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Research Article

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ϵ-mechanism driven pulsations in hot subdwarf stars with mixed H-He atmospheres

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Abstract: The ϵ mechanism is a self-excitation mechanism of stellar pulsations which acts in regions where nuclear burning takes place. It has been shown that the ϵ mechanism can excite pulsations in hot pre-horizontal branch stars before they settle into the stable helium core-burning phase and that the shortest periods of LS IV-14°116 could be explained that way. We aim to study the ϵ mechanism in stellar models appropriate for hot pre-horizontal branch stars to predict their pulsational properties. We perform detailed computations of non-adiabatic non-radial pulsations on such stellar models. We predict a new instability domain of long-period gravity modes in the $\log g$ – $\log T_{\rm eff}$ plane at roughly $22000\,{\rm K} \lesssim T_{\rm eff} \lesssim 50000$ K and $4.67 \lesssim \log g \lesssim 6.15$, with a period range from $\sim$ 200 to $\sim$ 2000 s. Comparison with the three known pulsating He-rich subdwarfs shows that the ϵ mechanism can excite pulsations in models with similar surface properties except for modes with the shortest observed periods. Based on simple estimates we expect at least 3 stars in the current samples of hot-subdwarf stars to be pulsating by the ϵ mechanism. Our results could constitute a theoretical basis for future searches of pulsators in the Galactic field.

Keywords: low-mass stars, stellar oscillations, horizontal-branch stars

1 Introduction

Hot horizontal branch stars are hot (effective temperature, $T_{\rm eff} \gtrsim 7000$ K) and evolved low-mass ($\sim 0.5\,M_\odot$) stars burning helium in their core (Heber 2016), that lost almost all of their H-rich envelope at (or near) the tip of the Red Giant Branch (RGB). Blue horizontal branch (BHB; $7000\,{\rm K} \lesssim T_{\rm eff} \lesssim 21000$ K) stars are located in the hot part of the horizontal branch (HB) to the left of RR-Lyrae gap in the Hertzsprung-Russell diagram. Extreme horizontal branch (EHB) stars form an extension of the HB at even higher temperatures. The position of stars in the BHB or the EHB depends mainly on their hydrogen-rich envelope mass, with stars harbouring less massive envelopes being located at higher effective temperatures. EHB stars have hydrogen envelopes too thin to sustain hydrogen burning (Heber 2016).

Before settling on the stable core He-burning stage, low-mass stars undergo a helium-core flash and subsequent subflashes. In this work pre-EHB and pre-BHB stars are classified as stars during this short lived ($\sim$ 2 Myr) phase, just before the stable He-core burning phase. Spectroscopically, EHB stars are identified with the hot subdwarf B stars in the field (sdB). The atmospheres of most sdB stars are almost H pure due to the action of gravitational settling. However, there are some sdBs with mixed H and He compositions. These stars could be at the pre-EHB phase where the ongoing diffusion has had no time to turn the envelope hydrogen pure (Naslim et al. 2010).

Among sdB stars, some of them exhibit multiperiodic photometric variations, likely due to global oscillations. There are two main families of pulsating sdB stars, the slow pulsators (V1093 Her stars or sdBVs, Green et al. 2003) with long periods ($\sim$ 2500 – 8000 s) associated with gravity (g) modes, and the rapid pulsators (V361 Hya stars or sdBVr, Charpinet et al. 1996; Kilkenny et al. 1997) with short periods ($\sim$ 80 – 400 s) associated with radial and non-radial pressure (p) modes (Kilkenny et al. 2010). In both cases the pulsational instabilities are explained by means of the κ mechanism acting on the opacity bump

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created by M-shell electrons of the iron group (Charpinet et al. 1997a; Fontaine et al. 2003). Apart from the pulsating sdB stars, there exists also some sdO stars that exhibit variability (Woudt et al. 2006; Rodríguez-López et al. 2010a; Randall et al. 2016). Pulsating sdO stars are rapid pulsators with periods of $\sim 60-130$ s, and are also understood by means of the κ mechanism (Fontaine et al. 2008; Rodríguez-López et al. 2010b; Randall et al. 2016).

Besides the main families of pulsators, there are a few hot-subdwarf stars with mixed H+He atmospheres that also show multiperiodic luminosity variations, attributed to long-period g modes whose pulsations cannot be explained by means of the κ mechanism. These stars are LS IV-14°116, KIC 1718290 and UVO 0825+15. LS IV-14°116 is a He-sdB star whose pulsations have periods in the range of sdBVs stars but its $\log g$ and $\log T_{\rm eff}$ values correspond to those of sdBVr stars (Ahmad et al. 2005; Green et al. 2011). KIC 1718290 is a cool sdB star or a hot BHB star ($T_{\rm eff} \sim$ 22100 K, Østensen et al. 2012). Its effective temperature is close to the sdBVs stars and its pulsation modes are compatible with long-period g modes, but it has long periods compared with those of the sdBVs stars (up to 11 h, Østensen et al. 2012). Finally, Jeffery et al. (2017) recently reported variability in the light curve of UVO 0825+15, a He-sdO star, compatible with non-radial pulsations associated with long-period g modes. UVO 0825+15 is located outside the instability region of sdBVs stars and its periods are also of the order of a few hours ($\sim$ 10 h). Due to the mixed H+He composition of their atmospheres, it is tempting to assume that these stars are in the short lived pre-HB stage, so that diffusion has had no time to turn the photosphere hydrogen-pure. In this connection, Miller Bertolami et al. (2011) suggested that the pulsations of LS IV-14°116 could be due to the ϵ mechanism acting during the He subflashes before the star settles into the quiescent He-burning phase. The ϵ mechanism is a self-excitation mechanism of stellar pulsations which acts on the regions inside the star where nuclear burning takes place. Due to the strong dependence of nuclear burning with temperature, temperature perturbations caused by oscillations lead to huge increases in the amount of nuclear energy released. This in turn can increase the local temperature. The process is unstable, resulting in a global instability that grows with time. Under usual conditions, the ϵ mechanism is not very efficient because pulsation amplitudes tend to be small in the high-temperature layers where nuclear energy is released. The ϵ mechanism driven pulsations have been predicted in a variety of scenarios, including white dwarf (WD) stars (Charpinet et al. 1997b; Córsico & Althaus 2014, 2016; Camisassa et al. 2016a; Calcaferro et al. 2017), pre-WD stars (Kawaler et al. 1986; Saio 1996; Gautschy 1997; Córsico et al. 2009; Maeda & Shibahashi 2014), post He-WD mergers (Miller Bertolami et al. 2013), post-main sequence B stars (Moravveji et al. 2012), and main sequence low-mass stars (Palla & Baraffe 2005; Rodríguez-López et al. 2012; Sonoi & Shibahashi 2012) among others. In particular, the ϵ mechanism was proposed as the responsible for the pulsations of a few individual stars: the supergiant B star Rigel (Moravveji et al. 2012), the PNNV star VV 47 (González Pérez et al. 2006; Córsico et al. 2009) and the He-sdB star LS IV-14°116 (Miller Bertolami et al. 2011), but none of these suggestions are conclusive. Consequently, if the pulsations of LS IV-14°116, or any other He-rich hot-subdwarf star, are confirmed to be triggered by the ϵ mechanism, it would be the first evidence that the ϵ mechanism can indeed excite pulsations in stars. Moreover, such a confirmation would be the first observational proof of a star undergoing the He core-flash and subflashes.

Due to the far-reaching implications of a possible identification of ϵ mechanism driven pulsations in He-rich subdwarf stars, it is of interest to have a detailed study of the theoretical predictions for pulsations triggered by the ϵ mechanism in pre-hot horizontal branch models. Such a study is lacking, since Miller Bertolami et al. (2011) studied just a single evolutionary sequence. Here we largely extend the study of Miller Bertolami et al. (2011) by performing a comprehensive stability analysis on stellar models appropriate for stars on the pre-BHB and pre-EHB that undergo the He subflashes. Our main aim is to determine the domain of instability due to the ϵ mechanism, and provide a more complete theoretical study that will allow us to make better comparisons with currently available and future observations. Moreover, our results could constitute a theoretical basis for guiding future searches of pulsating stars of this kind.

2 Methods

In the canonical stellar evolution picture the He core flash takes place when stellar models reach the tip of the RGB. However, under certain conditions, most of the H-rich envelope mass can be lost before the beginning of the He-core burning stage. Among these conditions are the enhancement of stellar winds due to stellar rotation (Sweigart 1997; Tailo et al. 2015), mass transfer due to stable Roche lobe overflow and common envelope systems (Han et al. 2003; Paczynski 1976). In addition, in He-enriched populations very low mass stars live short enough on the main sequence to reach the He-core burning stage. Due to the low initial envelope masses of these stars, even standard winds can lead to the almost complete removal of the H-rich envelope before the RGB-tip (Villanova et al. 2012; Althaus et al. 2003). In all these cases, when stars lose most of their H-rich envelope during the RGB they depart from it, contracting towards higher effective temperatures at constant luminosity. Castellani & Castellani (1993) showed that a He-core flash can still develop when the model is entering the WD cooling stage. This scenario leads to He-core burning models with a wide range of envelope masses and thus populating the hot end of the horizontal branch (Faulkner 1972, and references therein). D'Cruz et al. (1996) introduced the term "hot-flashers" for this scenario.

We constructed pre-EHB and pre-BHB models within the hot-flashers scenario. We followed the evolution of initially 1 $M_\odot$ models from the ZAMS to the RGB. At the tip of the RGB we switched on artificially-enhanced mass loss, removing different amounts of the envelope mass. As we are interested in the evolution after the mass loss episode, the particular value of the mass at the ZAMS and the treatment of mass loss at the RGB are not relevant, as long as we cover the whole range of masses that allow the formation of HB stars with $T_{\rm eff}$ higher than 7000 K. This is because, for an initial set of chemical compositions, it is only the mass at He ignition that determines the behaviour of the hot-flashers.

Models were computed for three different initial compositions. The adopted initial compositions are shown in Table 1. Two sets were computed with canonical initial He abundances according to the relation $Y = 2Z + 0.245$. Due to the evidence of He-enhanced populations in globular clusters (*e.g.* Marino et al. 2017), we calculated evolutionary sequences with $Y = 0.4$ to explore the instability domain of the ϵ mechanism for He-enriched compositions.

Table 1. Initial abundances by mass fraction of the stellar sequences computed in this work.

X	Y	Z
0.752	0.247	0.001
0.695	0.285	0.02
0.58	0.4	0.02

All the stellar evolutionary calculations were performed with the LPCODE stellar evolutionary code. LPCODE is a well tested code (Salaris et al. 2013; Miller Bertolami 2016) that has been used for a variety of studies regarding low-mass stars and WDs (see *e.g.* García-Berro et al. 2010; Wachlin et al. 2011; Camisassa et al. 2016b). The LPCODE is described in Althaus et al. (2003, 2005), and the improvements of the last version are detailed in Miller Bertolami (2016).

We performed a stability analysis over a total of 20 stellar evolutionary sequences corresponding to different values of initial chemical abundances and masses of the H-rich envelope. For each evolutionary sequence, we computed non-adiabatic, non-radial pulsations for 300 to 800 stellar models going through He subflashes, thus covering the whole He-core subflashes stage. Figure 1 shows four of the stellar evolution sequences for $Z = 0.02$ and $Y = 0.285$ in a $\log T_{\rm eff} - \log g$ diagram. The evolution during the He subflashes is highlighted with red lines. For each model studied we performed stability analyses of $\ell = 1$ modes within a period range of 50 to 7000 s. For one of the evolutionary sequences we also explored $\ell = 2$ and $\ell = 3$ modes, to determine the dependency of the excited periods with the harmonic degree. Stellar pulsation calculations were performed with the linear, non-radial, non-adiabatic stellar pulsation code LP-PUL. The LP-PUL pulsation code was widely used in studies of pulsation properties of low-mass stars (see *e.g.* Córsico et al. 2006; Romero et al. 2012; Córsico et al. 2016; Sánchez Arias et al. 2017). The LP-PUL pulsation code is fully described in Córsico et al. (2006) and references therein, with the inclusion of the ϵ-mechanism mode driving as described in Córsico et al. (2009). The non-adiabatic computations rely on the "frozen-in convection" approximation, in which the perturbation of the convective flux is neglected. In addition, it was assumed that $dS/dt = 0$ in the non-perturbed background model adopted in the non-adiabatic computations. A discussion of the validity of these assumptions in the study of the ϵ

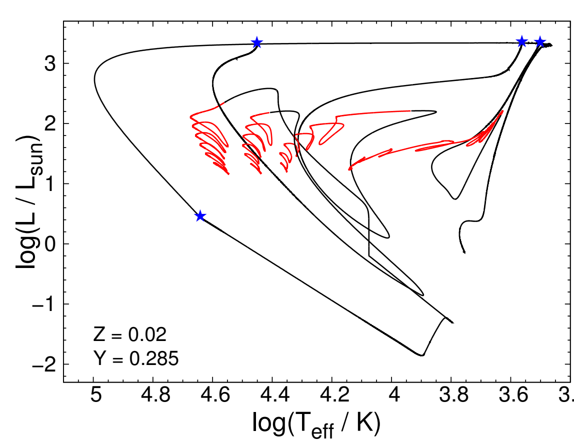

Figure 1. H-R diagram of four of the evolutionary sequences studied corresponding to initial chemical compositions of $Z = 0.02$ and $Y = 0.285$. The subflashes phase is plotted with red lines. Blue stars on each track mark the onset of core helium burning.

mechanism on the subflashes stage can be found in Miller Bertolami et al. (2011).

3 Results

We found a new theoretical instability domain in the $\log T_{\rm eff} - \log g$ diagram due to the ϵ mechanism acting on the He subflashes in the pre-HB phase. The pulsational instabilities correspond to intermediate/high-order g modes.

The instability domain in the $\log T_{\rm eff} - \log g$ diagram predicted by our calculations corresponds to the intersection of the locus of the evolutionary sequences during the He subflashes and the following temperature and gravity boundaries: $T_{\rm eff} \gtrsim 22000$ K and $\log g \gtrsim 4.8$, see Figure 2. Therefore, pre-EHB models show ϵ-mechanism driven pulsations during the He subflashes, but pre-BHB models do not. The high temperature and gravity boundaries of the instability domain are the direct consequence of the locus of the hot-flasher models in the $\log T_{\rm eff} - \log g$ diagram, as no stellar models are found beyond these limits. The lower temperature and gravity boundaries require a detailed analysis of the excitation and damping processess.

3.1 Driving and damping of pulsations

All g modes have relatively high amplitudes in the layers where the He subflashes take place, and consequently undergo some excitation through the ϵ mechanism. Yet, whether or not a mode is actually excited is determined by the competition between the driving mechanism and the damping of oscillations, mostly through radiative processess.

In Figure 3 we show the propagation diagrams of two different models during the peak of energy release in a He subflash. The model on the upper panel of Figure 3 corresponds to a high-gravity, high-temperature model ($\log g = 5.12$, $\log T_{\rm eff}/{\rm K} = 4.53$ and $M_\star = 0.4868\, M_\star$) that displays unstable modes with periods in the range $\sim 880 - 1130$ s, while the lower panel of Figure 3 corresponds to a low-gravity, low-temperature model ($\log g = 4.25$, $\log T_{\rm eff}/{\rm K} = 4.35$ and $M_\star = 0.4908\, M_\odot$) without unstable modes.

The Brunt-Väisälä frequency in both models has a local minimum in the outer layers. Modes with frequencies higher than this local minimum are mixed modes. Due to their relative large amplitudes in the envelope, these mixed modes are strongly radiatively damped in the outer layers of the star. Therefore, the mixed modes are always globally stable.

Modes with frequencies lower than the outer local minimum of the Brunt Väisälä frequency are pure g modes. Radiative damping also affects the pure g modes, but in the core of the star. The radiative damping of g modes in the stellar core strongly depends on the frequency of the modes (see Shiode et al. 2013). For lower frequencies (higher periods and wavenumbers) the radiative damping is higher. Consequently very low frequency g modes remain stable even if they are significantly excited by the ϵ mechanism on the He-burning shell.

Based on the previous discussion we can now understand the low $\log g$ and $T_{\rm eff}$ limits of the instability domain. The Brunt-Väisälä frequency in the outer layers of the star strongly depends on the local gravity in these layers. Therefore, in models with lower surface gravities, the Brunt-Väisälä frequency takes lower values at the outer layers (compare upper and lower panels of Figure 3). For models with surface gravities lower than $\log g \sim 4.8$ (the limit of the instability strip), as seen in the lower panel of Figure 3, the Brunt-Väisälä frequency is low enough so that all pure g modes have very low frequencies and are stabilized by strong radiative damping in the core. In addition, all of the mixed modes are globally stable due to the damping in the envelope and, consequently, in these stellar models ($\log g \lesssim 4.8$) all modes are globally stable. On the contrary, for models with surface gravities higher than $\log g \sim 4.8$, as seen in the upper panel of Figure 3, there is a range of frequencies for which there exist pure g modes with relatively high frequencies. Radiative damping in the core for these modes is not strong enough to counteract the action of the ϵ mechanism and the modes are globally excited. As the pre-EHB models have lower effective temperatures for lower surface gravities, a limit on surface gravity implies a limit on effective temperature, which turns out to be ~ 22000 K.

3.2 Periods of excited modes

We have obtained excited modes ($\ell = 1$) with periods in the range $\sim 200 - 2000$ s. In all cases, the range of excited periods becomes shorter with subsequent subflashes. This is exemplified in Figure 4 which shows the periods as a function of time for a sequence with $Z = 0.02$, $Y = 0.285$ and $M_\star = 0.457\, M_\odot$. The trend of the periods is a natural consequence of the continuous shrinking of the model as it approaches the ZAHB, which shifts the global pulsational properties to shorter periods.

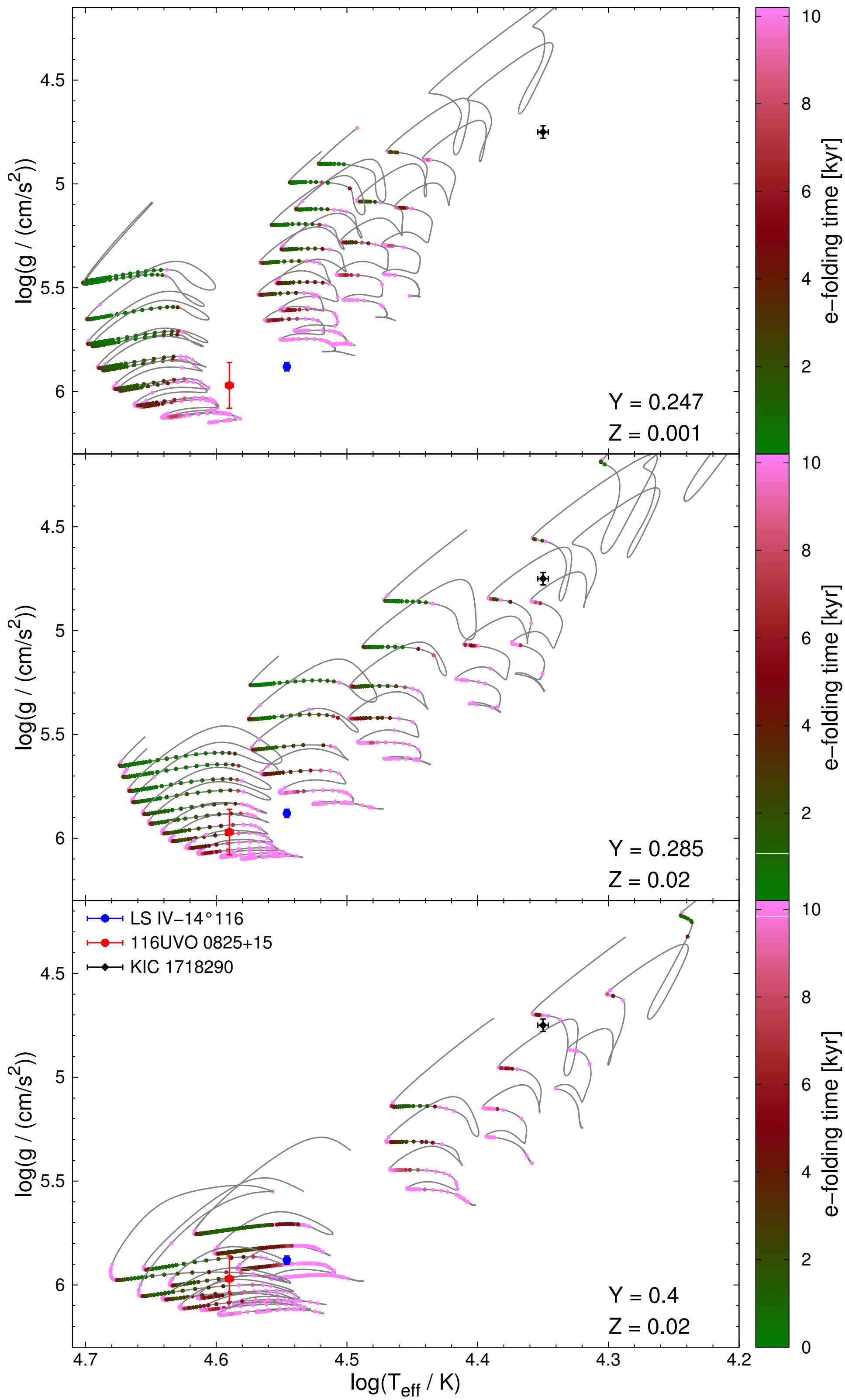

Figure 2. The phase of the He subflashes of the evolutionary sequences in the log $T_{\rm eff}$ − log g diagram (grey lines). Coloured points correspond to models with excited modes and the colour coding shows the minimum *e*-folding time for each model. Also shown for comparison is the location of the known He-rich hot subdwarf pulsators LS IV-14°116 (Randall et al. 2015), UVO 0825+15 (Jeffery et al. 2017), and KIC 1718290 (Østensen et al. 2012).

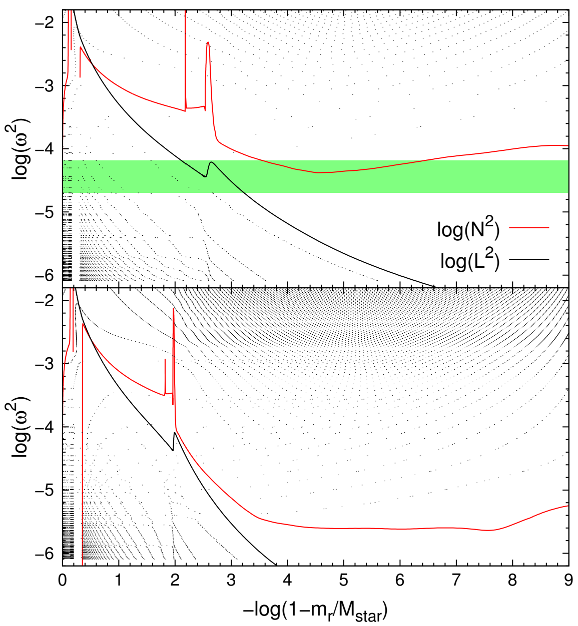

Figure 3. The logarithm of the squared Lamb and Brunt-Väisälä frequencies (black and red lines) in terms of the outer mass fraction coordinate. Black points mark the nodes of the radial eigenfunctions. Upper panel corresponds to a model with $\log g = 5.12$, $\log T_{\rm eff}/{\rm K} = 4.53$, $M_\star = 0.4868\,M_\odot$ with excited modes, whose range of frequencies is shown with a green strip. Lower panel corresponds to a model with $\log g = 4.25$, $\log T_{\rm eff}/{\rm K} = 4.35$, $M_\star = 0.4908\,M_\odot$ and no excited modes.

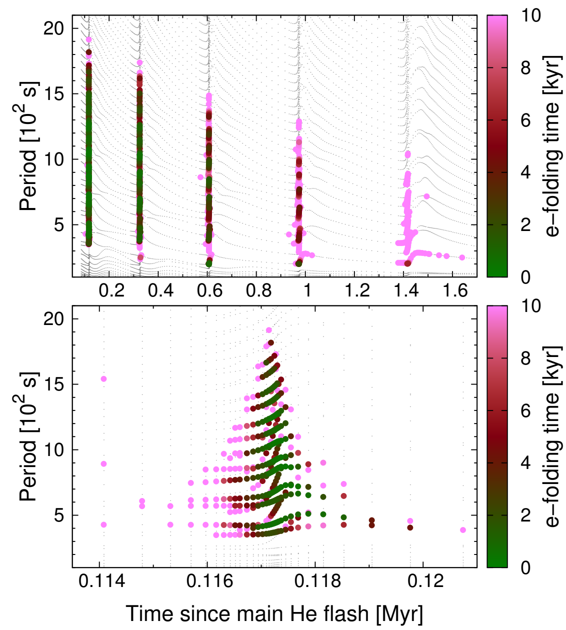

Figure 4. Upper panel: Period vs. time of a sequence with Z = 0.02, Y = 0.285 and $M_\star = 0.457\,M_\odot$. Excited periods are coloured with the *e*-folding time in colour coding. Lower panel: Zoomed in the first subflash.

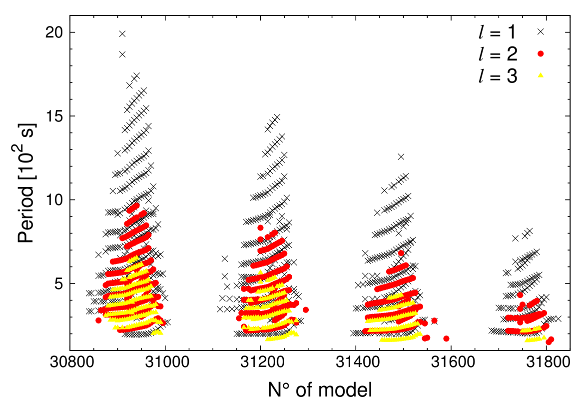

Figure 5. Period vs. number of model of sequences with Z = 0.02, Y = 0.4 and $M_\star = 0.445 M_\odot$, corresponding to $\ell = 1$ (black crosses), $\ell = 2$ (red points) and $\ell = 3$ (yellow triangles).

This trend is more notorious for the long-period limit. This limit is due to the dependence on frequency (and therefore, periods) of the radiative damping of *g* modes at the stellar core. During the first subflash, for $\ell = 1$, for all periods longer than $\sim$ 2000 s the radiative damping becomes more important than the excitation.

In subsequent subflashes, the nuclear energy release is lower and the ϵ mechanism is less efficient. Therefore, the damping becomes more important than the excitation for shorter periods.

The range of excited periods is also sensitive to the harmonic degree ℓ. This is a consequence of the dependence on ℓ of the radiative damping in the core of the star (Shiode et al. 2013). For higher values of ℓ the radiative damping is more important and therefore the period at which radiative damping overwhelms the excitation is shorter (see Figure 5).

Another interesting property predicted by our computations is the rate of period change $\dot{P}$ of the unstable modes. Due to the large structural changes in the stellar core produced by the sudden energy injection in the He subflashes, the periods of the normal *g* modes are strongly affected with typical values of $\dot{P}$ in the range of $\langle \dot{P} \rangle \sim 10^{-5} - 10^{-7}$ s/s. This corresponds to a period drift typically between 1 and 300 seconds per year that could be easily measured. As pure *g* modes are evanescent in convective regions, they are very sensitive to changes in the size of the He-flash driven convective zones.

3.3 Excitation timescales

The *e*-folding time (τ) is a measure of the time required by a given unstable mode to grow to observable amplitudes. Therefore, if the τ of a particular mode is shorter than the time span in which the mode is being excited, the amplitude of the mode can grow to observable values. We found that for all stellar models within the instability strip and for all the initial chemical compositions, there are several modes that satisfy this condition and reach observable amplitudes. In almost all cases the e-folding times are shorter during the earlier subflashes, when the intensity of He-burning is higher and the ϵ mechanism is consequently more effective. This is shown in Figure 4, where the e-folding times are colour coded. The exceptions are those evolutionary sequences in which the first subflashes occur at surface gravities lower than the limit of the instability strip.

4 Discussion

Comparing our predictions with the pulsational properties of known pulsating subdwarfs with mixed H+He surface compositions, namely LS IV-14°116 with observed periods $P \simeq 1950 - 5080$ s ($T_{\rm eff} = 35150 \pm 111$, $\log g = 5.88 \pm 0.02$, $\log n(He)/n(H) = -0.62 \pm 0.01$, Randall et al. 2015; Ahmad et al. 2005; Green et al. 2011), KIC 1718290 with $P \simeq 1 - 12$h ($T_{\rm eff} = 22100$, $\log g = 4.72$, $\log n(He)/n(H) = -0.45$, Østensen et al. 2012) and UVO 0825+156 with $P \simeq 10.8 - 13.3$h ($T_{\rm eff} = 38900 \pm 270$, $\log g = 5.97 \pm 0.11$, $\log n(He)/n(H) = -0.57 \pm 0.01$, Jeffery et al. 2017), we found that their values of $T_{\rm eff}$, $\log g$, and $\log n(He)/n(H)$ (Figure 2) are well reproduced by our theoretical predictions. Quantitatively, however, the observed periods in these stars are systematically longer than the predicted ones (200 – 2000 s). In the cases of the longest observed periods in KIC 1718290 and UVO 0825+156 the pulsations cannot be explained by the ϵ mechanism due to the strong radiative damping of high-order g modes in the stellar core. For LS IV-14°116, our computations are able to explain the shortest observed period as well as its location in the $\log T_{\rm eff} - \log g$ diagram and its He-enriched composition.

The discrepancy between theory and observation might well be a consequence of the shortcomings of the treatment of convection in this fast and badly tested stage of stellar evolution. If He subflashes were more intense than predicted by our sequences, the ϵ mechanism would excite modes with longer periods. Therefore, although we cannot reproduce the largest periods of LS IV-14°116, we cannot rule out the ϵ mechanism as responsible for its pulsations.

Another interesting question concerns the number of pre-HB stars expected to pulsate due to the ϵ mechanism. The total amount of time spent by the sequences in the stages of pulsation instability is about 50000 yr. Therefore, comparing this time with the timescale typical of the core He-burning phase ($\sim$ 100 Myr), we found that at least $\sim 0.05\%$ of the hot-subdwarf stars are undergoing ϵ-mechanism driven pulsations. Considering that in the recent sample of Geier et al. (2017) there are 5613 sdB stars, we expect that at least ~ 3 stars within this sample should be pulsating by the ϵ mechanism.

5 Conclusions

We performed non-adiabatic computations of stellar pulsations in pre-hot horizontal branch stellar models undergoing He subflashes, within the hot-flasher scenario. Our computations predict a new instability strip for hot-subdwarf stars in the $\log T_{\rm eff} - \log g$ diagram. The locus of the instability domain is roughly $22000\,{\rm K} \lesssim T_{\rm eff} \lesssim 50000$ K and $4.67 \lesssim \log g \lesssim 6.15$. The range of excited periods is $P \sim 200 - 2000$ s corresponding to intermediate/high-order g modes. Consequently, our computations show the excitation of long-period g modes driven by the ϵ mechanism associated with pre-EHB stellar models, but not with pre-BHB stellar models.

We found that a considerable number of excited modes are very likely to grow to observable amplitudes during the subflashes. Also, the rates of period change predicted are very high (1 – 300 s/yr). These properties indicate that it is possible to detect and identify the ϵ-mechanism driven pulsations in hot-subdwarf stars.

The values of $T_{\rm eff}$, $\log g$, and $\log n(He)/n(H)$ of the known hot subdwarf pulsators with mixed H+He surface compositions are well reproduced by our theoretical predictions, although the observed periods in these stars are systematically longer than the predicted ones. Still, we conclude that the ϵ mechanism remains the best available explanation for the pulsations in LS IV-14°116. Although, as only the shortest period can be explained it is necessary to continue exploring alternative scenarios.

Miller Bertolami et al. (2013) showed that the ϵ mechanism can excite pulsations during the He-shell flashes that take place after a double He-white dwarf merger. The merger of two He-white dwarfs is also a proposed scenario for the formation of He-sdO stars (Zhang & Jeffery 2012). Therefore, we intend to study in future works the properties of ϵ-mechanism excited pulsations in detailed double He-white dwarf post-merger models.

Finally, we conclude that our work could constitute a theoretical basis for future searches of pulsators in the Galactic field. In particular, based on simple numerical estimates we expect that at least ~ 3 stars in the current sample of hot-subdwarf stars should be pulsating by the ϵ mechanism.

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