1. Background

White dwarf stars represent the evolutionary endpoint for $\sim$ 98% of all stars. Thus, by studying their internal structure we can place constraints on the prior stages of stellar evolution which stars of up to 8 $M_\odot$ undergo. We are aided in this study by the fact that they are in some sense "simple" objects: the bulk of the star is supported by electron degeneracy pressure, so their mechanical structure is effectively decoupled from their thermal structure, making calculations of their cooling rates easier. These cooling rates do not depend on uncertainties in nuclear reaction rates or other unconstrained mixing processes that are present in the evolutionary calculations of Main Sequence stars. Indeed, the original estimates based on white dwarf cooling for the age of the Galactic disk were $\sim$ 9 Gyr (Winget et al. 1987; Wood 1992) at a time when the ages of the oldest globular clusters were thought to be $\sim$ 18 Gyr. Since then, the ages based on Main Sequence isochrones have been revised downward, while those based on white dwarf cooling have remained fairly constant (e.g., Wood & Oswalt 1998).

In addition to their simplified internal structure, white dwarf stars have one additional aspect which makes them ideal astrophysical laboratories for testing fundamental physics: they have two distinct temperature ranges ("instability strips") in which they pulsate. Since these stars are typically complex pulsators with many modes simultaneously present, we are able to use asteroseismology to study their interior structure in a way that is not possible for one- and two-mode pulsators such as the Cepheids or RR Lyrae stars.

2. White Dwarfs as Astrophysical Laboratories

Empirical Determinations of Convection

We 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 depth of the convection zone as a function of time (Montgomery 2005). 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). While we have analyzed only two stars to date, we find that MLT gives a reasonable characterization of the depth of the convection zone *if* the value of the mixing length ("α") is precisely adjusted. We are currently carrying out an NSF-funded program of observing and analyzing pulsating white dwarfs across both instability strips. This will allow us to empirically map how the depth of the convection zone varies as a function of $T_{\rm eff}$ and $\log g$, thus constraining the physics of turbulent heat transport in these objects. This data can be used to test hydrodynamical simulations of the convection zones of these stars as well as more fundamental approaches to the theory of convection (Canuto & Dubovikov 1998; Kupka & Montgomery 2002; Montgomery & Kupka 2004).

Neutrino Physics

Due to their dense and hot cores, white dwarf stars should produce large amounts of neutrinos. In fact, calculations show that the neutrino luminosity of these objects should exceed their photon luminosities for $T_{\rm eff} \gtrsim 25{,}000$ K (Winget et al. 2004). While the theoretical neutrino rates are solidly based on the standard model of particle physics (Itoh et al. 1996), it is nevertheless fortunate that white

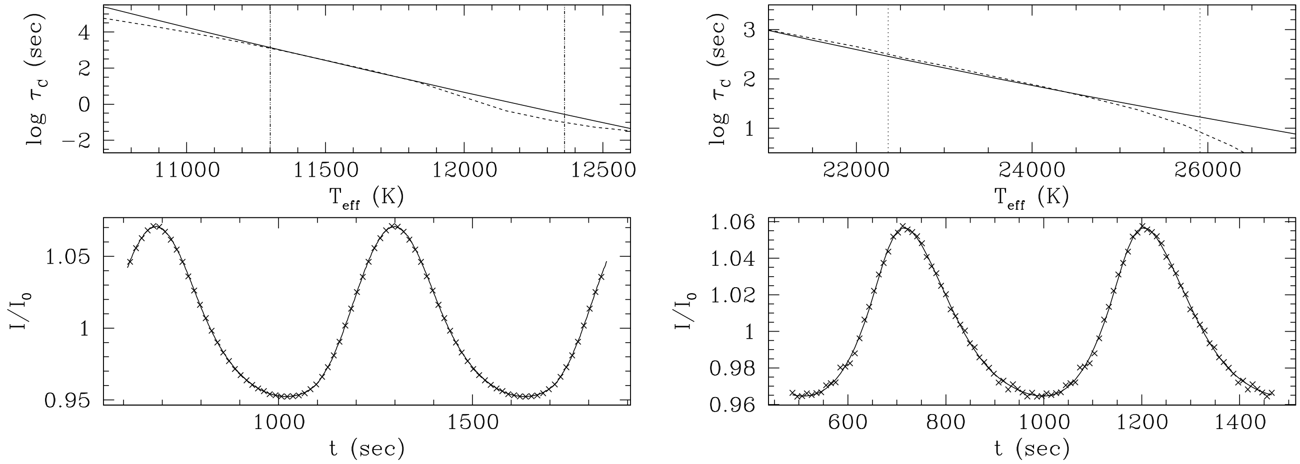

Fig. 1.— Fits to observed nonlinear light curves of two pulsating white dwarfs (left: G29-38, right: PG1351+489). The data are shown as crosses in the lower panels and the fits as the solid curve. In the upper panels we show the derived temperature dependence of the thermal timescale of the convection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

dwarf stars offer us the opportunity to empirically test these rates. This occurs because as a white dwarf cools, the period of a given pulsation mode slowly changes. While these changes in period are small, the accumulated phase shift over a long time baseline is detectable (see Fig. 2), which allows us to determine the rate of period change of the mode, $\dot{P}$. Since $\dot{P}$ is directly related to how fast the star is cooling, and since the neutrino losses directly affect the cooling rate of the star, we can compare the observed value of $\dot{P}$ to that derived from theoretical models to see if this is consistent with the standard rates. This research is NSF-funded and involves the graduate student Agnes Kim at UT-Austin whom I am co-supervising (Kim, Winget, & Montgomery 2005).

Crystallization

As white dwarfs cool, theory (e.g., Salpeter 1961) predicts that they will eventually begin crystallizing in their cores. The more massive the white dwarf, the hotter the temperature at which this process occurs. Most white dwarfs have masses of $\sim 0.6 M_{\odot}$ and begin crystallizing well after they have ceased pulsating. However, for more massive white dwarfs, models predict that crystallization can occur while the star is still in the instability strip. Several years ago, we realized that the pulsating white dwarf BPM 37093 was just such a candidate ($M_{\star} \sim 1.1 M_{\odot}$), and should be between 50% and 90% crystallized by mass (Winget et al. 1997). We have since solved the theoretical problem of how the pulsations should be affected by the presence of a crystallized core (Montgomery & Winget 1999), and we are now at the stage of fitting models to the observed pulsations of this star (Metcalfe, Montgomery, & Kanaan 2004, 2005). While only one such massive, pulsating white dwarf is currently known, we estimate that the Sloan Digital Sky Survey (SDSS) should provide us with at least ten more such stars. This will provide us with the first empirical test of the theory of crystallization in dense stellar plasmas. Since crystallization is associated with the release of latent heat, 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

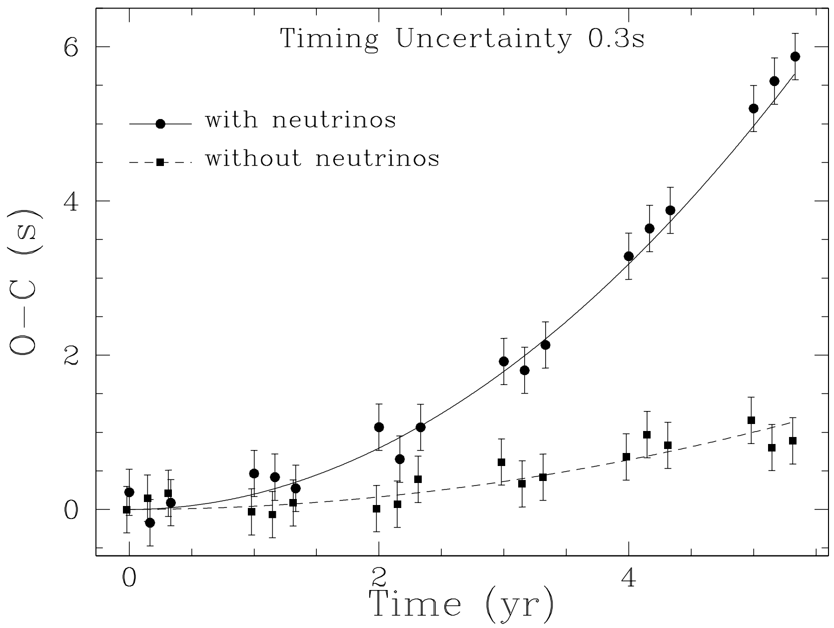

Fig. 2.— Simulated effect of neutrinos on the drift in phase of a DBV pulsator. As the star cools, the period of pulsation increases slowly, and pulsations arrive later than would be expected for constant period. The points are simulated data points with a scatter of 0.3 s consistent with what we expect from DBVs brighter than 18th magnitude. With this scatter in our observations we can distinguish between neutrino dominated cooling and no neutrinos in 3 years.

white dwarfs and their subsequent use as Galactic chronometers.

A non-local model of convection

To date, Fritz Kupka and I have produced the only successful numerical implementation of the non-local convection formalism of Canuto & Dubovikov (1998) in a stellar environment. Our work has focused on A-stars (Kupka & Montgomery 2002) and white dwarfs (Montgomery & Kupka 2004), since these should have relatively thin surface convection zones, making them easier to model. One important success of this model is that, with a *fixed* set of parameters, it is able to give reasonable results (compared to hydrodynamic simulations as well as some observational data) for both the A-stars ($\log g \sim 4.4$, $T_{\rm eff} \sim 8000$ K) *and* the white dwarfs ($\log g \sim 8.0$, $T_{\rm eff} \sim 12500$ K). In order for MLT to reproduce the peak fluxes, the α parameter needs to be adjusted from ~ 0.4 for the A-stars to ~ 1.7 for the white dwarfs, which effectively removes any predictive power of the theory. In addition, no value of α comes close to reproducing the velocity fields seen in the numerical simulations, while our non-local model does a reasonable job (Steffen, Freytag, & Ludwig 2005).

We are at present extending our code so that we will be able to treat stars with thicker and deeper convection zones. This will allow us to model the overshoot in the convective cores of massive stars as well as the envelope convection zone of the Sun; the convection zone of the Sun is well-constrained by helioseismology and would provide a stringent test of the theory. Eventually, we would like to make a version of this convection prescription available to the community as a callable routine, so that it could be included in stellar evolution codes, acting as a replacement for the current MLT prescription.

3. Observations

While my primary training is as a theorist, I have made observations in support of many of the projects described above, including the convection/light curve fitting and neutrino rate projects, as well as a project here at UT-Austin to search for planets around white dwarfs by looking at the pulse arrival time residuals (Mullally et al. 2003). Although white dwarfs are "faint" stars, they are bright in extragalactic terms, having V magnitudes between about 13 and 20. Thus, much of this science can be done with small to medium-sized telescopes. For instance, the majority of this work has been done with the Argos instrument at prime focus of the 2.1m telescope at McDonald, and this work would be completely suited to the capabilities of the ARC 3.5m telescope at Apache Point. In fact, observations of pulsating white dwarfs using SPIcam on the ARC 3.5m have been shown to be of excellent quality (Nitta et al. 2004). In addition, with the NIC-FPS instrument on the ARC telescope it is possible to look for infrared excess around white dwarfs, which can either be a sign of planets or a dusty disk (Kilic et al. 2005). Finally, the spectra (especially in the infrared) of the coolest and oldest white dwarfs (and therefore the ones most useful for deriving ages for the Galactic disk) show dramatic discrepancies with the models (Bergeron & Leggett 2002). Infrared spectra have been taken for only a handful of white dwarfs, and I am interested in obtaining more observations to examine in detail the way in which the spectra and the model atmosphere fits differ, with an eye to improving the physics in the model atmospheres.

4. REFERENCES

Bergeron, P., & Leggett, S. K., "*Model Atmosphere Analysis of Two Very Cool White Dwarfs,*" 2002, ApJ, 580, 1070

Canuto, V. M., & Dubovikov, M., "*Stellar Turbulent Convection. I. Theory,*" 1998, ApJ, 493, 834

Itoh, N., Hayashi, H., Nishikawa, A., & Kohyama, Y., "*Neutrino Energy Loss in Stellar Interiors. VII. Pair, Photo-, Plasma, Bremsstrahlung, and Recombination Neutrino Processes,*" 1996, ApJS, 102, 411

Kilic, M., von Hippel, T., Leggett, S. K., & Winget, D. E., "*Excess Infrared Radiation from the Massive DAZ White Dwarf GD 362: A Debris Disk?,*" 2005, ApJ, 632, L115

Kim, A., Winget, D. E., & Montgomery, M. H., "*Exploring Uncharted Territory in Particle Physics Using Pulsating White Dwarfs: Prospects,*" 2005, in Proceedings of the 14th European Workshop on White Dwarfs, ed. D. Koester & S. Moehler (San Francisco: ASP), 489

Kupka, F., & Montgomery, M. H., "*A-star Envelopes: a Test of Local and Non-local Models of Convection,*" 2002, MNRAS, 330, L6

Metcalfe, T. S., Montgomery, M. H., & Kanaan, A., "*Testing White Dwarf Crystallization Theory with Asteroseismology of the Massive Pulsating DA Star BPM 37093,*" 2004, ApJ, 605, L133

Metcalfe, T. S., Montgomery, M. H., & Kanaan, A., "*The Crystal Method: Asteroseismology of BPM 37093,*" 2005, in Proceedings of the 14th European Workshop on White Dwarfs, ed. D. Koester & S. Moehler (San Francisco: ASP), 465

Montgomery, M. H., "*A New Technique for Probing Convection in Pulsating White Dwarf Stars,*" 2005, ApJ, 633, 1142

Montgomery, M. H., & Kupka, F., "*White Dwarf Envelopes: Further Results of a Non-local Model of Convection,*" 2004, MNRAS, 350, 267

Montgomery, M. H., & Winget, D. E., "*The Pulsations of Crystallizing White Dwarf Stars,*" 1999, in ASP Conference Series 169: Proceedings of the 11th European Workshop on White Dwarfs, ed. J.-E. Solheim & E. G. Meištas (San Francisco: ASP), 133

Mullally, F., Mukadam, A., Winget, D. E., Nather, R. E., & Kepler, S. O., "*The Search for Planets around Pulsating White Dwarf Stars,*" 2003, in NATO ASIB Proc. 105: White Dwarfs, 337

Nitta, A., Kleinman, S. J., Krzesinski, J., Mukadam, A. S., Mullally, F., Nather, R. E., Thompson, S. E., Sullivan, D. J., & Winget, D. E., "*New White Dwarf Pulsators from the Sloan Digital Sky Survey,*" 2004, Bulletin of the American Astronomical Society, 205

Salpeter, E. E., "*Energy and Pressure of a Zero-Temperature Plasma.,*" 1961, ApJ, 134, 669

Steffen, M., Freytag, B., & Ludwig, H.-G., "*3D Simulation of Convection and Spectral Line Formation in A-type Stars,*" 2005, in Proc. 13th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ed. F. Favata, G. A. J. Hussain, & B. Battrick. ESA Publications, (astro-ph/0509464)

Winget, D. E., Hansen, C. J., Liebert, J., Van Horn, H. M., Fontaine, G., Nather, R. E., Kepler, S. O., & Lamb, D. Q., "*An Independent Method for Determining the Age of the Universe,*" 1987, ApJ, 315, L77

Winget, D. E., Kepler, S. O., Kanaan, A., Montgomery, M. H., & Giovannini, O., "*An Empirical Test of the Theory of Crystallization in Stellar Interiors,*" 1997, ApJ, 487, L191

Winget, D. E., Sullivan, D. J., Metcalfe, T. S., Kawaler, S. D., & Montgomery, M. H., "*A Strong Test of Electroweak Theory Using Pulsating DB White Dwarf Stars as Plasmon Neutrino Detectors,*" 2004, ApJ, 602, L109

Wood, M. A., "*Constraints on the Age and Evolution of the Galaxy from the White Dwarf Luminosity Function,*" 1992, ApJ, 386, 539

Wood, M. A., & Oswalt, T. D., "*White Dwarf Cosmochronometry. I. Monte Carlo Simulations of Proper-Motion- and Magnitude-limited Samples Using Schmidt's 1/V max Estimator,*" 1998, ApJ, 497, 870

Summary of Teaching Experience

- Gave a Graduate Student Lecture course (8 lectures) at the Institute of Astronomy on star formation (4 lectures) and on stellar pulsation (4 lectures) [Spring 2002 and 2004]
- Substituted for Douglas Gough for the final four lectures of Part I Mathematics (differential equations) at the University of Cambridge [Fall 2002]
- Gave two talks to amateur astronomers at the Alston Hall Amateur Astronomy Retreat, on stellar evolution and stellar pulsation, respectively [Spring 2001]
- Taught an introductory course on solar system astronomy for undergraduates at Austin Community College [Spring 1997]
- Teaching assistant for courses at the University of Texas at Austin, including introductory astronomy for scientists, self-paced astronomy, extraterrestrial life, stellar evolution, and the astronomy of exotic objects (black holes, neutron stars, white dwarfs, cataclysmic variables . . .) [1992–1995]
- Teaching assistant at Princeton University for freshman physics labs: mechanics, optics, and electro-magnetism [1991–1992]

Teaching Interests

My interest in teaching has led me to teach several courses which were in addition to my regularly required work and duties. As listed above, I taught an undergraduate course in solar system astronomy at Austin Community College in the Spring of 1997, and in the Spring of 2002 I gave a graduate course at the University of Cambridge on star formation and stellar pulsation, which I repeated in the Spring of 2004. Since my research is focused on stars and the physical processes of their interiors, I am comfortable teaching courses involving stellar evolution or stellar interiors. In addition, I enjoy learning about and teaching subjects which lie outside of my research, such as the course on star formation mentioned above. Finally, since I also have degrees in physics (B.S. and M.A.), I am interested in teaching courses involving mechanics, electromagnetism, thermodynamics and statistical mechanics, and quantum mechanics.

In addition to the everyday duties of teaching such as evaluating students through tests and homework, I believe it is a teacher's job to present the material in as coherent, lucid, and simple a way as possible. This means placing the subject matter in a clear context, so that new concepts do not appear to be disconnected from what has come earlier in the course. I think a valid question should always be "why are we talking about this?" Additionally, an indispensable aid in teaching is enthusiasm, in the form of an intrinsic interest in the subject matter, the teaching process, and the students themselves. Finally, in order for everything to function optimally, there needs to be direct interaction between the students and teacher so that the most effective means of communicating and explaining ideas can be found. These are the basic goals and objectives which I keep in mind when teaching a subject.