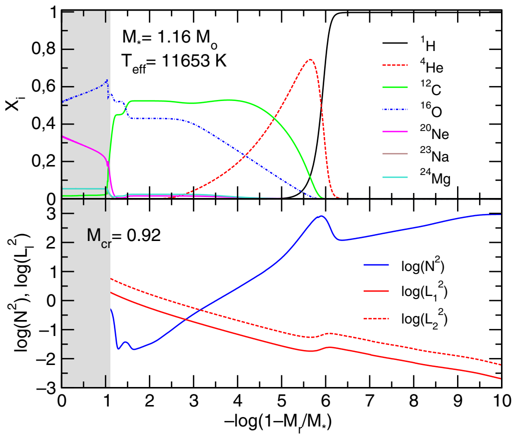

Figure 2. Chemical structure (upper panel), and the squared Brunt-Vaïsälä and Lamb frequencies (lower panel) of our best-fit model for BPM 37093.

4.1.1. Period spacing analysis

The large number of modes detected allow us to search for a constant period spacing. We found, by performing three significance tests (Kolmogorov-Smirnov, inverse variance and the Fourier Transform) a constant period spacing of ~ 17 s. This indicates that BPM 37093 is dominated by $\ell = 2$ modes and the stellar mass should be 1.16 or $1.29 M_\odot$.

4.1.2. Matching the observed periods

We searched for the model that best fit the observed periods by employing the function:

$$\chi^2(M_\star, M_{\rm H}, T_{\rm eff}) = \frac{1}{N}\sum_{i=1}^{N} \min[(\Pi_i^{\rm O} - \Pi_k^{\rm T})^2], \qquad (4.1)$$

where Π_k^T refers to the theoretical periods and Π_k^O the observed ones.

Table 1 shows the stellar parameters derived for our best-fit model ($\sigma^2 = 1.6$) together with the spectroscopic determinations. In Fig. 2 we show the chemical structure (upper panel) and the run of the Brunt-Väisälä and Lamb frequencies (bottom panel) derived for BPM 37093. A crystallized mass of 92% is obtained.

According to our mode identification of the pulsation periods, we derived a rotation period of ~ 55 h, consistent with the values derived from asteroseismology for WD stars.

4.2. *GD 518*

Hermes *et al.* (2013) discovered pulsations in this star (modes of 440.2 s, 513.2 s and 583.7 s). They determinations indicates $T_{\rm eff} \sim 12\,030$ K and log $g \sim 9.08$. According to the ONe-core WD evolutionary tracks of Camisassa *et al.* (2019), this star should have a stellar mass of 1.198 $M_\odot$.

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Due to the few modes exhibited we only attempted to perform period-to-period fits. We obtained a best-fit model ($\sigma^2 = 0.56$) characterized by $T_{\rm eff} \sim 12\,060$ K, $M_\star = 1.22\ M_\odot$ and $\log\, g = 9.15$. Our model reveals a crystallized mass of 95.5%.

4.3. *SDSS J084021.23+522217.4*

This star was discovered by Curd *et al.* (2017) and their determinations indicate $T_{\rm eff} = 12\,160$ K, $\log\, g = 8.93$ and $M_\star = 1.16 M_\odot$. Their preliminary asteroseismological analysis, by considering CO-core WD models, reveals $M_\star = 1.14 M_\odot$, $M_{\rm H} = 5.8 \times 10^{-7} M_\star$, $M_{\rm He} = 4.5 \times 10^{-4} M_\star$, $0.50 \leqslant M_{\rm cr}/M_\star \leqslant 0.70$ and $11\,850 \leqslant T_{\rm eff} \leqslant 12\,350$ K.

By contrast our analysis is based on ONe-core WD models. Our best-fit model ($\sigma^2 = 0.14$) is characterized by $T_{\rm eff} = 12550$ K, $M_\star = 1.10 M_\odot$, $M_{\rm H}/M_\star = 1.02 \times 10^{-7}$, $M_{\rm He}/M_\star = 3.0 \times 10^{-4}$ and 81% of crystallized mass.

5. Conclusions

We presented the results of the evolutionary and asteroseismological study of ultra-massive ZZ Ceti stars by employing an expanded set of grid of realistic ONe-core WD models presented in Camisassa *et al.* (2019). We found that all pulsating white dwarfs known to date in the literature with masses above $1.10 M_\odot$ should have more than 80% of their mass crystallized.

Detailed asteroseismological analysis of BPM 37093 indicates $T_{\rm eff} = 11\,650$ K, $M_\star = 1.16 M_\odot$, $\log(M_{\rm H}/M_\star) = -6$ and $M_{\rm cr}/M_\star = 0.92$ A rotation period of 55 h has been inferred. Preliminary analysis to GD 518 and SDSS J084021 indicates good agreement with the spectroscopic determinations, finding $M_{\rm cr}/M_\star = 0.97$ and 0.81 respectively.

Our results were obtained by assuming that ultra-massive WDs come from single-star evolution and must harbor ONe cores but, however, it cannot be discarded that these objects are the result of mergers of two WDs and harbor CO cores. New photometric observations are needed in order to perform reliable asteroseismological analyses that could help us to derive the core chemical composition and infer their evolutionary origin.

Acknowledgments

F.C.D.G and A.H.C. warmly thank the Local Organizing Committee of the IAU Symposium No. 357 for support that allowed him to attend this conference.

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