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Blue Large-Amplitude Pulsators (BLAPs): Possible Origin, Evolutionary Status, and Nature of their Pulsations

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Abstract

The Blue Large-Amplitude Pulsators (BLAPs) constitute a new class of pulsating stars. They are hot stars with effective temperatures of $T_{\rm eff} \sim 30\,000$ K and surface gravities of $\log g \sim 4.9$, that pulsate with periods in the range $\sim 20-40$ min. In Romero et al. (2018), we proposed that BLAPs are hot low-mass He-core pre-white dwarf (WD) stars that pulsate either in high-order non-radial g(gravity) modes or low-order radial modes, including the fundamental radial mode. The theoretical modes with periods in the observed range are unstable due to the κ mechanism associated with the Z bump in the opacity at $\log T \sim 5.25$. In this work, we extend the study of Romero et al. (2018) by assessing the rate of period changes of nonradial g modes and radial modes and comparing them with the values measured for BLAPs, in an attempt to validate the proposed evolutionary scenario, and to discern whether the observed modes are high-order g modes or radial modes.

1 Introduction

Blue Large-Amplitude Pulsators (BLAPs; Pietrukowicz et al., 2017) constitute a new class of pulsating stars recently discovered in the context of the Optical Gravitational Lensing Experiment (OGLE; Udalski et al., 2015). The first BLAP star (OGLE-BLAP-001) was first tentatively classified as a δ Scuti-type variable star and named OGLE-GD-DSCT-0058. At present, 14 BLAPs are known. Their average apparent magnitudes are $V = 17.71$ mag and $I = 17.22$ mag. The fourth phase of OGLE monitors photometrically the Galactic bulge, the Galactic disc, and the Magellanic Clouds (see Fig. 1). BLAPs have been discovered only in the Galactic disk and bulge (high-metallicity environments), but not in the Magellanic Clouds, which constitute a low-metallicity environment (Pietrukowicz, 2018). These variables are not observed in globular clusters nor in the Galactic halo. All this suggests high metallicity in these pulsating stars, something that is confirmed by our theoretical models.

A number of properties observed in BLAPs make these stars striking:

- They are very hot stars, with an average effective temperature of $T_{\rm eff} \sim 30\,000$ K. Their effective temperature and colour change over a complete pulsation cycle, confirming that their variability is due to genuine pulsations;
- The lightcurves of BLAPs have a saw-tooth shape, reminiscent of Cepheids and RR Lyrae-type stars that pulsate in the radial fundamental mode;
- The amplitudes are large, in the range $0.2-0.4$ mag, much larger than the amplitudes of pulsating sdB stars, β Cephei stars, Slowly Pulsating B (SPB) stars, etc, which exhibit amplitudes of mmag (milli magnitudes);
- BLAPs exhibit single short pulsation periods (Π) in the range $\sim 1200-2400$ sec. These periods are much shorter than those of β Cephei stars, SPBs, etc. The fact that only a single period has been detected up to date in BLAPs does not mean that these stars are not multi-periodic stars. Indeed, they could be pulsating with other periods that have not been detected due to an insufficient observation time.
- The periods of BLAPs show a secular drift with typical values of the relative rate of period change of $\dot{\Pi}/\Pi = d(\log \Pi)/dt = 10^{-7}$ yr^{-1}, both positive (increasing periods) and negative (decreasing periods). The magnitudes of the rate of period change suggest that BLAPs are stars that are slowly evolving on nuclear timescales;
- BLAPs exhibit envelopes made of a mixture of H and He.

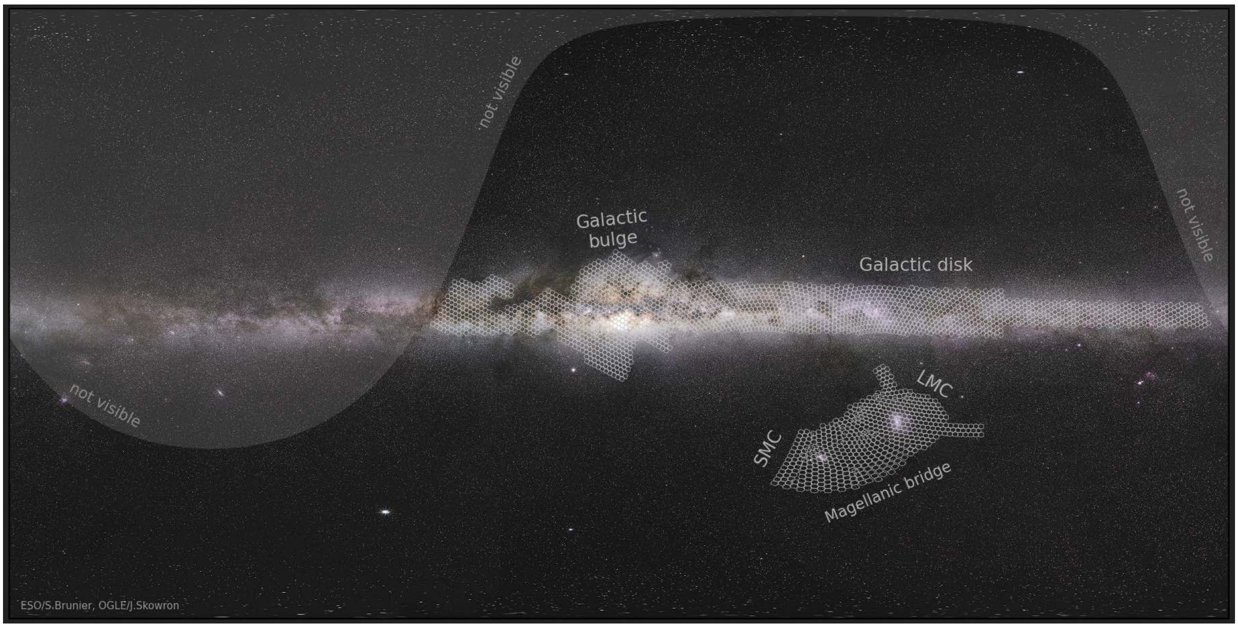

Figure 1: The sky map with OGLE-IV fields, taken from `http://www.astrouw.edu.pl/~jskowron/ogle4-sky/`.

2 A Possible Evolutionary Origin of BLAPs

Any evolutionary/pulsational model proposed to explain the existence of BLAPs and the nature of their pulsations must satisfy the observational constraints listed in the previous section. In the case of 4 BLAPs, it was possible to derive their $T_{\rm eff}$ and $\log g$ from spectroscopy (Pietrukowicz et al., 2017). These stars are located in a region in the $T_{\rm eff} - \log g$ diagram that is not occupied by any previously known kind of pulsating star, as depicted in Fig. 2. Indeed, BLAPs have similar gravities as pre-ELMVs, but are hotter than them; they are much hotter and more compact than δ Scuti/SX Phe stars; they have similar $T_{\rm eff}$s but are less compact than pulsating sdBs (V361 Hya and V1093 Her types); finally, they are much hotter and less compact than ELMVs. In view of the above-mentioned properties, the following questions arise: what is the internal structure and the evolutionary status of BLAPs, and what is their evolutionary origin? Several possibilities to explain the formation, evolution and internal structure of these stars have been proposed (Pietrukowicz et al., 2017). On one hand, the evolution of a single isolated low-mass star seems impossible to explain BLAPs, because the evolutionary timescales involved in such a scenario are longer than the Hubble time. On the other hand, binary-star evolution through stable mass transfer and/or common envelope ejection appear as more plausible evolutionary channels for these intriguing pulsating stars. Pietrukowicz et al. (2017) proposed two main possibilities:

- He-core shell H burning low-mass stars ($\sim 0.30 M_{\odot}$)
- core He-burning stars ($\sim 1.0 M_{\odot}$)

In Romero et al. (2018), we proposed that BLAPs are hot He-core shell H burning low-mass pre-WD stars with masses $\sim 0.30 M_{\odot}$. In Fig. 2 we display the evolutionary tracks for low-mass He-core pre-WD models of Althaus et al. (2013) which neglect element diffusion, corresponding to solar metallicity ($Z = 0.01$) and super-solar metallicity ($Z = 0.05$). Clearly, the location of the BLAPs is well accounted for by these evolutionary tracks, demonstrating that the scenario proposed by Romero et al. (2018) is plausible.

3 Nature of the Pulsations of BLAPs

In Fig. 3, we show the internal chemical profiles and the Ledoux term B (that is crucial in the computation of the Brunt-Väisälä frequency) in terms of the outer mass fraction coordinate (upper panel), and a *propagation diagram* —the run of the logarithm of the squared critical frequencies, that is, N^2 (the Brunt-Väisälä frequency), and $L^2_{\ell=1}$ (the Lamb frequency) — with the nodes of the radial eigenfunction for nonradial ($\ell = 1$) g and p modes and also radial ($\ell = 0$) modes (lower panel), corresponding to a template model with $M_{\star} = 0.3208 M_{\odot}$, $T_{\rm eff} = 31\,341$ K, and $Z = 0.01$ whose location in the $T_{\rm eff} - \log g$ diagram is marked in Fig. 2 with a black square. The pulsation computations were carried out with the adiabatic version of the `LP-PUL` pulsation code (Córsico & Althaus, 2006). For this specific template model, high-order g modes with radial

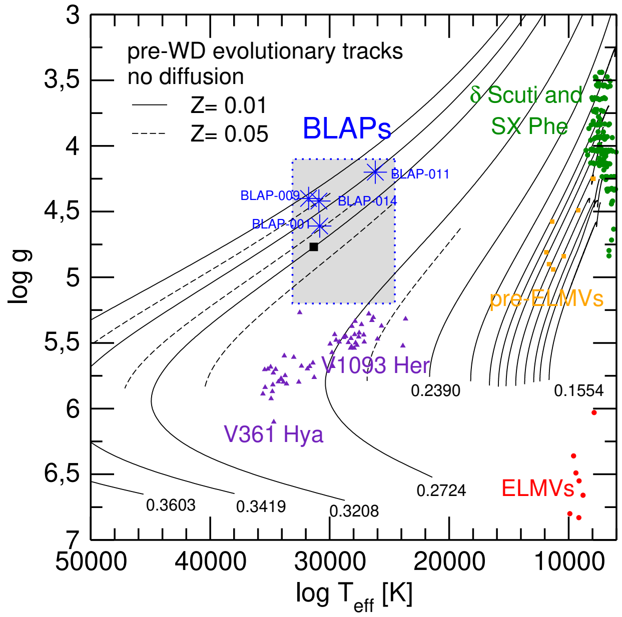

Figure 2: $T_{\rm eff} - \log g$ diagram showing the location of the BLAP stars (shaded rectangle area), along with other families of already known pulsating stars: ELMVs (red dots), pre-ELMVs (orange dots), pulsating sdBs (V361 Hya and V1093 Her; violet triangles) and δ Sct/SX Phe stars (green dots). Solid black lines correspond to low-mass He-core pre-WD evolutionary tracks computed neglecting element diffusion and $Z = 0.01$. Numbers correspond to the stellar mass of some sequences. Also included are portions of evolutionary tracks corresponding to $Z = 0.05$ for some stellar masses. Blue star symbols indicate the location of the four BLAP stars with measured atmospheric parameters. The black square on the evolutionary track of $M_\star = 0.3208 M_\odot$ indicates the location of a template model.

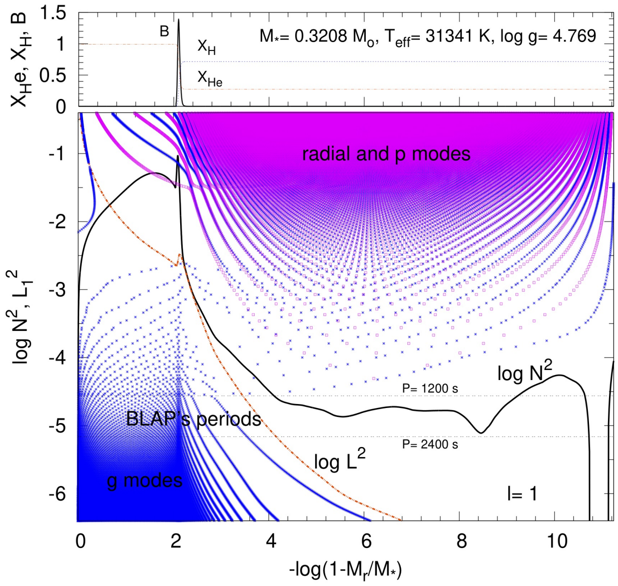

Figure 3: Internal chemical profiles for He and H and the Ledoux term B (upper panel) and the propagation diagram (lower panel), in terms of the outer mass fraction coordinate, corresponding to the pre-ELM WD template model of $M_\star = 0.308 M_\odot$ and $T_{\rm eff} \sim 31\,300$ K marked in Fig. 2 with a black square. In the lower panel, tiny star symbols (in blue) correspond to the spatial location of the nodes of the radial eigenfunction of nonradial dipole ($\ell = 1$) g and p modes. Tiny squares (in magenta) mark the location of the nodes for radial ($\ell = 0$) modes. The (squared) frequency interval corresponding to the modes observed in BLAPs (with periods in the range $\sim 1200 - 2400$ s) is emphasized with two horizontal black dotted lines.

orders $k = 25 - 50$ and radial modes with the lowest radial order ($k = 0$) have pulsation periods in the observed interval ($\sim 1200 - 2400$ s). Therefore, the periodicities exhibited by BLAPs can be associated either to nonradial g modes, or to radial modes (Romero et al., 2018).

Linear nonadiabatic pulsation computations performed with the nonadiabatic version of the LP-PUL pulsation code (Córsico et al., 2006) do not predict pulsations for models with $Z \leq 0.03$. However, for higher metallicities, unstable radial and nonradial modes with periods compatible with those observed in BLAPs are found. In particular, for a template model with $Z = 0.05$ ($M_\star = 0.3419 M_\odot$ and $T_{\rm eff} = 31\,100$ K) we found that high-order g modes with radial orders $k = 25 - 39$ ($\ell = 1$) and $k = 46 - 67$ ($\ell = 2$), and radial modes with low radial order $k = 0$ (fundamental mode) are destabilized by the κ mechanism due to the "Z bump" in the Rosseland opacity at $\log T \sim 5.25$ due to Fe (and the iron group) like in β Cephei stars, SPBs, and variable sdB stars. It is worth mentioning that the He^{++} bump in the opacity at $\log T \sim 4.45$, which is located at more external regions of the star, is unable to destabilize pulsations, unlike what happens in the case of pre-ELMVs (Córsico et al., 2016).

By extending the stability calculations to evolutionary sequences with different stellar masses and covering the range of effective temperatures of interest, it is possible to define the complete domains of instability of BLAPs in the $T_{\rm eff} - P$ diagrams. We show the results in Figs. 4, 5, and 6, corresponding to unstable modes with $\ell = 0$, $\ell = 1$, and $\ell = 2$, respectively. In the case of radial modes (Fig. 4), only the fundamental mode is unstable. Note that the observed periodicities $(1200 \leq P \leq 2400)$ s are well accounted for by the theoretical computations if we consider a range of stellar masses, $0.33 \leq M_\star/M_\odot \leq 0.36$. It is apparent that the radial fundamental modes are the most unstable ones among the studied cases ($\ell = 0, 1, 2$). Indeed, they are destabilized during very short times (e-folding times) as compared with the evolutionary timescales at that stage of evolution. The results for $\ell = 1$ and $\ell = 2$ are virtually the same, i.e., the domains of instability for nonradial modes do not depend on the value of ℓ.

At this point, and considering the results of our anal-

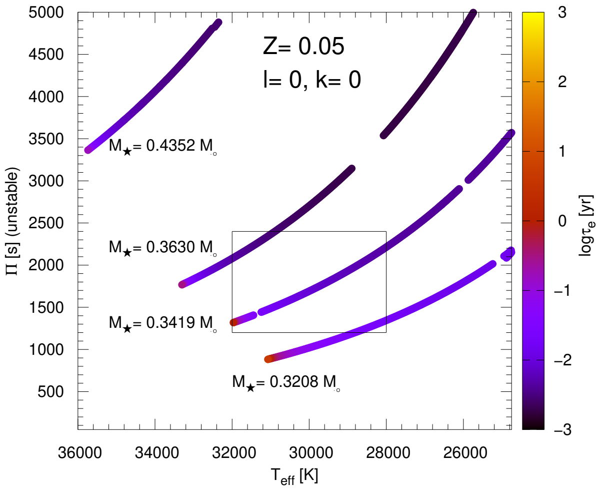

Figure 4: Periods of unstable fundamental ($k = 0$) radial mode ($\ell = 0$) in terms of $T_{\rm eff}$ for pre-WD models of the indicated masses and $Z = 0.05$. The palette of colors at the right scale indicates the value of the logarithm of the e-folding time (in yrs). The e-folding times range from $\sim 10^{-3}$ to $\sim 10^{3}$ yr, much shorter than the typical evolutionary timescales at that stage of evolution. The rectangle corresponds to the interval of effective temperature measured for BLAPs and the range of detected periods.

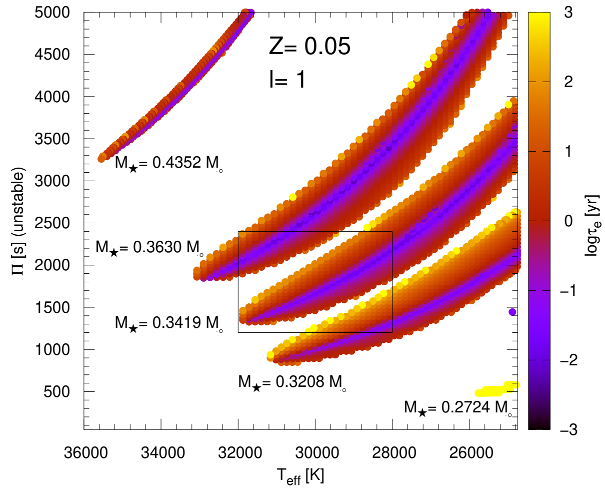

Figure 5: Same as in Fig. 4, but for the case of nonradial g modes with $\ell = 1$ and a range of radial orders k.

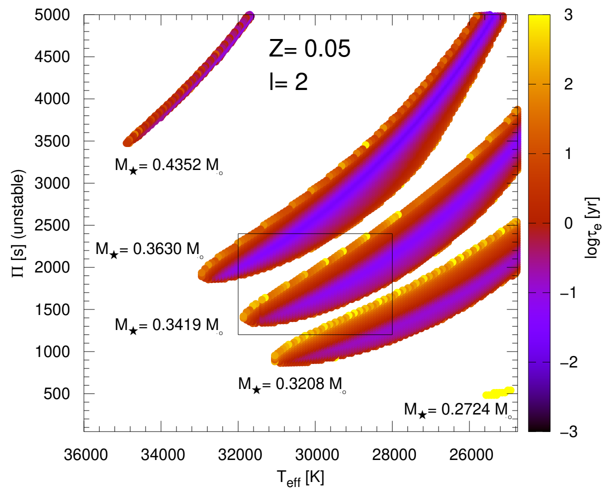

Figure 6: Same as in Fig. 5, but for the case of $\ell = 2$.

ysis, it seems that the variability of the BLAPs is better explained by the possible excitation of the fundamental radial mode in these stars, rather than by the high-order g modes, for a number of reasons: *(i)* the fundamental radial mode has the correct period, *(ii)* it is pulsationally unstable in the range of effective temperatures of interest, *(iii)* it is more unstable than the nonradial g modes, and *(iv)* the fact that BLAPs exhibit a single mode with large amplitude in the lightcurves, reminiscent of a radial mode. In the next Section, we analyze in detail the sign and magnitude of the theoretical rates of period change of our models for radial and nonradial modes, and compare them with the values measured in BLAPs.

4 Rate of Period Changes of BLAPs

In general, the rates of period change in pulsating stars are associated to their evolutionary timescale. In the case of BLAPs, Pietrukowicz et al. (2017) (their Table 1) have measured the relative rates of period change (positive and negative) of 11 stars with an average absolute value of $|\dot{P}/P| \sim 10^{-7}$ yr^{-1}, and extreme values of $(+7.65 \pm 0.67) \times 10^{-7}$ yr^{-1} and $(-2.85 \pm 0.31) \times 10^{-7}$ yr^{-1}. These are relatively large values of the rates of period change, which suggest that BLAPs are slowly evolving on nuclear timescales. We have computed the rates of period change for our He-core shell H burning pre-WD models for the cases of radial and and nonradial modes. In Fig. 7 we plot the evolution with $T_{\rm eff}$ of the pulsation periods for radial modes ($\ell = 0$, left panel) and nonradial $\ell = 1$ g modes (right panel), corresponding to an evolutionary sequence with $M_\star = 0.3419 M_\odot$ and $Z = 0.05$. In general, the slope of the periods of radial modes is much larger than in the case of g modes, indicating a larger rate of change of periods in the case of radial modes. On the other hand, all the periods of radial modes decrease with increasing $T_{\rm eff}$, showing that the rates of change of these periods must all be negative. In contrast, in the case of the g modes, there are parts of the evolution where the periods decrease and other parts where the periods grow, indicating that negative and positive values of the rates of period changes are expected for g modes.

In the upper and lower panels of Fig. 8 we depict the period (Π) and the relative rate of period

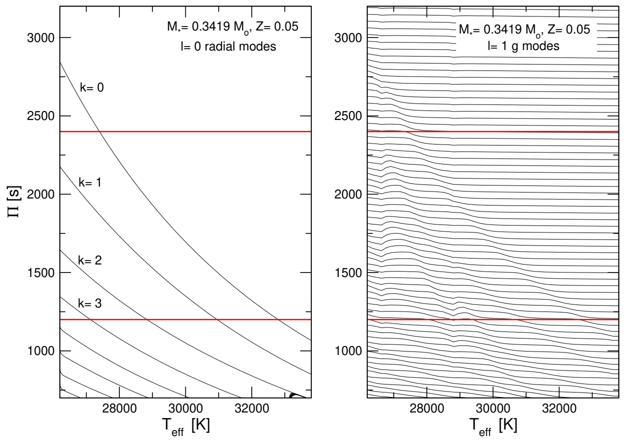

Figure 7: The pulsation periods of radial modes (left panel) and nonradial g modes with $\ell = 1$ (right panel) in terms of the effective temperature, for a sequence of models with $M_\star = 0.3419 M_\odot$ and $Z = 0.05$. The red horizontal lines correspond to the limits of the period interval observed in BLAPs.

change ($\dot{\Pi}/\Pi$), respectively, for the radial fundamental mode —the only radial mode that is predicted to be pulsationally unstable according to our nonadiabatic computations— in terms of the effective temperature, for model sequences with different stellar masses and $Z = 0.05$. Horizontal dashed lines correspond to the periods (upper panel) and the relative rates of period changes (lower panel) measured for BLAPs. Note that the radial fundamental mode ($\ell = 0, k = 0$) for different values of $M_\star$ has a period in excellent agreement with the periods observed in BLAPs in the range of effective temperature in which these stars are found, except in the case of $M_\star = 0.2724 M_\odot$. On the other hand, from the lower panel of the figure it is clear that the absolute value of the rate of period change for the fundamental mode ($|\dot{\Pi}/\Pi| \sim 10^{-5} - 10^{-6}$ yr^{-1}) is largely in excess when compared with the values measured for BLAPs ($\sim 10^{-7}$ yr^{-1}), except in the case of $M_\star = 0.2724 M_\odot$. In addition, all the values are negative, as anticipated in the left panel of Fig. 7. We conclude that, according to the values of the rate of period change measured for BLAPs, the pulsations of all these stars can not be attributed to the radial fundamental mode (nor to radial modes in general).

What about nonradial g modes? In the upper panel of Fig. 9 we show the periods of the $\ell = 1$ g modes with $k = 25$ and $k = 55$ for the sequence with $M_\star = 0.3419 M_\odot$ and $Z = 0.05$. These periods are close to the limits of the interval of periods measured in the BLAPs (dashed horizontal lines). In the upper panel of the figure we depict the corresponding values of $\dot{\Pi}/\Pi$. At variance with what happens for the fundamental radial mode (lower panel of Fig. 8), in this case the rates of period change are positive and negative, and for certain ranges of $T_{\rm eff}$, they adopt values compatible with those

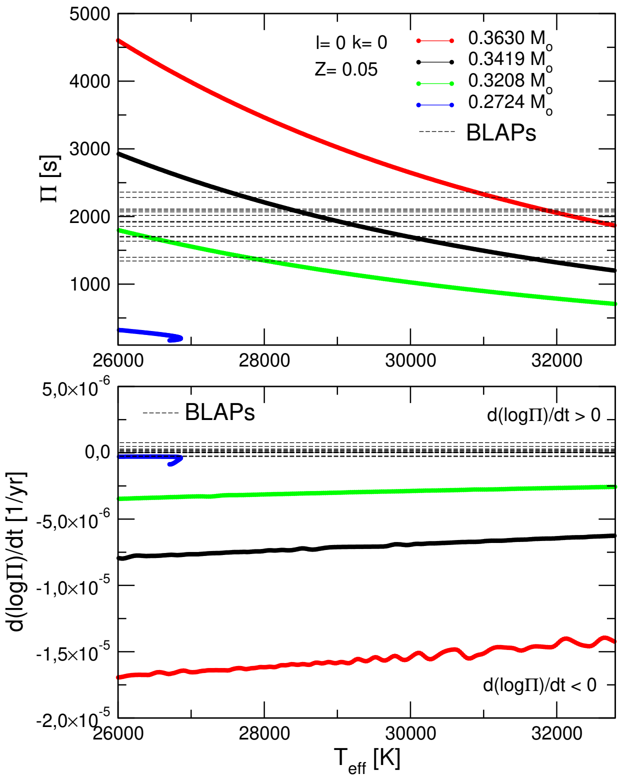

Figure 8: Upper panel: the periods of radial fundamental mode ($\ell = 0, k = 0$) versus the effective temperature, for model sequences with different stellar masses and $Z = 0.05$. Horizontal dashed lines are the periods observed in BLAPs. Lower panel: same as upper panel but for the case of the relative rates of period changes. The horizontal dashed lines are the values of $\dot{\Pi}/\Pi$ measured in BLAPs.

measured in BLAPs (dashed horizontal lines). Thus, we can conclude that the rates of period changes exhibited by BLAPs could be satisfactorily explained by high-order nonradial g modes.

5 Conclusions

In this work, we have investigated a possible evolutionary origin for the BLAP stars as being the hot counterpart of the already known pre-ELMV stars —pulsating low-mass He-core shell H burning pre-WD stars, (Córsico et al., 2016). According to this evolutionary scenario, BLAPs could be $\sim 0.3 M_\odot$ pre-WDs at $T_{\rm eff} \sim 30\,000$ K with He/H envelopes resulting from binary-star evolution (see Romero et al., 2018, for details). If this scenario were correct, the companion star should be observed. However, no companion star is observed in any BLAP[1]. This could be simply due to the faintness of the companion —no eclipses are seen, no lines of companions are detected. Similar investi-

[1]We note that in sdB stars, about half of the supposed companions are also not observed.

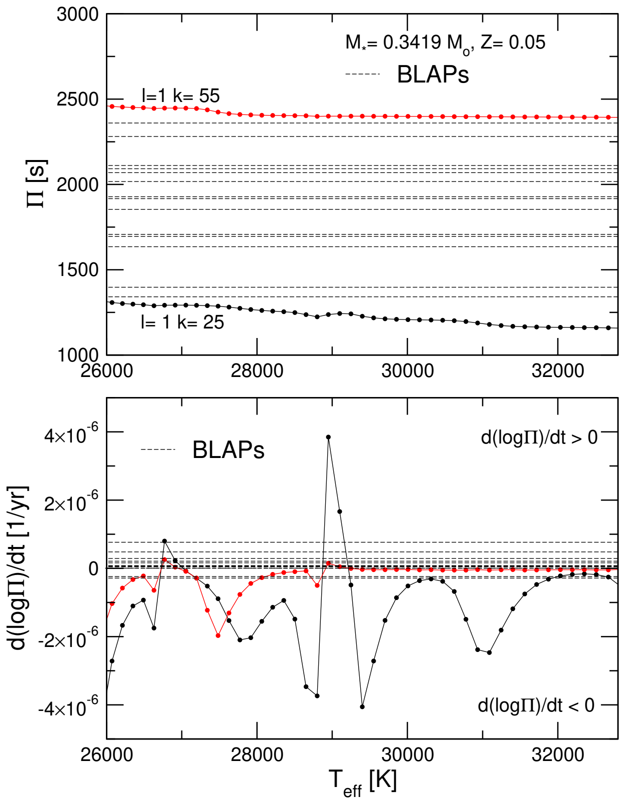

Figure 9: Upper panel: the periods of the nonradial mode ($\ell = 1$) with $k = 25$ (black dotted line) and $k = 55$ (red dotted line) in terms of $T_{\rm eff}$, for a model sequence with $M_\star = 0.3419 M_\odot$ and $Z = 0.05$. Horizontal dashed lines are the periods observed in BLAPs. Lower panel: same as upper panel but for the case of the relative rates of period changes. The horizontal dashed lines are the values of $\dot{\Pi}/\Pi$ measured in BLAPs. Note that $|\dot{\Pi}/\Pi| < 4 \times 10^{-6}$ yr^{-1} for models.

gation should be done for BLAPs. Another alternative is that BLAPs are the result of mergers of ELM+ELM binary systems (each component with $\sim 0.15 M_\odot$). Finally, another possibility is that BLAPs are actually core He-burning stars with masses $\sim 1.0 M_\odot$ (Pietrukowicz et al., 2017), although in that case, no feasible evolutionary channel is known. Gaia distance for OGLE-BLAP-009, of about 2.63 kpc, seems to favour the low-mass ($\sim 0.30 M_\odot$) solution over the $1.0 M_\odot$ solution (Pawel Pietrukowicz, private communication). We conclude that the evolutionary origin of BLAPs is still an open problem.

Regarding the kind of pulsation modes responsible for the variability of BLAPs, we have obtained two possible interpretations. On one hand, the pulsations of these stars could be due to the radial fundamental mode ($\ell = 0, k = 0$). These modes have the right value of the periods at the correct effective temperatures and gravities (stellar masses), and, in addition, they are strongly destabilized by the κ mechanism due to the Z bump, provided that stellar models with enhanced metallicity $Z \sim 0.05$ are considered. It is important to mention that the fundamental radial mode is the only radial mode that is destabilized in our computations. On the other hand, high-order nonradial g modes also have pulsation periods in agreement with those observed in BLAPs, at the right effective temperatures and gravities. A lot of these modes also are unstable by the κ mechanism due to the Z bump, although they are not so strongly destabilized as the fundamental radial mode is. In view of this, and taking into account the fact that in BLAPs just a single period has been detected to date with a large amplitude in the lightcurves, it seems that the natural interpretation of the variability in BLAPs should be the radial fundamental mode. However, when we examine the rates of period changes of our models, we found that nonradial g modes with high radial order k are characterized by $\dot{\Pi}/\Pi$ values in much better agreement with the values measured in BLAPs than the fundamental radial mode. In summary, the exact nature of the pulsation modes responsible for the variability of BLAPs remains a matter of debate.

Finally, there is the issue of the high metallicity necessary to excite pulsation modes through the κ mechanism. In our models, the metallicity is *globally* enhanced in order to have an enhanced Z bump in the Rosseland opacity. However, it would be possible to found instability with a *local* enhancement of the opacity at the region of the star in which the Z bump is located. This could be achieved if radiative levitation is operative, in such a way that Fe locally accumulates at the driving zone. This problem needs to be investigated consistently and will be addressed in a future work.

Acknowledgements

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