The pulsating low-mass He-core white dwarfs

A. H. Córscio¹,², L. G. Althaus¹,², and A. D. Romero³

¹Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, (1900) La Plata, Argentina
²Instituto de Astrofísica La Plata, CONICET-UNLP, Argentina
³Departamento de Astronomia, Universidade Federal do Rio Grande do Sul, Av. Bento Goncalves 9500, Porto Alegre 91501-970, RS, Brazil

Abstract. Recent years have witnessed the discovery of many low-mass (≤ 0.45\,M_⊕) white dwarf (WD) stars — expected to harbor He cores— in the field of the Milky Way and in several galactic globular and open clusters. Recently, three pulsating objects of this kind have been discovered: SDSS J1840+6423, SDSS J1112+1117, and SDSS J1518+0658. Motivated by these very exciting findings, and in view of the valuable asteroseismological potential of these objects, we present here the main outcomes of a detailed theoretical study on the seismic properties of low-mass He-core WDs based on fully evolutionary models representative of these objects. This study is aimed to provide a theoretical basis from which to interpret present and future observations of variable low-mass WDs.

1. Introduction

The population of low-mass WDs has masses lower than 0.45\,M_⊕ and peaks at ≈ 0.39\,M_⊕ (Kleinman et al. 2013). Recently, a large number of low-mass WDs with masses below ~ 0.20 – 0.25\,M_⊕ has been discovered (Brown et al. 2010, 2012; Kilic et al. 2011, 2012); they are referred to as extremely low-mass (ELM) WDs. The low-mass WD population is probably produced by strong mass-loss episodes at the red giant branch (RGB) phase before the He-flash onset. As such, these WDs are expected to harbor He cores, in contrast to average mass WDs, which all likely contain C/O cores. The internal structure of WDs can be disentangled by means of asteroseismology (Winget & Kepler 2008; Althaus et al. 2010), that allows us to place constraints on the stellar mass, the thickness of the compositional layers, and the core chemical composition, among other relevant properties. Recently, three pulsating ELM WD stars have been discovered: SDSS J184037.78+642312.3 (T_\text{eff} = 9390±140 K and log g = 6.49±0.06), SDSS J111215.82+111745.0 (T_\text{eff} = 9590±140 K and log g = 6.36±0.06), and SDSS J151826.68+065813.2 (T_\text{eff} = 9900±140 K and log g = 6.80±0.06) (Hermes et al. 2012, 2013). The exciting discovery of these stars opens the possibility of applying the powerful machinery of asteroseismology to these low-mass, presumed He-core WDs. In Fig. 1 we show a log T_\text{eff} – log g diagram displaying the location of the different known classes of pulsating WD stars: GW Vir or pulsating PG1159 stars (blue dots), V777 Her or DBV stars (orange dots), DQV stars (green dots), ZZ Ceti or DAV stars
Figure 1. The location of the several classes of pulsating WD stars in the log $T_{\text{eff}}$ − log $g$ plane, marked with dots of different colors. Two post-VLTP (H-deficient) evolutionary tracks are plotted for reference. Also shown is the theoretical blue edge of the instability strip for the GW Vir stars (Córsico et al. 2006), the V777 Her stars (Córsico et al. 2009a), the DQV stars (Córsico et al. 2009b), the ZZ Ceti stars (Fontaine and Brassard 2008), and the pulsating ELM WDs. For this last class, we show the blue edge according to Hermes et al. (2013) (dotted red line), Córsico et al. (2012) (solid red line), and Steinfadt et al. (2010) (dashed red line). Small black dots correspond to low-mass WDs that either are nonvariable or have not been observed to vary.

Motivated by the asteroseismic potential of pulsating low-mass WDs, and stimulated by the discovery of the first variable ELM WDs, we have started in the La Plata Observatory a theoretical study of the pulsation properties of low-mass, He-core WDs with masses in the range $0.17 - 0.46 M_\odot$. Here we present the main results of our study, and refer to the paper by Córsico et al. (2012) for a full description of the methods and findings.

2. Adiabatic properties

We have analyzed the adiabatic pulsation properties ($g$- and $p$-modes) of a large set of low-mass and ELM WD models extracted from the computations of Althaus et al. (2009). Specifically, we have considered 8 model sequences of He-core WD generated with the LPCODE evolutionary code, with stellar masses 0.170, 0.198, 0.220, 0.251, 0.303, 0.358, 0.400, and 0.452 $M_\odot$, metallicity $Z = 0.03$ and the MLT for convection with the free parameter $\alpha = 1.6$. A time-dependent treatment of the gravitational settling and chemical diffusion has been accounted for, as well as residual nuclear burning (see for details Althaus et al. 2009). The pulsation computations of our adiabatic survey were performed with the nonradial pulsation code described in detail in Córsico & Althaus (2006). We
have explored the adiabatic pulsation properties of these models, including the expected range of periods and period spacings, the propagation properties and mode trapping of pulsations, the regions of period formation, as well as the dependence on the effective temperature and stellar mass. For the first time, we assessed the pulsation properties of He-core WDs with masses in the range $0.20 - 0.45 M_\odot$. In particular, we found appreciable differences in the seismic properties of objects with $M_* \gtrsim 0.20 M_\odot$ and the ELM WDs ($M_* \lesssim 0.20 M_\odot$). We summarize our findings below:

- ELM WDs have a H envelope that is much thicker than for massive He-core WDs ($\approx 0.20 - 0.45 M_\odot$), due to the very different evolutionary history of the progenitor stars. In particular, ELM WDs did not experience diffusion-induced CNO flashes, thus they harbor thick H envelopes.

- By virtue of the thicker H envelope characterizing ELM WDs, they experience H burning via the pp chain, and consequently their evolution is extremely slow. This feature makes these stars excellent candidates to become pulsating objects. However, He-core WDs with $M_* \approx 0.40 - 0.45 M_\odot$ should have evolutionary timescales of the same order, also making them attractive targets for current searches of variable low-mass WDs.

- The thickness of the He/H transition region is markedly wider for the ELM WDs than for massive He-core WDs. This is due to the markedly lower surface gravity characterizing ELM WDs, that results in a less impact of gravitational settling, and eventually in a wider chemical transition.

- The Brunt-Väisälä frequency ($N$) for ELM WDs is globally lower than for the case of massive objects, due to the lower gravity characterizing ELM WDs. A lower Brunt-Väisälä frequency profile leads to longer pulsation periods.

- The bump of $N^2$ at the He/H transition region is notoriously more narrow and pronounced for the massive WDs than for the ELM WDs. This feature results in a weaker mode trapping in ELM WDs, something that severely limits their seismological potential to constrain the thickness of the H envelope.

- As already noted by Steinfadt et al. (2010), the Brunt-Väisälä frequency of the ELM WDs is larger in the core than in the envelope. This is in contrast with the case of models with $M_* \gtrsim 0.20 M_\odot$ in which the Brunt-Väisälä frequency exhibits larger values at the outer layers, thus resembling the situation encountered in ZZ Ceti stars. So, g-modes in ELM WDs probe mainly the stellar core and have an enormous asteroseismic potential, as it was first recognized by Steinfadt et al. (2010).

- Similarly to ZZ Ceti stars, the g-mode asymptotic period spacing (and the periods themselves) in low-mass He-core WDs is sensitive primarily to the stellar mass, and to a somewhat less extent, to the effective temperature. Specifically, $\Delta \Pi^g_\ell$ is longer for lower $M_*$ and $T_{\text{eff}}$. Also, there is a non-negligible dependence with the thickness of the H envelope, where $\Delta \Pi^g_\ell$ is longer for thinner H envelopes (small $M_H$). Typically, the asymptotic period spacing range from $\approx 55$ s for $M_* = 0.45 M_\odot$ and $T_{\text{eff}} = 11 500 \text{ K}$, up to $\approx 110$ s for $M_* = 0.17 M_\odot$ and $T_{\text{eff}} = 8000 \text{ K}$. 




2.1. Effects of element diffusion

Time-dependent element diffusion modifies the shape of the He and H chemical profiles as the WD cools, causing H to float to the surface and He to sink down. In particular, diffusion not only modifies the chemical composition of the outer layers, but also the shape of the He/H chemical transition region itself. This is clearly shown in Fig. 2 for the case of the 0.17\(M_\odot\) sequence in the \(T_{\text{eff}}\) interval (11 000 – 8000 K). For the model at \(T_{\text{eff}} = 11\ 000\) K, the H profile is characterized by a diffusion-modeled double layered chemical structure, which consists in a pure H envelope atop an intermediate remnant shell rich in H and He (upper panel). This structure still remains, although to a much less extent, in the model at \(T_{\text{eff}} = 9500\) K (middle panel). Finally, at \(T_{\text{eff}} = 8000\) K, the H profile has a single-layered chemical structure (lower panel). Element diffusion processes affect all the sequences considered in this work, although the transition from a double-layered structure to a single-layered one occurs at different effective temperatures. The markedly lower surface gravity that characterizes the less massive model, results in a less impact of gravitational settling, and eventually in a wider chemical transition in the model with \(M_* = 0.17M_\odot\). Because of this fact, the sequences with larger masses reach the single-layered structure at higher effective temperatures.

The changes in the shape of the He/H interface are translated into non-negligible changes in the profile of the Brunt-Väisälä frequency, as can be appreciated in the plot. In fact, at high effective temperatures, \(N^2\) is characterized by two bumps, which merge into a single one when the chemical profile at the He/H interface adopts a single-layered structure. In the light of our results, we conclude that the assumption diffusive equilibrium is valid in the He/H transition region, which has been adopted in other
works, is clearly wrong. We found substantial changes in the value of the periods when diffusion is neglected, depending on the specific mode considered and the value of the effective temperature. For instance, for the $k = 3$ mode ($\Pi_3 \approx 460$ s) at $T_{\text{eff}} \approx 9000$ K, a variation of 5% in the value of the period is expected.

3. Stability analysis

In order to investigate the plausibility of excitation of pulsations in our models, we performed a linear stability analysis on our complete set of evolutionary sequences. We employed the nonadiabatic pulsation code described in detail in Crisco et al. (2006). The nonadiabatic computations rely on the frozen convection approximation, in which the perturbation of the convective flux is neglected. While this approximation is known to give unrealistic locations of the $g$-mode red edge of instability, it leads to satisfactory predictions for the location of the blue edge of the ZZ Ceti (DAV) instability strip (van Grootel et al. 2012). We found that a dense spectrum of $g$-modes are excited by the ($\kappa - \gamma$)-mechanism acting in the H partial ionization zone for all the masses considered, and that there exists a well-defined blue (hot) edge of instability of He-core WDs, which is the low-mass analog to the blue edge of the ZZ Ceti instability strip. We also found numerous unstable $p$-modes; the corresponding blue edge is hotter than the $g$-mode blue edge and has a lower slope. We warn that the location of the blue edges are sensitive to the efficiency of convection adopted for the equilibrium models. So, had we adopted a different convective efficiency, then the predicted blue edges of the ELM and low-mass He-core WDs instability domain should appreciably change. In Fig. 1 we show the location of our $g$-mode blue edge (solid red line), along with those obtained by Hermes et al. (2013) (dotted red line) and by Steinfadt et al. (2010) (dashed red line). It seems that our blue edge and that of Steinfadt et al. (2010) are somewhat cool as compared with the location of the three pulsating ELM WDs. But, as mentioned, the location of
the blue edge can be easily accommodated by tuning the convective efficiency of the models.

In Figs. 3 and 4 we show the instability domains of dipole \( g \)- and \( p \)-modes on the \( T_{\text{eff}} - \Pi \) plane corresponding to our set of models with \( M_* = 0.17M_\odot \) and \( M_* = 0.198M_\odot \), respectively. Also shown are the periodicities measured in the three known pulsating ELM WDs. Note that our theoretical results for the range of periods of unstable \( g \)-modes are roughly compatible with the observations, but there is not a good quantitative agreement regarding the effective temperature of the instability domains. In particular, the short periods suspected to be due to \( p \)-modes in SDSS J1112+1117 are roughly accounted for by our computations in the case of models with \( M_* = 0.17M_\odot \), although the effective temperatures of the theoretical instability domain are somewhat lower than the \( T_{\text{eff}} \) of the star.

4. Summary and future work

We have presented a brief description of a thorough theoretical study on the seismic properties of low-mass He-core WDs based on fully evolutionary models representative of these objects (Córsico et al. 2012). This study was aimed to provide a theoretical basis from which to interpret present and future observations of variable low-mass WDs. As the next step, we are planning to compute a fine grid (in stellar mass) of fully evolutionary ELM WD sequences derived consistently from binary evolution with solar metallicity progenitors and different H envelope thicknesses, to be employed in asteroseismological studies. A good target for asteroseismology is SDSS J111215 + 111745 because this star exhibits numerous \( g \)- and (suspected) \( p \)-modes, with a robust period determination. Also, we plan to perform extensive stability analysis of these models employing different efficiencies of convection, and explore mode driving through the \( \epsilon \)-mechanism due to H burning.

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