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An overview of Whole Earth Telescope

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Abstract.

Asteroseismology explores some of the most unique and extreme conditions in the universe, and impacts research in a wide range of fields including thermodynamics, energy transport, nuclear physics, particle physics, and magnetism (among many others). Traditionally, research in stellar physics relies on extrinsic properties such as temperature, radius, and surface composition. Just as the interior of the Earth and Sun are revealed with remarkable clarity using seismology and helioseismology, we are now successfully employing asteroseismology to study stellar interiors. Stellar oscillations are a more sensitive probe of interior structure than virtually any other measurement. Given a sufficient sample of resolved pulsation frequencies (modes), we can use stellar models to build detailed maps of the interior pressure, density, and chemical composition of individual stars.

The Whole Earth Telescope (WET) is an international cooperative network structured to provide precision time-series photometric observations on multiple targets during campaigns lasting 2-8 weeks. Continuous observations with these time bases are required to fully capitalize on the tools of asteroseismology. Because of their numbers and availability, small telescopes (apertures less than 2 meters) play vital roles in the WET network. We will present an overview of the WET network, observing and data reduction techniques, current science objectives and future goals.

Key words: asteroseismology – white dwarfs – photometry

1. Introduction

Convection is one of the largest sources of theoretical uncertainty in our understanding of stellar physics. For example, Tremblay et al. (2010) show that the use of mixing length theory (MLT) to treat convective energy transport in white dwarf (WD) atmospheres is the single largest source of theoretical uncertainty in calculations of WD atmospheric structure. Bergeron et al. (1995) show that basic model parameters such as flux, line profiles, energy distribution, color indices, and equivalent widths are extremely sensitive to the assumed MLT parameterization. A detailed discussion of MLT parameterizations (ML1, ML2, and ML3) can be found in Bergeron et al. (1995). These authors demonstrate that these theoretical uncertainties produce systematic errors ranging from 25% for effective temperatures to 11% for derived mass and radius. The systematic errors propagate to a range of fields, as we rely on these models to supply information about WD interiors, masses, and temperatures needed to calibrate WD cooling sequences. WD cooling sequences in turn produce detailed age estimates for WDs and an independent estimate of the age of the Galactic disk. Similar problems with MLT are apparent in studies ranging from determinations of the ages of massive stars, to understanding the structure of F and early A stars, to understanding the atmosphere of Titan.

MLT is a phenomenological theory, but with its adjustable constant α, it lacks predictive power. More physically self-consistent approaches based on hydrodynamic simulations will eventually supplant it (or at the very least calibrate it), but such models will need to be validated. An empirical determination of convection in different environments is thus an important goal with implications for a wide range of astrophysical fields. A unique technique introduced by Montgomery (2005) provides such a test, using information encoded in nonlinear (nonsinusoidal) pulse shapes to make empirical measurements of the physical properties of convection in pulsating WD envelopes. This is profound, since until the implementation of convective light curve fitting, our Sun was the only star for which empirical information on its convection zone could be obtained.

The Whole Earth Telescope (WET) was founded in the 1980s to overcome the problem of discontinuous photometric observations. The WET is a cooperative international network of astronomers and optical telescopes distributed in longitude around the globe with the goal of obtaining 24 hour photometric coverage of pulsating stars over periods of several weeks. While multi-site campaigns have long played a role in the study of pulsating stars, the WET is unique in that it functions as a single instrument. During a WET run, headquarters at Mt. Cuba Observatory in Delaware (HQ) maintains daily contact with each observer, assigning targets based on scientific priorities, local weather conditions, and overlapping coverage. Should an observatory following the primary target cloud over, HQ informs a second overlapping site following a secondary target to switch to the primary target, assuring continuous coverage. Observers collect data on their designated target star(s) and transmit the raw CCD frames (up to several gigabytes a night) to HQ, where it is compiled into a single light curve and analyzed in real time. This initial analysis is made available to observers via the DARC website (see http://www.physics.udel.edu/~darc/wet/campaign.html for a complete list of WET runs).

In the following, we will describe our current observational program to utilize the strengths of the WET to attack the problem of convection in stellar photospheres.

2. Convective Light Curve Fitting

Approximately two-thirds of all WD pulsators show significant nonlinearities in their light curves (e.g., see Fig. 1). As was first pointed out by Brickhill (1992), the likely cause is the rapid local change in thickness experienced by the convection zone (cz) during a pulsation cycle. The WD cz attenuates (and delays) the pulsations traveling through it. Simultaneously, pulsation temperature variations modulate the local depth of the cz, altering the amount of attenuation. The result is a distortion of the observed light curve, with narrow peaks and wider valleys.

Building on the work of Brickhill (1992), Montgomery et al. (2010) showed that the rate at which flux enters the base of the convection zone, $F_{\rm base}$, can be related to the flux which emerges at its top (i.e., the photosphere), $F_{\rm phot}$, by the relation

$$F_{\rm phot} = F_{\rm base} + \tau_C \frac{dF_{\rm phot}}{dt}, \tag{1}$$

where τ_C describes the changing heat capacity (thickness) of the convection zone as a function of local photospheric flux. To make as few assumptions about convection as possible, we parametrize τ_C as $\tau_C = \tau_0 \, (T_{\rm eff}/T_{\rm eff,0})^{-N}$, where τ_0 is the average thermal timescale of the convection zone, $T_{\rm eff,0}$ and $T_{\rm eff}$ are the instantaneous and time-averaged effective temperatures, and N is a parameter describing its sensitivity to temperature changes. Static envelope models using standard MLT predict that the cz mass of a hydrogen atmosphere WD should scale with temperature as $M_{CZ} \sim {T_{\rm eff}}^{-95}$, and a helium atmosphere cz should scale as $M_{CZ} \sim {T_{\rm eff}}^{-23}$ (Provencal et al. 2012). A pulsating hydrogen WD experiencing temperature excursions of ± 200 K will see the mass of its convection zone vary by more than a factor of 10 during one pulsation cycle. A pulsating helium atmosphere WD experiences temperature excursions of 3000 K during a pulsation cycle. The cz's heat capacity will vary similarly, resulting in observable light curve nonlinearities.

Equation 1 is a first-order, albeit highly nonlinear, ordinary differential equation in time. Our approach is to numerically obtain a fully nonlinear solution for equation (1). An advantage of this approach over the analytical one of is that we automatically include all higher-order nonlinearities. Since we are using complete light curves rather than folded pulseshapes, we are able to break many of the parameter degeneracies and obtain unique solutions (Montgomery et al. 2010). This approach is also computationally efficient, allowing us to calculate hundreds of models to converge to a best-fit solution.

With the further assumption that the angular dependence of $F_{\rm base}$ is given by the spherical harmonic Y_{lm}, we can calculate the bolometric flux changes at the surface of the model and average them appropriately over the visible disk of the model. Limb darkening is included using tabulated values based on the appropriate model atmosphere grid. Local bolometric fluxes are then mapped into variations in the observed wavelength band (Figure 1).

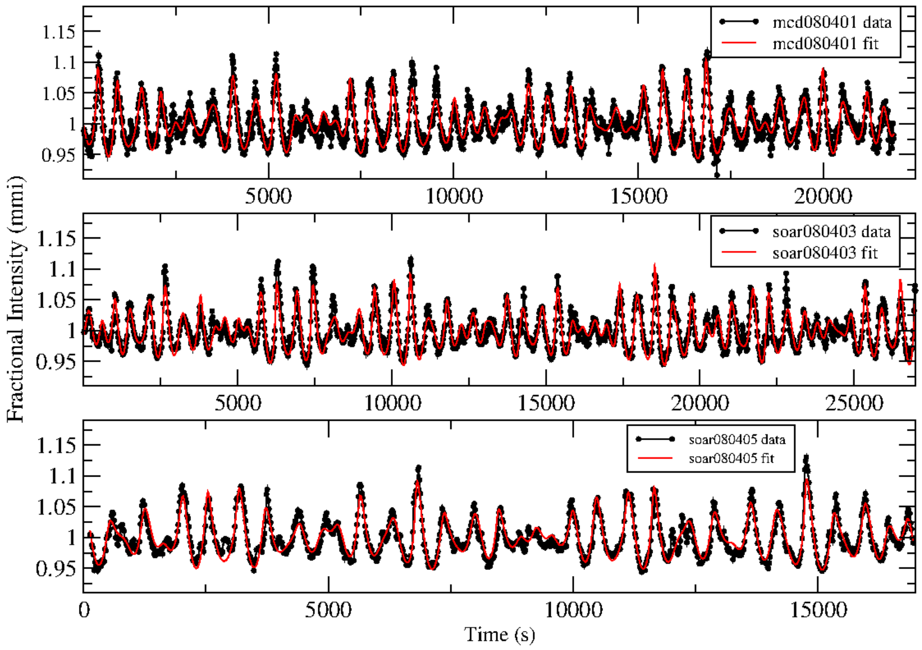

Figure 1. Simultaneous fit of the periods of 19 modes (solid line) to the light curves of EC14012-1446 from McDonald and SOAR (filled circles). Note the change in x axis for each plot.

3. Current Results

Figure 2 presents our current investigation establishing the validity of convective light curve fitting. Analysis of the DBs is seriously hampered by the large error bars associated with existing determinations of $T_{\rm eff}$ using optical spectra. We are working to resolve this issue with Cycle 20 *Hubble Space Telescope* ultraviolet spectra of these targets. For the DAVs, we find similar values of τ_0 for stars with similar temperatures. In both cases, our data does indicate an expected increase in τ_0 (and hence an increase in depth/mass of the convection zone) with decreasing temperature, arguing that the convective light curve fitting method is sound.

We have also noticed a relationship between the observed dominant oscillation period and the theoretical value of $P_{\rm max}$ that has additional implications. Our treatment of the nonlinearities in WD light curves is based on the larger picture of how a surface convection zone leads to driving in these stars. In particular, Brickhill (1991) demonstrate that the excitation of g-mode pulsations should occur when convective driving exceeds radiative damping. In terms of pulsation periods, this relation requires that g-modes are driven when $P \leq P_{\rm max}$,

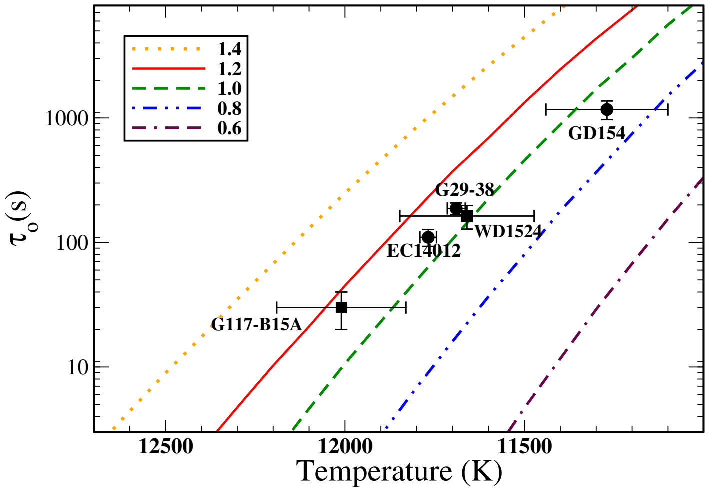

Figure 2. A comparison of the derived convective parameters log τ_0 vs $T_{\rm eff}$ with values expected from currently accepted $ML2/\alpha$ parameterization of convection for the DAV instability strip. Curves represent theoretical calculations of the thermal response time for the convection zone for various values of the MLT mixing length α.

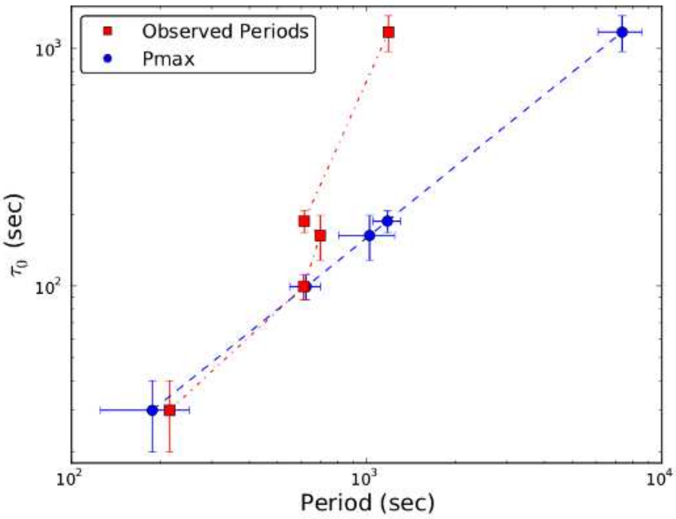

Figure 3. Comparison of the convective light curve fit (solid dot-dashed curve, red squares) with the theoretical value of $P_{\rm max}$ (dashed line, blue circles) for each DAV star with a measured value of τ_o. While simple theory predicts that these curves should be very similar, we find a significant departure for cooler stars.

where $P_{\mathrm{max}} = 2\pi\tau_o$ and P is the period of the given mode. In Figure 3, we compare the observed dominant oscillation period in each of the DAVs in Figure 2 with their theoretical value of P_{max}, as calculated from each star's value of τ_o. The agreement is good for $\tau_o < 100$ s, but the values diverge for larger τ_o values. Given that τ_o is related to T_{eff} this says that the agreement is good from the hot end to near the middle of the DA instability strip, but from that point to the cool edge an unknown effect is operating that prevents the dominant periods from increasing as rapidly as P_{max}. This phenomenon is likely related to the predicted sudden deepening of the convection zone as WDs cool toward the red edge of the instability strip. We will explore this connection as well as other mechanisms that could produce this behavior.

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