White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
Proceedings IAU Symposium No. 357, 2019
M. A. Barstow, S. J. Kleinman, J. L. Provencal & L. Ferrario, eds.
doi:10.1017/S1743921320000320

Pulsating white dwarfs and convection

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Abstract. Convection is a highly turbulent, three dimensional process that is traditionally treated using a simple, local, time independent description. Convection is one of the largest sources of theoretical uncertainty in stellar modeling. We outline recent progress in studies using pulsating white dwarfs to constrain convection and calibrate mixing length theory.

Keywords. convection, white dwarfs, oscillations

1. Introduction

The dynamics of convection influence many key aspects of stellar modeling, ranging from the effects of convective overshoot to supernovae to stellar ages. We know that convection is a highly turbulent, three dimensional process that involves nonlocal motions. Yet convective energy transport in stellar environments is typically modeled using Mixing Length Theory (MLT). MLT is a simple one dimensional theory in which convective cells of the same size travel a given distance (the "mixing length") before dissipating and releasing or absorbing energy. MLT, with its free mixing length parameter α, lacks predictive value. More physically self-consistent approaches based on hydrodynamic simulations are beginning to supplant it or at the very least calibrate it (i.e. Tremblay *et al.* 2015), but such models need to be rigorously validated. An empirical determination of convection dynamics in different stellar environments is thus an important goal with implications for a wide range of astrophysical fields.

2. Convective Light Curve Fitting

Pulsating WDs are invaluable asteroseismic laboratories to probe stellar convection. The g-mode pulsations ($P \approx 100$–1500 s) are linked to the inevitable development of surface hydrogen or helium CZs as every WD cools. The CZ is very sensitive to temperature changes. Pulsating hydrogen atmosphere WDs (DAVs) experience local $\Delta T = \pm 200$K, while helium pulsators (DBVs) swing through variations as large as $\Delta T = 3000$ K. These changes produce significant variations in the local heat capacity of the CZ. All of this means that, at any given time, the CZ of a pulsating WD cannot be considered as a structure of uniform depth over the entire star. The direct result is an observed nonlinear light curve with narrow peaks and wider valleys. Fig. 1 illustrates the increased nonlinearities in observed light curves as a function of temperature.

The complete methodology of convective light curve fitting can be found in Montgomery (2005) and Montgomery *et al.* (2010). In very broad brush strokes, convective light curve fitting uses observed nonlinearities to recover the parameter τ_o, which

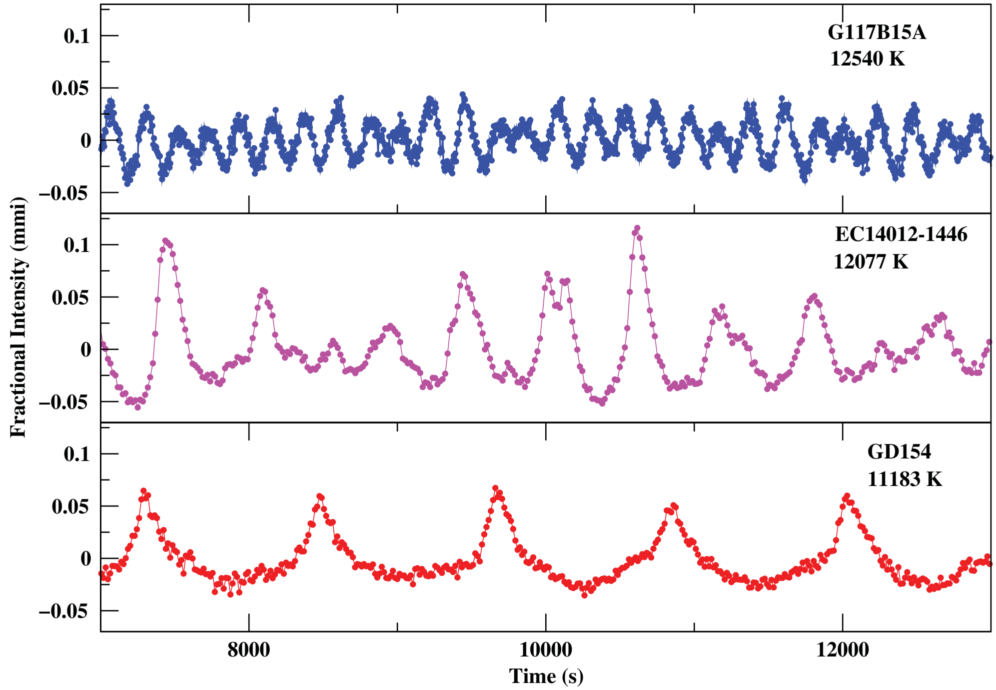

Figure 1. The general evolution of pulsating white dwarf light curves as a function of T_{eff}. Nonlinearities increase as the convection zone deepens and evolves in cooler stars.

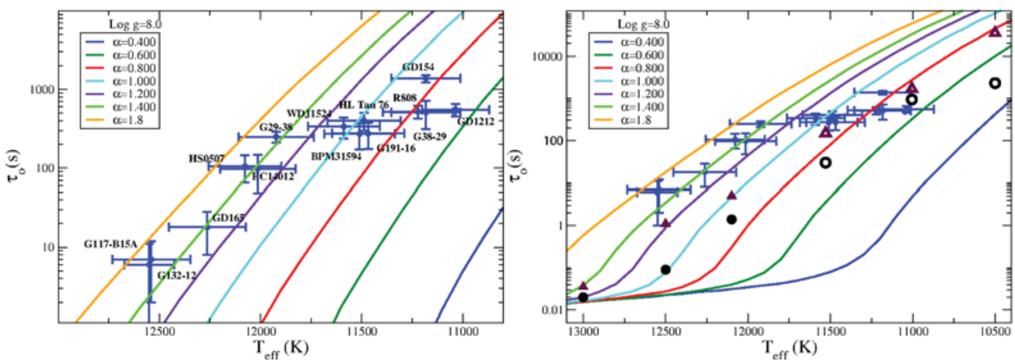

Figure 2. For DA pulsating white dwarfs. Left: Comparison of convective light curve fitting results (blue points) with predictions of MLT (colored lines). Right: Similar comparison, but including the recent 3D radiation hydrodynamical convection simulations of Tremblay *et al.* (2015). The triangular symbols use the flux boundary to define the CZ, while the circular symbols use the Schwarzchild criterion. Note changes in the x and y axes.

represents the time-averaged heat capacity of the CZ in each star. The Whole Earth Telescope (WET) is in the midst of a long term project to produce an empirical description of τ_o as a function of effective temperature across the DAV and DBV instability strips. Our goal is to provide insight into convection dynamics in WD environments. Fig. 2 presents the comparison of current convective light curve fitting results for DAVs with the expectations of MLT (left) and 3D radiation hydrodynamical convection simulations of Tremblay *et al.* (2015) (right). Each τ_0 determination in each panel is based on

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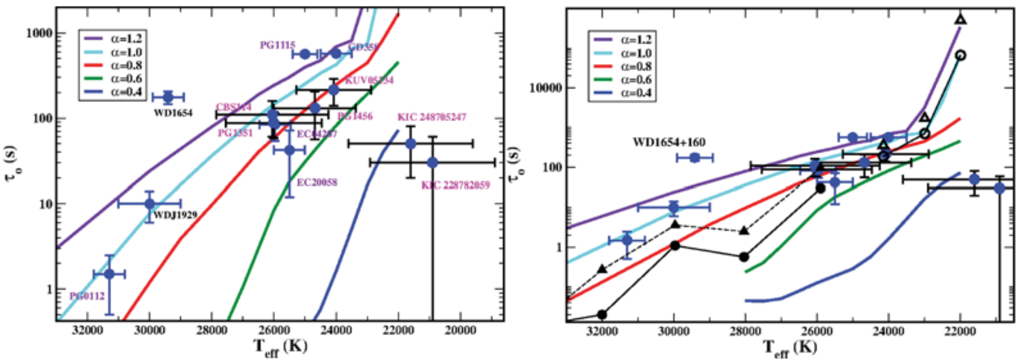

Figure 3. For DB white dwarfs. Left: Comparison of convective light curve fitting results (blue points) with predictions of MLT (colored lines). Blue error bars represent UV temperature determinations, while black error bars are optical determinations. Black object labels contain no photospheric metals. Purple labels contain traces of photospheric hydrogen, carbon, and other metals. Right: Similar comparison, but including the recent 3D radiation hydrodynamical convection simulations of Cukanovaite *et al.* (2019). The triangular symbols use the flux boundary, while the circular symbols use the Schwarzchild criterion. Note changes in the x and y axes.

extensive Whole Earth Telescope (WET) ground based photometric campaigns Provencal *et al.* (2012). Once we have determined τ_o for an object, we require an accurate effective temperature to place the WD at its location in the T_{eff} plane. For this, we rely on published spectroscopic T_{eff} measurements.

Fig. 2 (left) clearly shows that τ_o does not follow the predictions of MLT for any single value of the mixing parameter α. The value of τ_0 reaches a plateau at ≈800 s near $T_{\rm eff}$=12000 K. Our results argue for an increasing time-averaged heat capacity and a high convective efficiency for stars hotter than 12,000 K, but a nearly constant time-averaged heat capacity (and a changing convective efficiency) for stars cooler than ≈12,000 K. This translates into a much slower deepening of the CZ for cooler pulsators than predicted by theoretical calculations. The 3D models of Tremblay *et al.* (2015) (right) offer a theoretical improvement, predicting a change in alpha, or convective efficiency, as a function of $T_{\rm eff}$. However, there remains some differences, such as the observed plateau, with the 3D predictions.

Fig. 3 presents a similar comparison for the DBVs. To date, we have determined τ_o for 11 DBVs. The situation here is more complex than for the DAVs. Our greatest limitation in interpreting the behavior of τ_o across the DB instability strip lies in the errors associated with $T_{\rm eff}$ determinations. This well known issue stems from the high temperatures of the DBVs and resulting difficulties of determining temperatures from optical spectroscopy, as well as the effects of trace amounts of hydrogen and other elements. In Fig. 3 left, objects with optical temperature determinations have black error bars, while UV determinations have blue error bars. Objects containing elements such as carbon or hydrogen in their photospheres have purple name labels. In Fig. 3 right, we present comparisons with the recent 3D convective simulations of Cukanovaite *et al.* (2019). 3D helium convection, in addition to the issues with overshooting, etc., is further complicated by the presence of a second convection zone (HeII) that may or may not be merged with the He I convection zone. In short, much work remains to be completed before we can understand the behavior of the DB pulsators.

An additional probe of convection may be given by a comparison of the predicted maximum pulsation periods for given values of $\tau_{\rm o}$ with the observed maximum pulsation periods for stars in our sample (Fig. 4). Brickhill 1991 shows that g-mode pulsations

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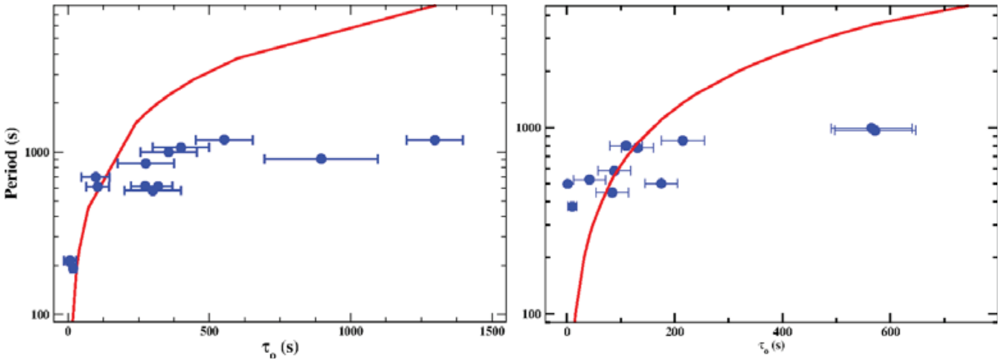

Figure 4. Left: Comparison of observed pulsation periods (blue points) with predicted maximum periods (red line) for DAVs. Right: The same comparison, but for DBVs. In both cases, some mechanism is limiting observed pulsation periods to ≈ 1000 s.

should occur when convective driving exceeds radiative damping. This condition is met when the pulsation period P is less than P_{max}, where $P_{max} = 2\pi\tau_o$. In Fig. 4, we compare observed maximum pulsation periods (blue points) with the predicted maximum period (red line). Agreement is fairly good for hotter stars (low values of τ_o, but observed pulsation periods do not exceed ≈1000 s for cooler stars. Combined with our results from convective light curve fitting, an unknown mechanism is functioning to limit tau_o and keep observed pulsation periods from increasing as as predicted.

3. Summary and Implications

Convective light curve fitting uses the observed nonlinearities in pulsating white dwarf light curves to probe white dwarf convection in both hydrogen and helium atmospheres. Our results for hydrogen atmospheres show a plateau in the parameter tau_o, which is related to the thermal response timescale at the base of the convection zone. Our results show that no single value of the MLT parameter α is appropriate for all white dwarfs. Our results compare more favorably with recent 3D simulations, but some differences remain that require additional investigation. The situation is even more complex for the DBVs, where difficulties in temperature determinations, the existence of trace metals, and the possible presence of two convection zones complicate our analysis. A comparison of observed pulsation frequencies with theoretical predictions further argues that an unknown mechanism, acting to limit tau_o and keep observed pulsation periods from increasing as as predicted, is missing from our analysis.

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