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Letter to the Editor

Asteroseismic test of rotational mixing in low-mass white dwarfs

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ABSTRACT

We exploit the recent discovery of pulsations in mixed-atmosphere (He/H), extremely low-mass white dwarf precursors (ELM proto-WDs) to test the proposition that rotational mixing is a fundamental process in the formation and evolution of low-mass helium core white dwarfs. Rotational mixing has been shown to be a mechanism able to compete efficiently against gravitational settling, thus accounting naturally for the presence of He, as well as traces of metals such as Mg and Ca, typically found in the atmospheres of ELM proto-WDs. Here we investigate whether rotational mixing can maintain a sufficient amount of He in the deeper driving region of the star, such that it can fuel, through HeII-HeIII ionization, the observed pulsations in this type of stars. Using state-of-the-art evolutionary models computed with MESA, we show that rotational mixing can indeed explain qualitatively the very existence and general properties of the known pulsating, mixed-atmosphere ELM proto-WDs. Moreover, such objects are very likely to pulsate again during their final WD cooling phase.

Key words. asteroseismology – binaries: close – white dwarfs – stars: evolution

1. Astrophysical context

Gianninas et al. (2016) recently reported the discovery of pulsations in three mixed-atmosphere, extremely low-mass white dwarf precursors (ELM proto-WDs). Their location in the $\log g$–$T_{\rm eff}$[1] diagram and the detected periods are similar to those of the first discovered pulsating ELM proto-WDs WASP 0247-25B ($T_{\rm eff}$ = 10 840 ± 300 K, $\log g$ = 4.576 ± 0.011; Maxted et al. 2013) and WASP 1628+10B ($T_{\rm eff}$ = 9200 ± 600 K, $\log g$ = 4.49 ± 0.05; Maxted et al. 2014). It is expected that the nature of the pulsation driving is the same in both types of systems (see, e.g., Jeffery & Saio 2013; Córsico et al. 2016). While the (likely) presence of He in the atmosphere of the two WASP systems has yet to be confirmed[2], the results of Gianninas et al. (2016) represent the first empirical evidence that pulsations in relatively hot ELM proto-WDs can only occur when a significant amount of He is present in their atmospheres. We disregard here the two cool-ELM proto-WD candidates proposed by Corti et al. (2016), and also the system discussed by Zhang et al. (2016), as their nature is currently unclear.

Helium is the ingredient needed to drive pulsations in a regime of effective temperature well above the blue edge of the ZZ Ceti instability strip, as well as its extension into the low-gravity domain (e.g., Steinfadt et al. 2010; Córsico et al. 2012; Van Grootel et al. 2013). The ZZ Ceti instability strip only contains pure H atmosphere (DA) WDs for which pulsation driving is confined to the regions of partial ionization of H. Van Grootel et al. (2015) showed that a full continuum of instability strips, from the cooler pure H ZZ Ceti to the hotter pure He V777 Her domain, is obtained uniquely as a function of the He/H envelope ratio along the WD cooling tracks. In this case, pulsation driving is due to the combined effects of partial ionization of H and He. Non-adiabatic stability analysis of simple envelope models indicates that the pulsations in the newly discovered three mixed-atmosphere proto-WDs are caused mostly by a standard κ-mechanism associated with the second ionization of He, in conjunction with some convective driving (Gianninas et al. 2016).

Regarding the evolution of ELM WDs, Istrate et al. (2016) investigated the combined effects of rotational mixing and diffusion processes[3] on the (proto-) WDs that are formed through the low-mass X-ray binary channel. After the end of the mass-transfer phase, the envelope of the newly formed proto-WD contracts significantly, rotating thus faster than the helium core. This gives rise to rotational instabilities, with Eddington-Sweet circulation being the main process responsible for the mixing of material. In particular, rotational mixing was shown to be a mechanism able to compete efficiently against gravitational settling, which would otherwise lead to the formation of a pure H atmosphere on a very short timescale (e.g., Althaus et al. 2001, 2013).

[1] *J0756+6704*: $T_{\rm eff}$ = 11 640 ± 250 K, $\log g$ = 4.90 ± 0.14, X(He) = 0.50 ± 0.20; *J1141+3850*: $T_{\rm eff}$ = 11 290 ± 210 K, $\log g$ = 4.94 ± 0.10, X(He) = 0.54 ± 0.14; *J1157+0546*: $T_{\rm eff}$ = 11 870 ± 260 K, $\log g$ = 4.81 ± 0.13, X(He) = 0.53 ± 0.20.

[2] A difficult task as the light of the A-type companion dominates the optical spectrum.

[3] Gravitational settling, thermal diffusion, and chemical diffusion.

This is in agreement with what has been observed in ELM proto-WDs, where substantial amounts of He, as well as traces of metals such as Mg and Ca, are often detected in their atmospheres (Kaplan et al. 2013; Gianninas et al. 2014; Hermes et al. 2014; Latour et al. 2016). While the influence of radiative levitation has yet to be investigated quantitatively in these stars, it is certain that it cannot explain the detected relatively large amounts of He. This is because radiative levitation is only able to support traces of various elements in a dominant background because of line saturation. Considering this, rotational mixing is most likely a fundamental process that should be taken into account in the evolution of ELM (proto-) WDs with important consequences in the future asteroseismological studies of this class of objects.

In this Letter we demonstrate that the new available evolutionary models can account for the existence of the observed pulsating mixed-atmosphere ELM proto-WDs.

2. Results

We identified several evolutionary sequences from Istrate et al. (2016) and recomputed them to achieve a higher density of models in the region of interest. These new tracks have been calculated using the publicly available binary stellar evolution code MESA, version 7624 (Paxton et al. 2011, 2013, 2015). The details regarding the input physics are the same as in Istrate et al. (2016). It should be noted here that there are still many uncertainties in our theoretical understanding of rotational mixing. For instance, the effects of the Eddington-Sweet circulation (Heger et al. 2000) and of the Tayler-Spruit dynamo (Spruit 2002) are both not well constrained. Models including magnetic fields reproduce the angular momentum content of stellar cores much better (Suijs et al. 2008), although the validity of this process has been questioned (Zahn et al. 2007). Additional effects such as gravity waves (which were not considered in the models of Istrate et al. 2016) might also play an important role in the transport of angular momentum (Fuller et al. 2014).

We carried out a stability analysis of these evolutionary models using the Montréal pulsation codes (Brassard et al. 1992; Fontaine et al. 1994). For each retained model, we investigated the stability of all pulsation modes in the range of periods from 50 to 4000 s and with degree index $\ell = 0$, 1, and 2. When present, convection was handled through the so-called frozen flux approximation, for which the perturbations of the convective flux are ignored. To the extent that convective driving does not dominate the excitation process in ELM proto-WD models, this was deemed sufficient (Van Grootel et al. 2012, 2013, 2015); see also Sect. 3 below.

Figure 1 shows the five evolutionary tracks used in this work in the $\log g - T_{\rm eff}$ diagram. Following Istrate et al. (2016), we investigated the pulsational behavior of three different configurations, with roughly the same WD mass, computed for a metallicity of $Z = 0.001$: (i) *basic*, where no element diffusion nor rotational mixing are included, (ii) *diffusion*, in which element diffusion operates, and (iii) *diffusion+rotation*, in which both element diffusion and rotational mixing are present. The chemical stratification of the envelope in the case of the *basic* configuration is set by the outcome of the binary evolution and it is changed only by the hydrogen shell burning. The choice of metallicity is partly motivated by the fact that both J0756+6704 and J1141+3850 are probably halo stars (Gianninas et al. 2015; Brown et al. 2016)[4]. Additionally, we also study the influence of the WD mass and metallicity on the excited modes.

[4] In the case of J1157+0546, the population membership is still unknown.

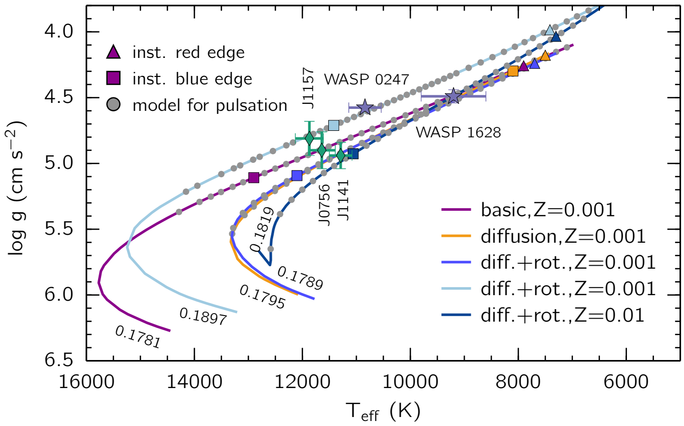

Fig. 1. ELM WD evolutionary tracks representative of the observed proto-WD pulsators used for pulsation analysis. The mass ($M_\odot$) is indicated by the numbers next to each track.

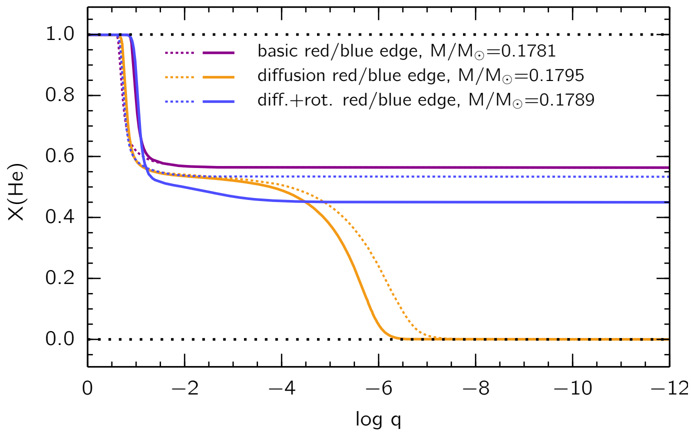

Fig. 2. Helium mass fraction, X(He), as a function of the fractional mass depth, $\log q \equiv \log\,(1 - M(r)/M_*)$ for the red and blue edge profiles for the models in *basic*, *diffusion*, and *rotation+diffusion* configurations. The assumed metallicity is $Z = 0.001$.

Figure 2 illustrates that rotational mixing plays a key role in maintaining relatively large amounts of He in the envelope of the models on the proto-WD branch. In contrast, pure diffusion leads very early on to the formation of a pure H envelope. From a pulsation point of view, this is a fundamental difference as He is needed, through its second ionization stage, for exciting pulsation modes via a κ-mechanism in the domain where the pulsating ELM proto-WDs are found, that is, in a regime of temperature where H is completely ionized and cannot help in the destabilization process. We note that the region of damping or driving is typically located in the range $-7 \gtrsim \log g \gtrsim -11$ in the envelope of ELM proto-WD models (Córsico et al. 2016). The *diffusion+rotation* (*basic*) model predicts that the He content in the damping or driving region is the same as in the outermost layers (see Fig. 2). In this case, the atmospheric He abundance, as determined through standard spectroscopic techniques, provides a direct measure of the quantity of that element in the much deeper, unobservable damping or driving region. This can become a very useful diagnostic tool.

Figure 3 summarizes our stability analysis results for $\ell = 1$ modes[5]. For the *basic* model, the He content in the envelope remains fixed at a value of $X(\mathrm{He}) \simeq 0.57$, which leads to a maximum extension of the instability domain. In the early cooler

[5] The excited $\ell = 1$ modes map essentially the same domain in the period-effective temperature plane as the $\ell = 0$ and $\ell = 2$ modes.

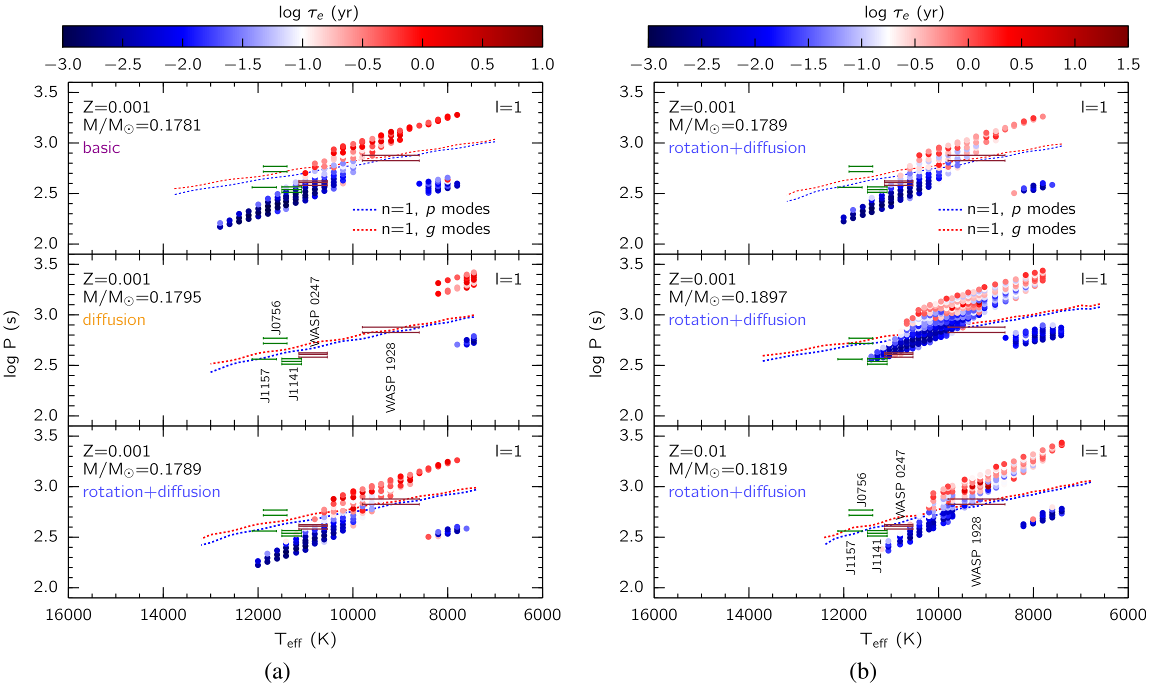

Fig. 3. Calculated period spectrum for the excited modes for each of the retained models represented by the gray circles in Fig. 1. The color code indicates the logarithm of the e-folding time, τ_e. The blue dotted curve defines the upper limit (radial order $n = 1$) of the p-mode spectrum, while the red dotted curve corresponds to the lower limit (radial order $n = 1$) of the g-mode spectrum. The green (magenta) lines denote the three observed mixed-atmosphere pulsators (two WASP pulsators). *Left panel*: comparison between the *basic*, *diffusion*, and *diffusion+rotation* for roughly the same WD mass; *right panel*: comparison of different WD masses and metallicities in the *rotation+diffusion* configuration.

phase ($T_{\rm eff} < 9000$ K) of ELM proto-WD evolution, two instability islands can clearly be seen, one corresponding to p-modes (acoustic modes), and the other to g-modes (gravity modes). With increasing $T_{\rm eff}$, a single broad band of excited periods persists, initially consisting of g-modes, and finally consisting of p-modes at the blue edge ($T_{\rm eff} \simeq 12\,800$ K).

In the *diffusion* model, pulsational instabilities are found only in the cooler models ($T_{\rm eff} < 8200$ K), which are already characterized by a pure H composition in the driving region. Although in reality unimpeded diffusion is unlikely to occur, such configurations would correspond to cool pulsating ELM proto-WDs lying in the extension of the classical ZZ Ceti instability strip. This case of pure diffusion, however, is in direct conflict with the existence of the known pulsating ELM proto-WD stars, which are found at much higher effective temperatures. This has been pointed out previously by Córsico et al. (2016).

In the case of the *diffusion+rotation* model, we find that rotational mixing is able to maintain, against gravitational settling, a sufficient amount of He in the envelope of ELM proto-WDs to drive pulsations in the regime of effective temperatures in which the observed pulsators are found. Specifically, the initial helium content in the envelope is $X({\rm He}) \simeq 0.54$ and only slowly drops to $X({\rm He}) \simeq 0.46$ (see Fig. 2) by the time the model has reached the blue edge of the instability region. The latter is located at $T_{\rm eff} \simeq 12\,000$ K, cooler than that of the *basic* sequence as expected, but still providing a very adequate coverage of the observed instability domain.

The predicted domain of instability in the period-effective temperature plane is very sensitive to the stellar mass, but also depends on the assumed metallicity. The dependence of the computed domain of instability on stellar mass has been described in detail by Córsico et al. (2016). The main effect of increasing the mass, all other things being equal, is to displace the instability domain to a somewhat cooler and longer-period region. For instance, the blue edge is shifted from $T_{\rm eff} \simeq 12\,000$ K (0.1789 $M_\odot$) to $T_{\rm eff} \simeq 11\,400$ K (0.1897 $M_\odot$), while the red edge is lowered by $\simeq$200 K. This is directly related to the lower initial amount of He left in the envelope of the proto-WD after the end of the mass-transfer phase. With an increased metallicity, $Z = 0.01$, we find that the blue edge is instead lowered to $T_{\rm eff} \simeq 11\,100$ K. This behavior is again caused by the lesser initial amount of He that is available at the outset of the final evolutionary phase. For a given mass, binary evolution leads to an envelope composition less enriched in He if the assumed metallicity is higher (Istrate et al. 2016).

Summarizing, we find that evolutionary models that include rotational mixing provide a natural explanation for the observed pulsational instabilities in the ELM proto-WD regime. Additionally, we obtain that the qualitative match between the predicted domain of instability and the observations is better for the sequence with the relatively low mass of 0.1789 $M_\odot$ and metallicity of $Z = 0.001$.

3. Discussion

To compare the detected pulsation periods with the computed periods, we need to fold in the important sensitivity of the pulsation results on the WD mass. Figure 1 shows that both the 0.1789 $M_\odot$ and the 0.1819 $M_\odot$ sequence might serve as the basis for a seismic model for both WASP 1628+10B and J1141+3850. Likewise, the 0.1897 $M_\odot$ sequence might be of interest for WASP 0247−25B and J1157+0546. In this connection, the top panel in Fig. 3b indicates that the two periods detected in WASP 1628+10B (Maxted et al. 2014) and the three pulsations detected in J1141+3850 (Gianninas et al. 2016) correspond rather well to predicted values, taking into account the uncertainties on the estimates of the effective temperature of these stars. In addition, for J1141+3850, we have an estimate of the spectroscopic abundance of helium, $X(\mathrm{He}) = 0.54 \pm 0.14$ (Gianninas et al. 2016). While the uncertainties are relatively large, this agrees with the range of helium abundance expected in the envelope of the 0.1789 $M_{\odot}$ models.

The agreement between the two observed periods in WASP 1628+10B and the predicted values improves slightly by considering the $Z = 0.01$, 0.1819 $M_{\odot}$ sequence. In contrast, the predicted excited periods are somewhat shorter than those observed in J1141+3850. We also find that the results of the 0.1897 $M_{\odot}$ sequence are in qualitative agreement with the three periods detected in WASP 0247−25B, while the predicted blue edge of the instability domain falls slightly short of the location of J1157+0546. The single detected period of 364 s is, however, consistent with the calculated periods at that blue edge. The atmospheric value of the He abundance in J1157+0546 is $X(\mathrm{He}) = 0.53 \pm 0.20$ (Gianninas et al. 2016); this is not well constrained, but nevertheless consistent with the expected values shown in Fig. 2.

With perhaps one exception, we thus find an overall good agreement between the predictions of the rotation+diffusion approach and the general properties of the known pulsating ELM proto-WD stars. The exception is J0756+6704, which appears to be somewhat problematic as a result of the combination of a relatively high estimated effective temperature with two long detected periods at 521 and 587 s (Gianninas et al. 2016).

Taking into account the current revision of the convective efficiency for the atmospheric modeling of DA WDs from $\mathrm{ML2}/\alpha = 0.8$ to $\mathrm{ML2}/\alpha = 0.7$ (Pierre Bergeron 2016, priv. comm.), we computed a new grid of models for the atmospheric modeling and refitted the spectra for the three pulsators. As a result of less efficient convective transport, we expect that the estimated effective temperatures to be revised downward. However, there is practically no convective flux in the atmospheric layers of these relatively hot proto-WDs, and therefore the estimated effective temperatures are not affected by the change in convective efficiency. Nevertheless, there is still a non-negligible convective flux in the much deeper layers, near the driving region in evolutionary models of such stars.

There are several possibilities that could help solve the apparent conflict between observations and theory in the case of J0756+6704. First, the efficiency of rotational mixing is poorly constrained; a higher efficiency would extend the region of instability to higher T_{eff}. However, the effect is limited, and can be measured by using configurations in the *basic* mode. Second, the band of excited periods can potentially be widened and the blue edge can be pushed to higher temperatures when perturbations of the convective flux are taken into account. This has been demonstrated for ZZ Ceti stars for which pulsational instabilities are due to pure convective driving (Van Grootel et al. 2013). As indicated above, most of the driving in pulsating ELM proto-WD models is due to a κ-mechanism associated with HeII-HeIII ionization, but convective driving also contributes. It remains to be seen, with detailed calculations, whether these effects would be important in a ELM proto-WD context. And third, the convective efficiency assumed in our current evolutionary models has an additional, if indirect, effect on the pulsation properties: it affects the stratification of the envelope. In the present case, the efficiency assumed in the construction of the models (see Istrate et al. 2016) is lower than the $\mathrm{ML2}/\alpha = 1.0$ version that has been calibrated in the work of Van Grootel et al. (2013) for ZZ Ceti stars. Using the latter version would increase the contribution of convective driving and, presumably, widen the band of excited periods and the width of the instability strip. Moreover, the additional pressure arising from the turbulent convective motion can be as high as a few percent, which could lead to more structural differences and observational effects (Grassitelli et al. 2015). We are thus optimistic that the case of J0756+6704 can be solved.

We conclude that our current evolutionary models of ELM WDs appear indeed quite compatible with the very existence of pulsating ELM proto-WD stars. Rotational mixing is able to oppose gravitational settling and maintain a sufficient amount of He in the envelopes of such stars for the models to develop pulsational instabilities with characteristic periods that generally agree well with the detected periods. By the time such an object enters its cooling track and crosses the blue edge of the ZZ Ceti instability strip, gravitational settling dominates rotational mixing. Thus, the star has developed a pure H envelope that is able to drive pulsations again, but, this time, through pure H ionization, and as a cool, low-mass ZZ Ceti (ELMV) star (Hermes et al. 2013). Hence, a pulsating ELM proto-WD star is very likely to pulsate again during its final WD cooling phase.

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