Background

White dwarf stars are the evolutionary endpoint for $\sim 98\,\%$ of all stars and thus contain a record of the history of star formation in the Galaxy. Their high surface gravities ($\log g \sim 8$) make chemical diffusion efficient in their envelopes, producing atmospheres composed predominantly of either hydrogen (spectral type DAs) or helium (spectral type DBs). White dwarfs make useful chronometers; we can determine ages of individual white dwarfs (e.g., Bergeron, Ruiz, & Leggett 1997) and stellar populations, such as the local Galactic disk, using the observed white dwarf luminosity function (e.g., Winget et al. 1987), open clusters (e.g., Ferrario et al. 2005; Jeffery et al. 2007), and globular clusters (e.g., Hansen et al. 2007; Bedin et al. 2008; Moehler & Bono 2008). We use the subset of pulsating white dwarfs to calibrate internal structure and cooling for chronometry and to probe fundamental physical processes.

In white dwarf pulsators, as in most pulsating stars, the excitation mechanism is tied to the presence of a surface partial ionization zone of an abundant chemical element in the envelope of the star (e.g., Winget & Kepler 2008). DB variables (DBVs) have temperatures between about 22,000 K and 29,000 K ("the DB instability strip," Beauchamp et al. 1999), corresponding to partial ionization of helium, and the DA variables (DAVs) have temperatures in the range 11,000 K to 12,000 K ("the DA instability strip," Mukadam et al. 2004; Bergeron et al. 2004), corresponding to partial ionization of hydrogen. Recently, our group has discovered an entirely new class of white dwarf pulsators, those whose atmospheres are dominated by carbon (the "DQVs," Montgomery et al. 2008b); this is the first new class of WD pulsators found in the last 25 years. The pulsations observed in all of these objects are nonradial g-modes of low spherical harmonic degree ℓ. The periods are typically between 100 and 1500 s, and the displacements are primarily horizontal, along gravitational equipotential surfaces.

These pulsations are fortuitous for two reasons. First, we can apply asteroseismology, the comparison of the observed pulsation periods with those calculated from models, to learn about and constrain many aspects of their internal structure. Second, as they cool all white dwarfs should pass through one of the instability strips, so they are representative—what we learn from the pulsators should apply to all white dwarfs.

Asteroseismology

Empirical Determinations of Convection

I have recently developed a technique for fitting the non-linear light curves observed in many large-amplitude pulsating white dwarfs (see lower panels, Fig. 1), which allows us to derive the thermal response timescale, τ_C, of the convection zone, a proxy for its depth (Montgomery 2005, 2006, 2007, 2008) These determinations are empirical in that they make no assumptions concerning the validity of mixing length theory (MLT), although they do allow us to compare the results against those expected from MLT (see upper panels, Fig. 1). The nonlinearities arise from the extreme temperature sensitivity of the convection zone: equilibrium models using MLT predict the mass should scale as $M_{CZ} \sim T_{\rm eff}^{-95}$ for the DAVS and $M_{CZ} \sim T_{\rm eff}^{-25}$ for the DBVS. While I have analyzed only three stars to date in each instability strip, some patterns have emerged. I find the expected qualitative trend of thicker convection zones with decreasing $T_{\rm eff}$, although the $T_{\rm eff}$ dependence appears to be *weaker* than the predictions of constant-α MLT for the DAVs and *stronger* than constant-α MLT for the DBVs. Our goal is to study many more stars in each instability strip in order to map convection as a function of both $T_{\rm eff}$ and $\log g$.

In my role as Director of Science Operations of the Delaware Asteroseismic Research Center, which runs the Whole Earth Telescope (WET) collaboration, the WET has taken this project on board as one of its major observational efforts. The WET is a coordinated global network of observers who use small- to medium-sized telescopes to obtain nearly continuous data on pulsating, multi-periodic objects.

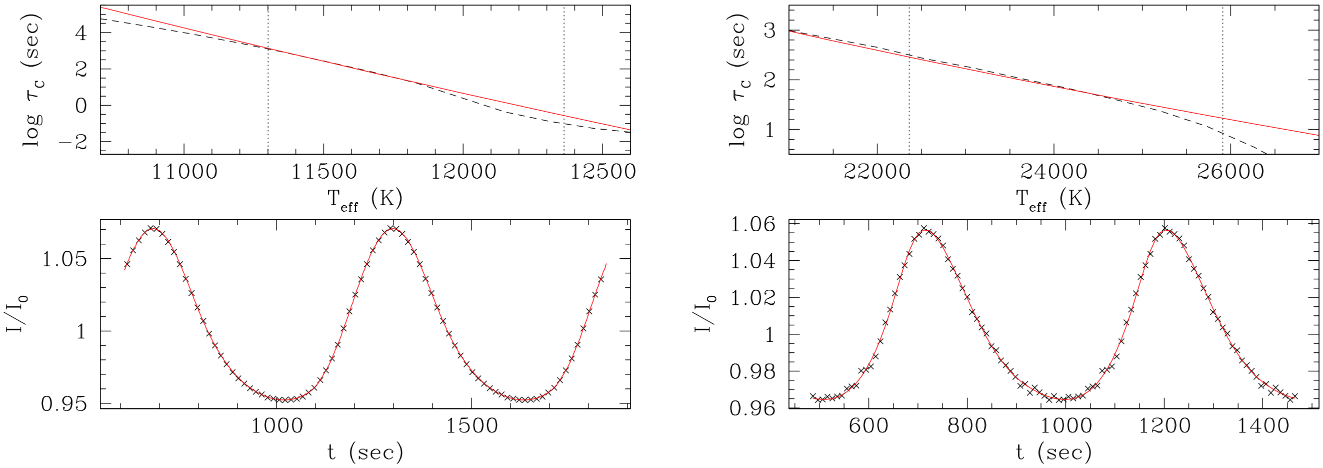

Fig. 1.— Fits to observed nonlinear light curves of two pulsating white dwarfs (left: the DAV G29-38, right: the DBV PG1351+489). The phased ("folded") observations are shown as crosses in the lower panels and the fits are the solid curves. In the upper panels I show the derived temperature dependence of the thermal timescale of the convection zone (solid curve) as compared to that expected from MLT (dashed curve), where the parameter "α" has been chosen to provide the closest match; the vertical lines show the maximum and minimum temperature excursions during the pulsations.

Comparison with Models of Convection

The results of the above work will provide detailed information on how convection works in white dwarf stars. Complementing this effort, I will perform 3D hydrodynamic simulations of convection in white dwarf envelopes. This work will be done in collaboration with H. Muthsam and F. Kupka, who have developed a state-of-the-art hydrodynamics code (Muthsam et al. 2007a,b). I will first use the simulations to calculate the location of the blue edges of the DAV and DBV instability strips, which has never been done for white dwarfs. Next, I will calculate values of τ_C for the individual stars with empirically determined values of τ_C. This will provide a direct comparison of the models and the simulations. In addition, I will "post-process" the simulations to obtain model spectra of the emergent flux, allowing us to assess the effect which overshooting into the photosphere has on the observed spectra. Since both the $T_{\rm eff}$ and $\log g$ determinations are based on fits to the spectral lines, this has important consequences for the field as a whole. Finally, using the simulations and the empirical determinations I will continue my work with F. Kupka on developing an accurate Reynolds Stress formalism for convection in white dwarfs (Montgomery & Kupka 2004) and other stars (Kupka & Montgomery 2002). This will hopefully lead to improvements in our understanding and modeling of convection, which will be transferable to many astrophysical environments, such as stellar envelopes and the convective cores of stars.

The DQVs

The hot DQs (carbon-atmosphere white dwarfs) show evidence for significant carbon partial ionization at the surface. A nonadiabatic analysis led us to search for pulsations in these objects. This search was successful (Montgomery et al. 2008b), resulting in the discovery of the first "DQV." Quite recently, Barlow et al. (2008) discovered two additional carbon pulsators, making this a bona fide class of objects, the DQV stars. This is the first new class of white dwarf pulsators discovered since the DBVs, 25 years ago (Winget et al. 1982).

The pulsations in two of the three objects, including the prototype, seem to be different from other known white dwarf pulsators: they each have a single frequency and its harmonic dominating their light curves. These same two objects show evidence for a strong magnetic field (~ 2 MG, Dufour et al. 2008)). It is possible that the strong magnetic field alters the fluid motions in the surface layers, and this leads to the observed pulse shapes. These stars could be the ideal laboratory for studying the interaction of pulsation and magnetic fields in the relatively simple context of the white dwarf stars, and I will explore models for this interaction.

In addition, the third member of the DQVs is a multi-periodic pulsator, which allows us to bring to bear the tools of asteroseismology to explore the interiors of these enigmatic stars, thereby shedding light on their evolutionary origins. Finally, I also plan to obtain phase-resolved spectra of the DQV stars, along with select non-variable DQs, to enhance and calibrate our asteroseismic investigations. We have much to learn from these unusual stars.

The Geometry and Time-dependence of Metal Accretion on WDs

The extremely high surface gravity of white dwarfs ($\log g \sim 8$) leads to the efficient settling of heavy elements such as Ca and Mg; these elements should sink from view on time scales of the order of one or two weeks in DA stars (Koester & Wilken 2006). Thus, their observed presence (Zuckerman et al. 2003) is evidence for ongoing accretion, and this accretion is not necessarily expected to be uniform on the surface of the star. Recently, I have developed with collaborators a technique whereby the temperature variations associated with pulsations lead to an observable diagnostic of the surface metal distribution (Montgomery, Thompson, & von Hippel 2008a). Using archival data of the DAV G29-38 we found tentative evidence of an *equatorial* concentration of the heavy elements. In addition, we showed how variations in the total accretion rate could explain recent claims of time variability of the measured abundances of Ca and Mg (von Hippel & Thompson 2007) and how the variations in the observed abundances of two or more elements could lead to constraints on the relative settling rates of the various chemical species. The refinement and application of this method awaits future data sets.

Crystallization

Crystallization is associated with the release of latent heat (van Horn 1968); it provides an additional energy source for cooling white dwarfs, and can lengthen cooling ages by $\sim$ 1–2 Gyr (Winget et al. 1987); calibrating this effect can potentially remove one of the largest remaining uncertainties in the cooling physics of white dwarfs and their subsequent use as Galactic chronometers.

As white dwarfs cool, theory (e.g., Salpeter 1961) predicts that they will eventually begin crystallizing in their cores. The point at which a plasma crystallizes is described by the parameter Γ, which is the ratio of the average Coulomb energy of nearby ions to their average kinetic energy; crystallization is believed to occur when Γ reaches a given value, which traditionally is $\Gamma \approx 175$, independent of composition (e.g., Potekhin & Chabrier 2000). However, recent molecular dynamics simulations of material with a composition representative of neutron star crusts (Horowitz et al. 2007) have found $\Gamma \approx 240$. In an effort to resolve this discrepancy I will repeat these calculations for compositions typical of white dwarf interiors.

Asteroseismology offers another important avenue for investigation of this effect. Massive white dwarfs ($M_\star \gtrsim 1.0 M_\odot$) should begin crystallizing at temperatures hot enough to place them in the DAV instability strip. The pulsating white dwarf BPM 37093 is such a candidate ($M_\star \sim 1.1 M_\odot$) — theoretical models say it should be between 50% and 90% crystallized by mass (Winget et al. 1997). We have solved the theoretical problem of how the pulsations are affected by the presence of a crystallized core (Montgomery & Winget 1999) and have fit preliminary models to the observed pulsations of this star (e.g., Metcalfe, Montgomery, & Kanaan 2004, 2005); these fits indicated that the star is substantially crystallized, although obtaining a unique value of the crystallized mass fraction was not possible. I have since realized that using a realistic carbon/oxygen profile (e.g., Salaris et al. 1997) is crucial for removing this degeneracy and I have begun a new analysis. From the Sloan Digital Sky Survey (SDSS) we now know of approximately five such massive, potentially pulsating white dwarfs. Asteroseismology of these stars, together with BPM 37093, will provide us with the first empirical test of the theory of crystallization in dense stellar plasmas.

Additional Interests

I have also worked on many other topics, including but not limited to 1) measuring axion (Bischoff-Kim, Montgomery, & Winget 2008) and neutrino (Winget et al. 2004) emission from white dwarfs, 2) the effect of starspots on the pulsations of Ap stars (Montgomery & Gough 2003), 3) the effect of different convective prescriptions on mode driving in Delta Scuti stars (Montgomery 2000), and 4) comparing a Reynolds Stress model of convection to numerical simulations of convection in A-star envelopes (Kupka & Montgomery 2002). In addition, I am a member of the Kepler Asteroseismic Science Consortium (KASC), which will perform asteroseismic analysis of selected targets within the *Kepler* field of view. I have also written a "Perspective" for *Science* magazine on some of the early results from the CoRoT mission on solar-like stars (Montgomery 2008).

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