Driving Pulsation Modes in Models of the Two Pre-ELM Helium-Core White Dwarfs WASP 0247-25B and WASP 1628+10B

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Introduction

Multi-periodic pulsations have recently been detected in two pre-extremely low mass (pre-ELM) helium-core white dwarfs as reported in Maxted et al. (2013, Nature, 498, 463) and Maxted et al. (2014, MNRAS, 444, 208). As such, they define a new class of pulsating stars in the HR diagram. Both objects are the secondary components in eclipsing close binaries, with solar-type main sequence stars as primaries. They are believed to be the remnants of former red giant stars stripped down of most of their mass through an active phase of binary evolution. The first of those is WASP 0247-25B, characterized by $M = 0.186 \pm 0.002\ M_{\odot}$, $\log g = 4.576 \pm 0.011$, and $T_{\rm eff} = 11{,}380 \pm 400$ K (Maxted et al. 2013). Three pulsation modes have been detected so far, with periods of 381 s, 406 s, and 421 s. The second one, showing two modes with 669 s and 755 s, is WASP 1628+10B, with $M = 0.135 \pm 0.020\ M_{\odot}$, $\log g = 4.49 \pm 0.05$, and $T_{\rm eff} = 9200 \pm 600$ K (Maxted et al. 2014). Adiabatic calculations using suitable evolutionary models have been presented in these publications, showing that the pulsation periods correspond to low-degree, mid-order p-mode oscillations (probably including radial modes). The question of the driving mechanism, however, has been left open, and we address that issue here.

The pulsating pre-ELM stars in relation to the pulsating white dwarfs

The locations of the two pulsating pre-ELM stars in the $\log g - T_{\rm eff}$ domain are indicated in Figure 1, where a detailed view of the ZZ Ceti instability strip is also provided. The theoretical blue and red edges illustrated in the plot account remarkably well for the distribution of constant *vs* variable stars. The excitation mechanism responsible for the pulsations detected in ZZ Ceti stars is convective driving associated with partial recombination of hydrogen in the pure-H envelopes of those stars. Rigorously speaking, the theoretical instability strip refers specifically to g-modes with a degree index of $l = 1$. However, it is known that the blue edge for low-degree p-modes is only slightly hotter than the blue edge illustrated here. It is further known that the same driving mechanism, convective driving, is responsible for the excitation of both p- and g-modes in models of ZZ Ceti stars. Hence, on the basis of a modest extrapolation of the theoretical boundaries into the pre-ELM domain in Figure 1, one can firmly conclude that convective driving in pure H is not the cause of the p-modes detected in WASP 0247-25B and WASP 1628+10B since those two objects are hotter than the extended ZZ Ceti blue edge.

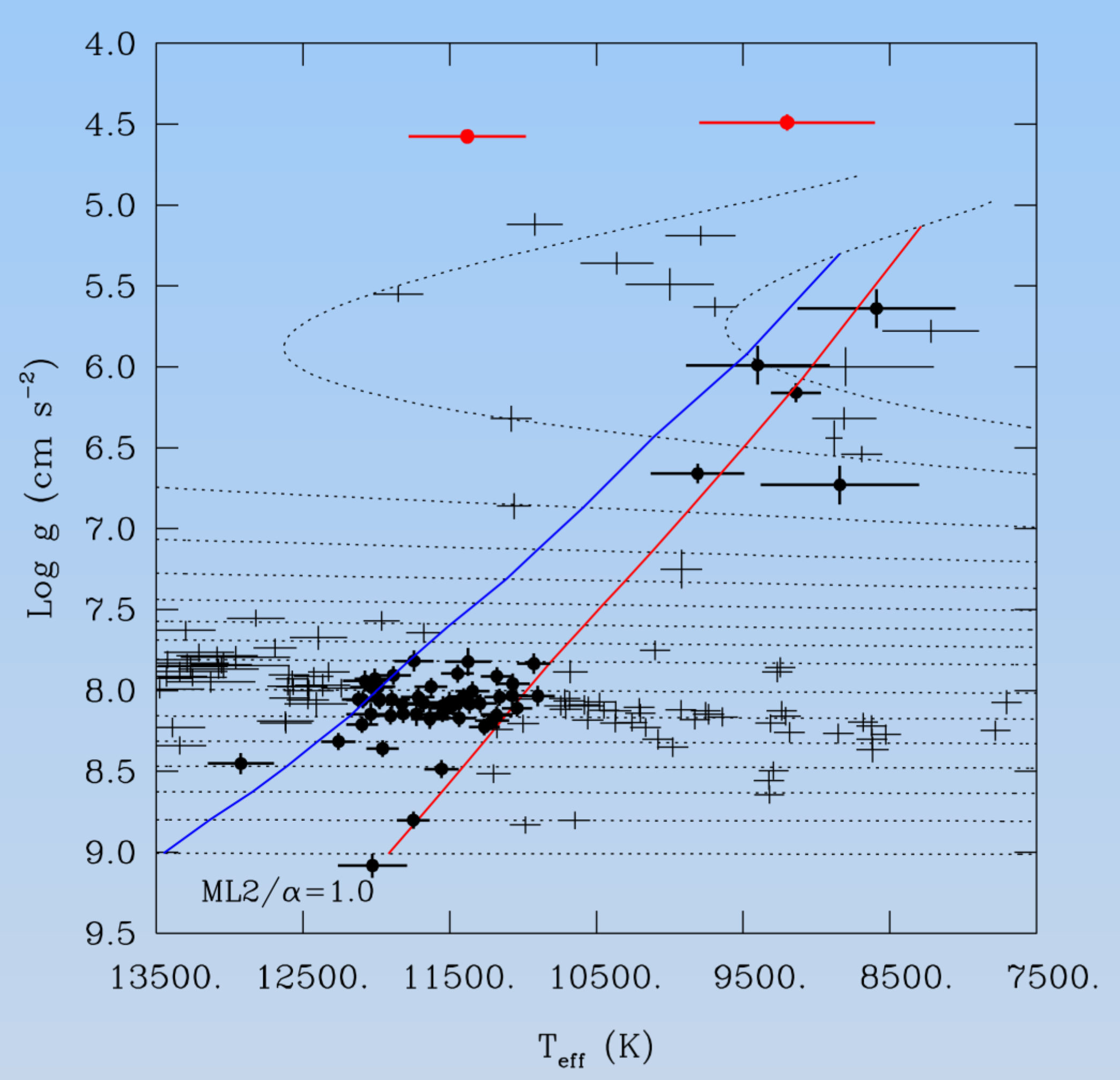

Figure 1. The locations of the two pulsating pre-ELM stars in the surface gravity-effective temperature diagram (red dots and error bars) in relation to the pure H (ZZ Ceti) instability strip. The targets found not to vary are represented by light crosses, while known pulsators, including five pulsating ELM helium-core white dwarfs, are indicated by black dots and heavy crosses. These objects are all g-mode pulsators. The dotted curves are representative evolutionary tracks for DA white dwarfs (with C/O and He cores, depending on the mass). The blue and red curves define the theoretical boundaries of the ZZ Ceti strip as obtained from the detailed nonadiabatic calculations carried out by Van Grootel et al. (2013, ApJ, 762, 57). These boundaries account very well for the empirical data. They are based on the so-called ML2/α=1.0 calibration of the Mixing-Length Theory used in the equilibrium models.

The possibility that convective driving may have something to do with the instabilities seen in both WASP objects should not be summarily dismissed, however. Indeed, the mechanism operates also in a pure helium envelope (it is responsible, in that case, for the existence of the much hotter V777 Her instability strip encountered by cooling He-envelope DB white dwarfs), as well as in white dwarfs with mixed H-He envelopes of the GW Lib type. In fact, as indicated in the extensive investigation of Van Grootel et al. (2015, A&A, 575, A125) on the latter type, convective driving leads, in white dwarfs, to instability strips that may be found anywhere in effective temperature between the pure H ZZ Ceti strip ($T_{\rm eff} \sim 11{,}500$ K at $\log g \sim 8$) and the pure He V777 Her domain ($T_{\rm eff} \sim 25{,}000$ K at $\log g \sim 8$) . The exact location depends on the ratio of H to He in the envelope. Hence, it may be the case that both WASP pre-ELM pulsators find themselves in low-gravity extensions of white dwarf instability strips associated with mixed H/He envelopes. Although He is rather difficult to detect optically at their relatively low effective temperatures, efforts should be made at the spectroscopic level to detect it, if any, and derive its abundance as may be the case. Note that this suggestion is based on the assumption that the atmospheric H/He abundance ratio is the same as that below in the driving/damping region, which may or may not be justified.

Results of a preliminary nonadiabatic survey

We carried out exploratory stability calculations with the help of the same numerical tools as those described in Van Grootel et al. (2013, 2015). The equilibrium models that we constructed are envelope models -- entirely suitable for investigating the stability problem -- specified by the fixed values of the effective temperature, surface gravity, and mass, and a variable value of the envelope composition (a mixture of H and He in varying proportions). Mode driving, if any, is associated only with the partial ionization of H and He as we put no metals at all in our models at this stage. Some of our results are depicted in Figure 2, where we show the behavior of the spectrum of excited p-modes (with $l = 0$ in this specific example) as a function of the mass fraction of hydrogen in the envelope mixture. In both cases, we do find H/He mixtures that potentially could account for the observed pulsation periods. For instance, taken at face value, our plot indicates that an envelope with a composition in the range X(H) ~ 0.25-0.30 (X(He) ~ 0.75-0.70) drives a radial mode (with a radial order $n = 8$) having a period quite comparable to those detected in WASP 0247-25B. Likewise, in the case of WASP 1628+10B, an excited mode with $l = 0$ and $n = 4$ has a period comparable to those observed if the chemical composition in the driving/damping region is in the range X(H) ~ 0.55-0.60 (X(He) ~ 0.45-0.40). Interestingly, and quite encouragingly, our results for WASP 0247-25B are virtually the same as those derived by Jeffery & Saio (2013, IAU Symposium 301, Cambridge, 425) using completely independent envelope models (with a standard metallicity of Z =0.02 in their case) and pulsation codes.

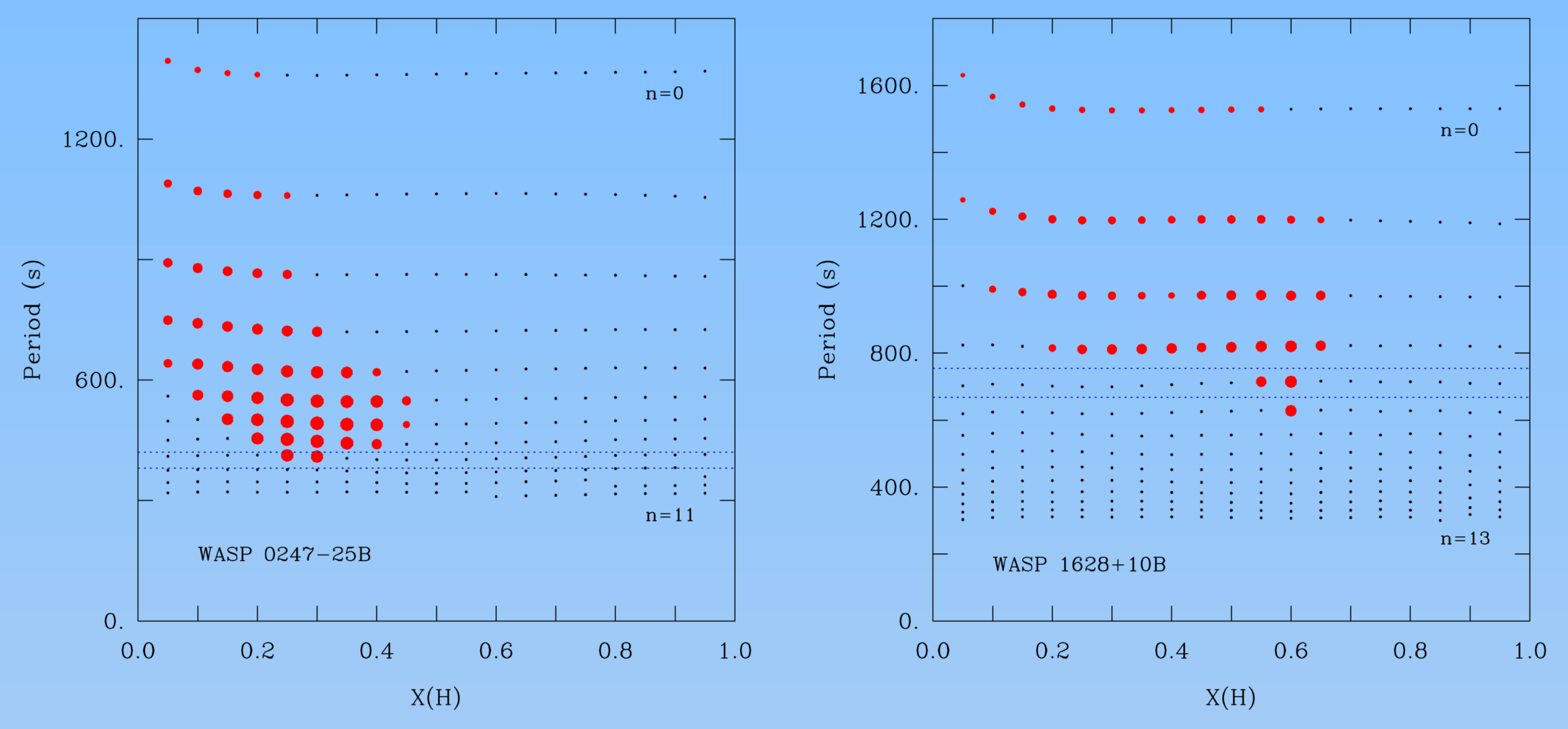

Figure2. Part of the period spectrum for radial modes as a function of envelope composition for models of WASP 0247-25B (on the left) and WASP 1628+10B (on the right). The excited modes are identified by red dots whose sizes provide a logarithmic measure of the imaginary part of the eigenfrequency: the bigger the dot, the more unstable the mode. The horizontal dotted blue lines indicate the range of observed periods.

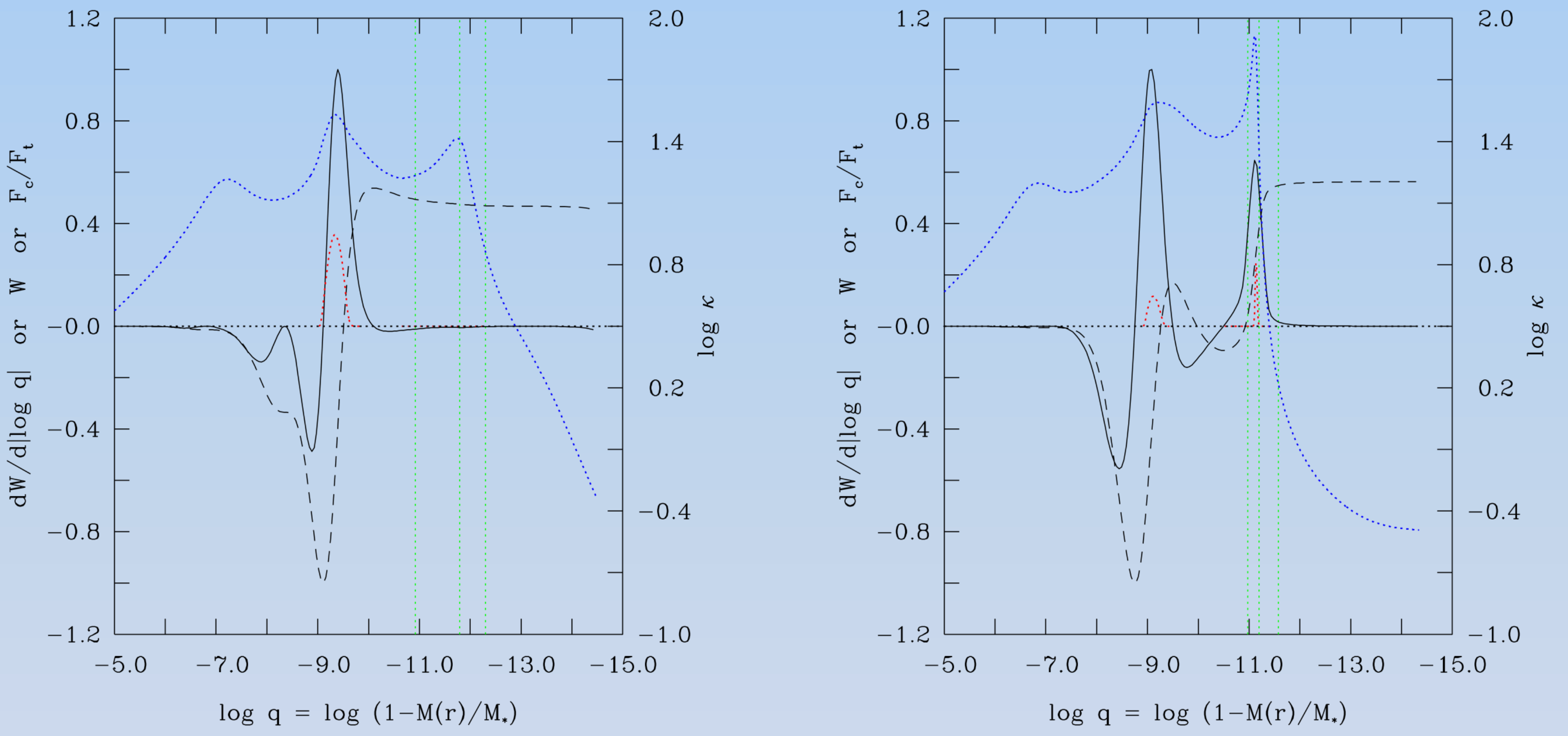

Figure 3. Details of the driving/damping process for the $l = 0$, $n = 8$, 409 s mode excited in our X(H) = 0.3 model of WASP 0247-25B (left panel), and similarly for the $l = 0$, $n = 4$, 715 s mode excited in our X(H) = 0.6 model of WASP 1628+10B (right panel). The solid curve shows the integrand of the work integral of the mode as a function of fractional mass depth. When positive (negative) the local layer contributes to driving (damping). The dashed curve shows the running work integral, from left to right, toward the surface of the model. A positive value of that quantity at the surface (as is the case here) indicates that the mode is globally driven. The dotted blue curve gives the profile of the Rosseland opacity, to be read on the right-hand ordinate axis. The vertical dotted green lines give the locations of the atmospheric layers characterized by a value of the optical depth of τ_R = 10.0, 1.0, and 0.1, from left to right. The dotted red curve gives the ratio of the convective to total flux.

An close examination of the details of the driving/damping process in our models of pulsating pre-ELM stars indicates that, contrary to the case of the pulsating white dwarfs (both ELM and "normal"), convection does not dominate the driving process. Indeed, as can be seen in Figure 3, convection is not totally negligible, but the fraction of flux carried by it is never dominant. The driving process rather mostly bears the signature of a classical kappa-mechanism: for a pure kappa-mechanism, the maximum in local driving (the black solid curve) should coincide with the maximum in opacity (dotted blue curve), and this is nearly the case here. We thus conclude that the kappa-mechanism working in a H/He mixture, along with some convective driving, is able to excite modes with periods comparable to those detected in the two WASP objects. To validate these results, it is essential that a detailed spectroscopic search for the presence of He in the atmospheres of these stars be carried out. We would love to have access to these private data!