Recent advances in the theoretical modeling of pulsating low-mass He-core white dwarfs

A. H. Córsico, 1 L. G. Althaus, 1 L. M. Calcaferro, 1 A. M. Serenelli, 2 S. O. Kepler, 3 and C. S. Jeffery 4

1 Facultad de Ciencias Astronómicas y Geofísicas (UNLP), La Plata, Argentina; acorsico@fcaglp.unlp.edu.ar
2 Institute of Space Sciences (IEEC-CSIC), Barcelona, Spain;
3 Instituto de Física (UFRGS), Porto-Alegre, Brazil;
4 Armagh Observatory, College Hill, UK

Abstract. Many extremely low-mass (ELM) white-dwarf (WD) stars are currently being found in the field of the Milky Way. Some of these stars exhibit long-period nonradial g-mode pulsations, and constitute the class of ELM pulsating WDs. In addition, several low-mass pre-WDs, which could be precursors of ELM WDs, have been observed to show short-period photometric variations likely due to nonradial p modes and radial modes. They could constitute a new class of pulsating low-mass pre-WD stars, the pre-ELMV stars. Here, we present the recent results of a thorough theoretical study of the nonadiabatic pulsation properties of low-mass He-core WDs and pre-WDs on the basis of fully evolutionary models representative of these stars.

1. Introduction

An increasing number of low-mass WDs, including ELM WDs ($M_\star \sim 0.18 - 0.20 M_\odot$, H-rich atmospheres), are currently being detected through the ELM survey (see Brown et al. 2016 and references therein). These WD stars, which likely harbor cores made of He, are thought to be the result of strong mass-loss events at the red giant branch stage of low-mass stars in binary systems before the He flash onset that, in this way, is avoided (Althaus et al. 2013; Istrate et al. 2016). The increasing interest in ELM WDs has lead to the discovery of long-period ($\Pi \sim 1000 - 6300$ s) g-mode pulsations in some of them (ELMVs). The existence of ELMV stars ($7000 \lesssim T_{\text{eff}} \lesssim 10,000$ K and $6 \lesssim \log g \lesssim 7$; red circles in Fig. 1) constitutes an unprecedented opportunity for probing their subsurface layers and ultimately to place constraints on the currently accepted formation scenarios by means of asteroseismology (Winget & Kepler 2008; Fontaine & Brassard 2008; Althaus et al. 2010). Apart from ELMVs, short-period ($\Pi \sim 300 - 800$ s) pulsations in five objects that are probably precursors of ELM WDs have been detected in the few last years. These stars have typically $8000 \lesssim T_{\text{eff}} \lesssim 13,000$ K and $4 \lesssim \log g \lesssim 5.5$ (green circles in Fig. 1) and show a surface composition made of H and He. They are called pre-ELMV stars and constitute a new class of pulsating stars. Also, the discovery of long-period ($\Pi \sim 1600 - 4700$ s) pulsations in three additional objects located at the same region of the HR diagram has been reported.
These stars are emphasized with black squares surrounding the green circles in Fig. 1. The nature of these objects is uncertain and could be identified as pre-ELM stars as well as SX Phe and/or δ Scuti pulsating stars. In Table 1 we include an updated compilation of the effective temperature, gravity and range of observed periods for all the known pre-ELMV and ELMV stars.

![Figure 1. The location of the known ELMVs (red circles) and pre-ELMVs (light green circles) along with the other several classes of pulsating WD stars (dots of different colors) in the log $T_{\text{eff}}$ − log $g$ plane. The three stars emphasized with squares surrounding the light green circles can be identified as pre-ELMV stars as well as SX Phe and/or δ Scuti stars. In parenthesis we include the number of known members of each class. Two post-VLTP (Very Late Thermal Pulse) evolutionary tracks for H-deficient WDs and two evolutionary tracks for low-mass He-core WDs are plotted for reference. Dashed lines indicate the theoretical blue edge for the different classes of pulsating WDs.](image-url)
models with stellar masses between 0.1 and 0.25 M⊙. We assumed the presence of a neutron star companion as the other component. A total of 14 initial He-core pre-WD models were derived from evolutionary calculations for binary systems consisting of an evolving Main Sequence low-mass component (donor star) of initially 1 M⊙. All of the He-core pre-WD initial models were computed for initial orbital periods at the beginning of the Roche lobe phase in the range 0.9 to 300 d.

2. Evolution and pulsation modeling

We employed stellar evolution models representative of ELM pre-WDs and WDs generated with the LPCODE stellar evolution code (see Althaus et al. 2013 and references therein). We carried out a pulsation stability analysis of radial and nonradial $p$ and $g$ modes employing the nonadiabatic versions of the LP-PUL pulsation code described in detail in Córsico et al. (2006). Our nonadiabatic computations rely on the frozen-convection (FC) approximation, in which the perturbation of the convective flux is neglected. This assumption could constitute a source of uncertainties in the location of the derived blue edges of instability. The equilibrium models employed in our analysis are realistic configurations for low-mass He-core pre-WDs and WDs computed by Althaus et al. (2013) by mimicking the binary evolution of progenitor stars. Binary evolution was assumed to be fully nonconservative, and the loss of angular momentum due to mass loss, gravitational wave radiation, and magnetic braking was considered, following the formalism of Sarna et al. (2000). All of the He-core pre-WD initial models were derived from evolutionary calculations for binary systems consisting of an evolving Main Sequence low-mass component (donor star) of initially $1M_\odot$ and a $1.4M_\odot$ neutron star companion as the other component. A total of 14 initial He-core pre-WD models with stellar masses between 0.1554 and 0.4352 M⊙ were computed for initial orbital periods at the beginning of the Roche lobe phase in the range 0.9 to 300 d.

Table 1. Stellar parameters and observed period range of the known pre-ELMV (upper half of the table) and ELMV (lower half of the table) stars. For ELMVs, the $T_{\text{eff}}$ and log $g$ values are computed with 1D model atmospheres after 3D corrections.

| Star            | $T_{\text{eff}}$ [K] | log $g$ [cgs] | $M_\star$ [M⊙] | Period range [s] | Ref. |
|-----------------|----------------------|---------------|-----------------|------------------|------|
| SDSS J115734.46+054645.6 | 11 870 ± 260 | 4.81 ± 0.13 | 0.186 | 364 | (3) |
| SDSS J075610.71+670424.7 | 11 640 ± 250 | 4.90 ± 0.14 | 0.181 | 521 – 587 | (3) |
| WASP J024743.37−251549.2 | 11 380 ± 400 | 4.576 ± 0.011 | 0.186 | 380 – 420 | (1) |
| SDSS J114155.56+385003.0 | 11 290 ± 210 | 4.94 ± 0.10 | 0.177 | 325 – 368 | (3) |
| KIC 9164561(*) | 10 650 ± 200 | 4.86 ± 0.04 | 0.213 | 3018 – 4668 | (5) |
| WASP J162842.31+101416.7 | 9200 ± 600 | 4.49 ± 0.05 | 0.135 | 668 – 755 | (2) |
| SDSS J173001.94+070600.25(*) | 7972 ± 200 | 4.25 ± 0.5 | 0.171 | 3367 | (4) |
| SDSS J145847.02+070754.46(*) | 7925 ± 200 | 4.25 ± 0.5 | 0.171 | 1634 – 3279 | (4) |

References: (*) Not secure identification as pre-ELM WD (see text); (1) Maxted et al. (2013); (2) Maxted et al. (2014); (3) Gianninas et al. (2016); (4) Corti et al. (2016); (5) Zhang et al. (2016); (6) Hermes et al. (2013b); (7) Hermes et al. (2013a); (8) Kilic et al. (2015); (9) Bell et al. (2015); (10) Hermes et al. (2012)
2.1. Pre-ELMVs

A complete description of the results presented in this section can be found in Córsico et al. (2016). Here, we mention only the main nonadiabatic results. We analyzed the stability properties of He-core, low-mass pre-WD models computed assuming the ML2 prescription for the MLT theory of convection (Tassoul et al. 1990) and covering a range of effective temperatures of $25 \,000 \,\text{K} \lesssim T_{\text{eff}} \lesssim 6000 \,\text{K}$ and a range of stellar masses of $0.1554 \lesssim M_{\star}/M_{\odot} \lesssim 0.2724$. First, we report on results of evolutionary computations that neglect the action of element diffusion. For each model, we assessed the pulsational stability of radial ($\ell = 0$), and nonradial ($\ell = 1, 2$) $p$ and $g$ modes with periods in the range $10 \,\text{s} \lesssim \Pi \lesssim 20 \,000 \,\text{s}$. In the left panel of Fig. 2 we show a spectroscopic HR diagram ($T_{\text{eff}} - \log g$) showing our low-mass He-core pre-WD evolutionary tracks (dotted curves). Green circles correspond to the known pre-ELMV stars, and black dots depict the location of stars not observed to vary. The dashed blue line indicates the nonradial $\ell = 1$ $p$-mode blue edge of the pre-ELMV instability domain (emphasized as a gray area) due to the $\kappa-\gamma$ mechanism acting at the He$^+-$He$^{++}$ partial ionization region, as obtained by Córsico et al. (2016). Right: The same diagram but for our low-mass He-core WD evolutionary tracks (final cooling branches). The locations of the seven known ELMVs are marked with red circles ($T_{\text{eff}}$ and $\log g$ computed with 1D model atmospheres after 3D corrections). The gray region bounded by the dashed blue line corresponds to the instability domain of $\ell = 1$ $g$ modes due to the $\kappa-\gamma$ mechanism acting at the H-H$^+$ partial ionization region according to Córsico & Althaus (2016).
theory of convection adopted in the equilibrium models. This is at variance with what happens in the case of ELMVs (see the next Section). The blue edge of radial modes is substantially cooler (~ 1000 K) than for nonradial modes. Our computations seem to account for the existence of some of the known pre-ELMVs, including the observed ranges of excited periods. However, our analysis is not able to predict pulsations in three pulsating objects (the hottest ones, see Fig. 2). This is directly related to the He abundance ($X_{\text{He}}$) at the driving region. Higher He abundances at the envelope of our models would be required in order to the blue edge be hotter, as to include these three stars within the instability domain. This could be achieved by adopting different masses for the initial donor star in the original binary system, that could led to low-mass pre-WD models with different He abundances at their envelopes. This issue will be explored in a future study.

When we take into account the action of element diffusion (due to gravitational settling and chemical and thermal diffusion), $X_{\text{He}}$ decreases rapidly at the driving region by virtue of gravitational settling, and thus the instability region (not shown) in the $T_{\text{eff}} - \log g$ plane becomes much narrower than in the case of non diffusion, so that none of the observed pulsating pre-ELMV stars is within that region. This important result suggests that element diffusion could not be operative in the pre-WD stage. Several factors could be playing a role to prevent the effects of element diffusion, namely stellar winds and/or stellar rotation. This interesting topic has been recently addressed by Istrate & Fontaine (these proceedings), who found that rotational mixing is indeed able to suppress the effects of element diffusion.

### 2.2. ELMVs

We have analyzed the stability properties of about 7000 stellar models of He-core, low-mass WDs with H-pure atmospheres taking into account three different prescriptions for the MLT theory of convection (ML1, ML2, ML3; see Tassoul et al. 1990 for their definitions) and covering a range of effective temperatures of $13000 \, \text{K} \lesssim T_{\text{eff}} \lesssim 6000 \, \text{K}$ and a range of stellar masses of $0.1554 \lesssim M_\star/M_\odot \lesssim 0.4352$. For each model, we assessed the pulsation stability of radial ($\ell = 0$) and nonradial ($\ell = 1, 2$) $p$ and $g$ modes with periods from a range $10 \, \text{s} \lesssim \Pi \lesssim 18000 \, \text{s}$ for the sequence with $M_\star = 0.1554M_\odot$, up to a range of periods of $0.3 \, \text{s} \lesssim \Pi \lesssim 5000 \, \text{s}$ for the sequence of with $M_\star = 0.4352M_\odot$. Full details of these calculations are given in Córsico & Althaus (2016). We show in the right panel of Fig. 2 the spectroscopic HR diagram for our low-mass He-core WD evolutionary tracks (final cooling branches), along with the location of the seven known ELMVs (red circles), where $T_{\text{eff}}$ and $\log g$ have been computed with 1D model atmospheres after 3D corrections. The instability domain of $\ell = 1$ $g$ modes due to the $\kappa - \gamma$ mechanism acting at the H-H$^+$ partial ionization region is emphasized with a gray region bounded by a dashed blue line corresponding to the blue edge of the instability domain. Our results are in good agreement with those of Córsico et al. (2012) and Van Grootel et al. (2013). Some short-period $g$ modes are destabilized mainly by the $\varepsilon$ mechanism due to stable nuclear burning at the basis of the H envelope, particularly for model sequences with $M_\star \lesssim 0.18M_\odot$ (see Córsico & Althaus 2014a for details). The blue edge of the instability domain in the $T_{\text{eff}} - \log g$ plane is hotter for higher stellar mass and larger convective efficiency. The ML2 and ML3 versions of the MLT theory of convection are the only ones that correctly account for the location of the seven known ELMV stars. There is no dependence of the blue edge of $p$ modes on the harmonic degree. In the case of $g$ modes, we found a weak sensitivity of the blue
edge with $\ell$. Finally, the blue edges corresponding to radial and nonradial $p$ modes are somewhat (~200 K) hotter than the blue edges of $g$ modes. We compared the ranges of unstable mode periods predicted by our stability analysis with the ranges of periods observed in the ELMV stars. We generally found an excellent agreement.

3. Conclusions

The origin and basic nature of pulsations exhibited by pre-ELMVs and ELMVs have been established (Steinfadt et al. 2010; Córsico et al. 2012; Jeffery & Saio 2013; Van Grootel et al. 2013; Córsico & Althaus et al. 2014ab, 2016; Córsico et al. 2016; Gianninas et al. 2016). The next step is to start exploiting the period spectra of these stars with asteroseismological analysis. Asteroseismology of low-mass He-core WDs will provide crucial information about the internal structure and evolutionary status of these stars, allowing us to place constraints on the binary evolutionary processes involved in their formation.

Acknowledgments. A.H.C. warmly thanks the Local Organising Committee of the 20th European White Dwarf Workshop for support that allowed him to attend this conference.

References

Althaus, L. G., Miller Bertolami, M. M., & Córsico, A. H. 2013, A&A, 557, A19
Althaus, L. G., Córsico, A. H., Isern, J., & García-berro, E. 2010, A&A Rev., 18, 471
Bell, K. J., Kepler, S. O., Montgomery, M. H., et al. 2015, 19th European Workshop on White Dwarfs, 493, 217
Brown, W. R., Gianninas, A., Kilic, M., Kenyon, S. J., & Allende Prieto, C. 2016, ApJ, 818, 155
Córsico, A. H., Althaus, L. G., Serenelli, A. M., et al. 2016, A&A, 588, A74
Córsico, A. H., & Althaus, L. G. 2016, A&A, 585, A1
Córsico, A. H., & Althaus, L. G. 2014b, A&A, 569, A106
Córsico, A. H., & Althaus, L. G. 2014a, ApJ, 793, L17
Córsico, A. H., Romero, A. D., Althaus, L. G., & Hermes, J. J. 2012, A&A, 547, A96
Córsico, A. H., Althaus, L. G., & Miller Bertolami, M. M. 2006, A&A, 458, 259
Corti, M. A., Kanaan, A., Córsico, A. H., et al. 2016, A&A, 587, L5
Fontaine, G., & Brassard, P. 2008, PASP, 120, 1043
Gianninas, A., Curd, B., Fontaine, G., Brown, W. R., & Kilic, M. 2016, ApJ, 822, L27
Hermes, J. J., Montgomery, M. H., Gianninas, A., et al. 2013a, MNRAS, 436, 3573
Hermes, J. J., Montgomery, M. H., Winget, D. E., et al. 2013b, ApJ, 765, 102
Hermes, J. J., Montgomery, M. H., Winget, D. E., et al. 2012, ApJ, 750, L28
Istrate, A., Marchant, P., Tauris, T. M., et al. 2016, arXiv:1606.04947
Jeffery, C. S., & Saio, H. 2013, MNRAS, 435, 885
Kilic, M., Hermes, J. J., Gianninas, A., & Brown, W. R. 2015, MNRAS, 446, L26
Maxted, P. F. L., Serenelli, A. M., Marsh, T. R., et al. 2014, MNRAS, 444, 208
Maxted, P. F. L., Serenelli, A. M., Miglio, A., et al. 2013, Nat, 498, 463
Sarna, M. J., Ergma, E., & Gerškevitš-Antipova, J. 2000, MNRAS, 316, 84
Steinfadt, J. D. R., Bildsten, L., & Arras, P. 2010, ApJ, 718, 441
Tassoul, M., Fontaine, G., & Winget, D. E. 1990, ApJS, 72, 335
Van Grootel, V., Fontaine, G., Brassard, P., & Dupret, M.-A. 2013, ApJ, 762, 57
Winget, D. E., & Kepler, S. O. 2008, ARA&A, 46, 157
Zhang, X. B., Fu, J. N., Li, Y., Ren, A. B., & Luo, C. Q. 2016, ApJ, 821, L32