A deeper understanding of white dwarf interiors

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ABSTRACT

A detailed record of the physical processes that operate during post-main-sequence evolution is contained in the internal chemical structure of white dwarfs. Global pulsations allow us to probe the stellar interior through asteroseismology, revealing the signatures of prior nuclear burning, mixing, and diffusion in these stars. I review the rapid evolution of structural models for helium-atmosphere variable (DBV) white dwarfs over the past five years, and I present a new series of model-fits using recent observations to illustrate the relative importance of various interior structures. By incorporating physically motivated C/O profiles into double-layered envelope models for the first time, I finally identify an optimal asteroseismic model that agrees with both diffusion theory and the expected nuclear burning history of the progenitor. I discuss the implications of this fundamental result, and I evaluate the prospects for continued progress in the future.

Key words: stars: evolution – stars: interiors – stars: oscillations – white dwarfs

1 INTRODUCTION

The internal structure of a white dwarf star contains a detailed record of the physical processes that operate during post-main-sequence evolution. The composition of the deep interior is determined by the nuclear reaction rates during core helium burning in the red giant progenitor, while the chemical profile in the outer core is set by helium shell burning and various mixing processes including convective overshoot. More than 99% of the mass in a typical white dwarf is contained in the C/O core, which is embedded in an envelope of C, He, and H with traces of heavier elements. Near the end of post-AGB evolution the white dwarf envelope can become uniformly mixed during a very late thermal pulse, which burns off most of the residual H and creates a born-again AGB star [Iben et al. 1983]. As this newly formed H-deficient star begins to descend the white dwarf cooling track, the high surface gravity (log $g \sim 8$) coupled with chemical and thermal diffusion leads to compositional stratification. The lighter elements float to the surface, slowly building a nearly pure surface He layer above the remainder of the envelope as the star cools.

Asteroseismology is the only observational method available to probe the interior structure of white dwarfs and calibrate theories of nuclear burning, mixing, and diffusion in these stars. The helium-atmosphere (DB) white dwarfs are particularly suitable for asteroseismic study, since they are observed to pulsate in a range of effective temperatures between 22,400 and 28,400 K [Beauchamp et al. 1999]. The mass of the pure He surface layer is predicted to grow by roughly an order of magnitude within this range, so an asteroseismic calibration of diffusion theory is possible by studying DB variables (DBVs) at various temperatures [Dehner & Kawaler 1995; Fontaine & Brassard 2002; Althaus & Còrsico 2004; Metcalfe et al. 2005]. Unlike the hotter class of variable white dwarfs (the PG 1159 stars) DBVs do not experience significant gravitational contraction, which simplifies the asteroseismic analysis since the mechanical and thermal structure are decoupled [Winget et al. 2004]. The cooler hydrogen-atmosphere variables (DAVs) also enjoy this advantage, but their cores are significantly more degenerate—reducing the influence of the deep interior structure on their pulsation periods.

Despite their extraordinary potential, only two DBV white dwarfs have been sufficiently characterized to allow detailed asteroseismic study. The brightest member of the class, GD 358, has been the target of three multi-site observing campaigns of the Whole Earth Telescope (WET; Nather et al. 1990; Winget et al. 1994; Vuille et al. 2000; Kepler et al. 2003). These data revealed a series of 11 dipole modes ($\ell=1$, $m=0$; Kotak et al. 2003) of consecutive radial overtone ($k=8$-18; Bradley & Winget 1994) that could be used for model-fitting. Prior to the Sloan Digital Sky Survey (SDSS; Nitta et al. 2005) the faintest member of the class was CBS 114, which was first subjected to detailed study by Handler et al. [2002]. A recent dual-site campaign on this star by Metcalfe et al. (2005) documented a total of 11 dipole modes with radial overtones ranging from $k=8$ to $k=20$.

In the following section, I review the recent development of detailed structural models for DBV white dwarfs with an emphasis on the published models for GD 358 over the past five years. I then present a series of new model-fits to the latest observations of CBS 114 in Section 3 to illustrate the relative importance of the various interior structures expected from stellar evolution theory. The final fit in this series represents the first successful application of a model containing a complete, physically motivated description of the white dwarf interior. Finally in Section 4 I discuss the impli-
cations of this result for theories of diffusion and nuclear burning, and I evaluate the prospects for future progress.

2 MODEL DEVELOPMENT

Although detailed observations of the DBV white dwarf GD 358 have been available since 1994, the realization of their full potential had to wait for the large-scale exploration of models made possible by fast, inexpensive computers. The original analysis by Bradley & Winget (1994) attempted to match the observed pulsation periods using a small grid of models around an initial guess based on general scaling arguments and analytical relations developed by Kawaler (1992), Kawaler & Weiss (1991), Brassard et al. (1992), and Bradley et al. (1993). The main physical parameters that were adjusted to fit the models to the data included the stellar mass ($M_*$), the effective temperature ($T_\text{eff}$), the mass of the surface He layer ($M_{\text{He}}$), and several fixed core profiles including uniform and variable C/O mixtures. The best-fit model from this analysis matched the observed periods with a precision of $\sigma_\tau = 2.69$ s, but had a surface He layer ($M_{\text{He}} \sim 10^{-5}$) that was thinner than expected from stellar evolution theory ($M_{\text{He}} \sim 10^{-3}$; Danti & Mazzitelli 1973). This pioneering work guided the development of a new model-fitting method based on a parallel genetic algorithm (Metcalf et al. 2003) running on a 64-node commodity-hardware Linux cluster (Metcalf & Nather 2000). Using essentially the same models as Bradley & Winget (2000) had the genetic algorithm explore a much broader range of the three main parameters ($M_*, T_\text{eff}, M_{\text{He}}$) with a similar set of fixed core profiles. This innovative search revealed a second family of solutions with the expected thick surface He layers, outside of the range considered by the original study, which provided a considerably better match to the observations ($\sigma_\tau = 1.50$ s). The results also demonstrated that the models were much more sensitive to the core composition than was previously believed. The conventional wisdom held that g-mode pulsations in white dwarf stars were primarily envelope modes. While it is true that the horizontal displacements in the envelope from the non-radial oscillations are so large that they make the motions in the core almost invisible, the inner 90% of the mass actually contains the first several nodes of the radial eigenfunction for the pulsations observed in DBV stars.

Motivated by this newly-discovered sensitivity to the core composition, Metcalfe et al. (2001) extended the genetic algorithm fitting method to optimize two additional parameters describing a generic C/O profile. The adjustable central oxygen mass fraction ($X_0$) was fixed to a constant value out to some fractional mass ($q$) where it then decreased linearly in mass to zero oxygen at 0.95 $M_*/M_*$. The optimization of these five parameters led to a model that matched the observations with a precision of $\sigma_\tau = 1.28$ s, representing a substantial improvement over the best strictly 3-parameter model ($\sigma_\tau = 2.30$ s). From this first asteroseismic measurement of $X_0$, Metcalfe et al. (2001) attempted to constrain the rate of the astrophysically important $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ nuclear reaction, extrapolating from the published chemical profiles of Salaris et al. (1997). A follow-up study by Metcalfe et al. (2002) quantified many possible sources of systematic error in this measurement, but failed to identify any that were substantially larger than the statistical errors. However, persistent disagreement between the derived values of $T_\text{eff}$ and $M_*$ and the spectroscopic estimates suggested room for improvement in the model.

Fontaine & Brassard (2002) disputed the results of Metcalfe et al. (2001), arguing that the model envelopes should include a double-layered structure. If we assume that DBV white dwarfs are the evolutionary descendants of the hotter PG 1159 stars, then the surface He layer should be only $M_{\text{He}} \sim 10^{-6} M_*$, situated above the still-uniform envelope ($M_{\text{env}} \sim 10^{-2} M_*$). This could explain the two families of solutions for $M_{\text{He}}$ found by Metcalfe et al. (2000) when assuming a single-layered structure.

To illustrate the potential of double-layered envelope models, Fontaine & Brassard attempted to match the pulsation periods of GD 358 with a targeted grid. Using several uniform core compositions, they adjusted four parameters ($M_*, T_\text{eff}, M_{\text{env}}, M_{\text{He}}$) and found a best-fit model with $\sigma_\tau = 1.30$ s. This suggested that double-layered envelope models with no structure in the core could explain the observations of GD 358 nearly as well as the single-layered models of Metcalfe et al. (2001) which had an adjustable C/O profile in the core.

Around the same time, Metcalfe (2003) identified two large sources of systematic error in the determination of $X_0$. Previous fitting had attempted to match not only the periods, but also the forward period spacing ($\Delta P = P_{k+1} - P_k$) simultaneously. Ironically, this was intended to minimize the impact of systematic errors on the calculated periods, but it biased the determinations of $X_0$ to be higher. A second bias in the same direction came from fixing the mixing-length/pressure scale height ratio too high, leading to overly efficient convection that modified the thermal structure of the models. By matching only the periods and using the $\text{ML}_2/\alpha = 1.25$ prescription for convection (Böhm & Cassinelli 1971; Beauchamp et al. 1999), the 5-parameter single-layered envelope fit for GD 358 improved to $\sigma_\tau = 1.05$ s and the derived value of $X_0$ suggested a $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate that was consistent with laboratory measurements (Angulo et al. 1998).

It finally became clear that neither of these models represented an adequate description of the white dwarf structure when Montgomery et al. (2003) identified an inherent symmetry in the way the pulsations sample the interior of DBV models. They found that generic perturbations caused by structure at specific locations in the core could not be distinguished from structure at corresponding locations in the envelope. This core-envelope symmetry could produce confusion between a C/O gradient near 0.5 $M_*/M_*$ from prior nuclear burning, and the base of the surface He layer in the outer $10^{-6} M_*$ from diffusion. However, by using realistic internal chemical profiles in both regions of the models, they determined the relative importance of the structures expected at various locations. This led them to conclude that the deep interior core structure should leave the largest imprint on the observed periods, while the base of the surface He layer was expected to have the smallest influence. The total envelope mass was less important than the core structure, but had a larger effect than the outermost layer.

To investigate whether the structure in the core and envelope could be measured simultaneously, Metcalfe et al. (2003) modified their models to include a parameterization of the double-layered envelopes used by Fontaine & Brassard (2002). They performed 4-parameter fits comparable to those of Fontaine & Brassard, as well as 6-parameter fits that also included an adjustable C/O profile. Although the addition of core structure led to a significant improvement, neither fit reached the level of precision attained by using single-layered envelope models, and the disagreement with the spectroscopic estimates of $T_\text{eff}$ and $M_*$ became even worse. However, by fitting the periods of the model from Fontaine & Brassard (2002), Metcalfe et al. discovered a systematic offset in the temper-
nature scales that could be attributed to the different radiative opacities used in the two models (Fontaine & Brassard 1999).

Confronted with so many fitting results for one set of observations—some of them from models with very different interior structures—a casual observer might lose all confidence in our ability to do asteroseismology. Ultimately this is a symptom of the fact that we are confined to forward modeling: we adopt a structural model and see how closely it can match the observations. We can inform this choice with theoretical expectations, but we will always find an optimal model—even when the model is incomplete. The results from an incomplete model are not meaningless; they provide clues that help us identify the missing ingredients. The two families of solutions for the surface He layer in single-layered models told us that the real star showed evidence of composition transition zones at two locations in the envelope. The systematic differences between the derived masses and effective temperatures compared to spectroscopic estimates hinted that we needed to update the constitutive physics. How closely we can match the observations with each of the incomplete models gives us insight about which structural ingredients are the most important.

3 NEW MODEL-FITTING RESULTS

Recent observations of CBS 114 by Metcalfe et al. (2005) finally give us an opportunity to evaluate the models reliably on a second DBV white dwarf. If we fit these new data using each of the models use the updated OPAL opacity tables (Iglesias & Rogers 1996), neutrino rates from Itoh et al. (1996), and the mixing-length prescription of Böhm & Cassinelli (1971), with ML2/σ = 1.25 convective efficiency as suggested by Beauchamp et al. (1999).

The new set of optimal models for CBS 114 are listed in Table 1. In each case, a model-fitting method based on a parallel genetic algorithm was used to search a broad range for each parameter and optimize the match between the observed and calculated periods. The range for each parameter and the details of the model-fitting procedure have been described by Metcalfe et al. (2000) for $N_p = 3$, Metcalfe et al. (2001) for $N_p = 5$, and Metcalfe et al. (2003) for $N_p = 4$ and $N_p = 6$.

Beyond the basic stellar parameters ($T_{eff}, M_\star$), the simplest of the models ($N_p = 3$) includes an adjustable mass for a single surface layer situated above a pure C core. The derived value of $T_{eff}$ falls comfortably within the range determined from spectroscopy ($T_{eff} = 23,300-26,200$ K, log $g = 7.98-8.00$) [Beauchamp et al. 1999], but the derived mass (log $g \sim 8.12$) is significantly above the spectroscopic estimate. Despite the many simplifications inherent in this model, the derived envelope mass is in the range expected from stellar evolution theory (Pantano & Mazzitelli 1979). As with GD 358, a second family of models with envelope masses near $10^{-6} M_\odot$ produce better than average fits to the observations of CBS 114, suggesting that double-layered models might be more appropriate (see Fig. 1).

The optimal parameters for the double-layered envelope model ($N_p = 4$) include values of $T_{eff}$ and $M_\star$ that are both consistent with the spectroscopic estimates, but the slight improvement to the fit is not significant. According to the Bayes Information Criterion (BIC; see Montgomery et al. 2001), the addition of one adjustable parameter to the fit should reduce the residuals from $\sigma_P = 2.44$ s for $N_p = 3$ to $\sigma_P = 2.19$ s for $N_p = 4$. The actual fit yields $\sigma_P = 2.33$ s for $N_p = 4$, which is statistically worse than the single-layered fit. In the absence of core structure, single-layered envelope models provide a statistically better match to the observations of CBS 114 than double-layered envelope models. Similar results were obtained for GD 358, where the double-layered fit of Metcalfe et al. (2003) $\sigma_P = 2.17$ s was also statistically worse than the single-layered fit of Metcalfe et al. (2003) $\sigma_P = 2.30$ s for pure C cores. Even so, the derived values of $M_{env}$ and $M_{fid}$ from both stars qualitatively agree with the expectations of diffusion theory (Metcalfe et al. 2005), suggesting that the double-layered fits might be measuring real structure even if the models are incomplete.

Table 1. New model-fitting results for CBS 114.

| $N_p$ | $T_{eff}$ (K) | $M_\star/M_\odot$ | log($M_{env}/M_\star$) | log($M_{fid}/M_\star$) | $X_0$ | $q$ | $\sigma_P$ (s) |
|-------|-------------|--------------------|------------------------|------------------------|------|----|---------------|
| 3     | 25,300      | 0.675              | -2.80                  | ...                    | ...  | ... | 2.44          |
| 4     | 25,800      | 0.630              | -2.42                  | -5.96                  | ...  | ... | 2.33          |
| 5     | 23,800      | 0.690              | -2.85                  | ...                    | 0.93 | 0.47| 1.81          |
| $a$   | 25,200      | 0.625              | -2.40                  | -5.94                  | 0.91 | 0.42| 1.51          |
| $b$   | 24,900      | 0.640              | -2.48                  | -5.94                  | 0.71 | 0.38| 1.27          |

$^a$ Generic C/O profile from Metcalfe et al. (2001).

$^b$ Physically motivated C/O profile based on Salaris et al. (1997).
fit to $\sigma_T = 1.81$ s, a statistically significant reduction. However, the derived values of $T_{\text{eff}}$ and $M_*$ do not agree nearly as well with spectroscopic estimates, and the value of $X_0$ is difficult to reconcile with the expectations from prior nuclear burning. Again, similar results were found for GD 358 by Metcalfe et al. (2001). Despite these systematic errors, the derived values for $M_{\text{env}}$ from the two single-layered fits agree with each other, suggesting that thick envelopes are a qualitatively robust structural feature of the results.

For models that contain an adjustable C/O profile in the core, the inclusion of double-layered envelopes ($N_p = 6$) produces a significant improvement in the residuals, and restores the agreement with spectroscopic estimates of $T_{\text{eff}}$ and $M_*$. The residuals from the $N_p = 5$ fit should decrease from $\sigma_T = 1.81$ s to $\sigma_T = 1.62$ s from the addition of one adjustable parameter, but the $N_p = 6$ fit with a generic C/O profile actually decreases the residuals to $\sigma_T = 1.51$ s. This statistically significant improvement is accompanied by derived values of $M_{\text{env}}$ and $M_{\text{He}}$ that once again qualitatively agree with diffusion theory. The only remaining concern with this model is the implausibly large derived value of $X_0$.

This may not be too surprising, considering the simplistic form of the generic C/O profile compared to chemical profiles generated by realistic stellar evolution calculations. Although a constant value of $X_0$ out to some fractional mass ($q$) is a generic feature of such simulations (see Metcalfe et al. 2003, their Fig. 2), the O profile in the outer core is expected to be more complicated than a linear decrease. For example, the models of Salaris et al. (1997) show an initially sharp drop in the O mass fraction near the edge of the progenitor’s convective core, surrounded by a more gradual decline produced during He shell burning, followed by an abrupt drop where the temperature and pressure in the progenitor were no longer sufficient to sustain shell burning. A new implementation of the adjustable C/O profiles continues to keep $X_0$ constant out to some fractional mass $q$, but then falls to zero oxygen at $0.95 M_*/M_*$. with a more physically motivated shape. For $X_0 = 0.76$ and $q = 0.46$, the profile closely resembles the results of Salaris et al. (1997, their Fig. 3), and for any other values of $X_0$ and $q$ the profile is scaled to maintain a similar shape between $q$ and $0.95 M_*/M_*$. (see Fig. 2).

By incorporating these physically motivated C/O profiles into double-layered envelope models, the optimal parameters for CBS 114 lead to an interior structure that agrees with both diffusion theory and the expected nuclear burning history. Without adding any adjustable parameters, this modification to the C/O profile in the outer core reduces the residuals from $\sigma_T = 1.51$ s to $\sigma_T = 1.27$ s, an improvement comparable to what would be expected from 1.5 additional free parameters. The derived values of $T_{\text{eff}}$ and $M_*$ are in reasonable agreement with spectroscopic estimates, the structure of the envelope is approximately as expected from diffusion theory, and the core C/O profile implies a rate for the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction that agrees with recent laboratory measurements. We should ultimately be able to refine theories of diffusion and nuclear burning to accommodate these new observational constraints.

4 DISCUSSION

The past five years have seen unprecedented progress in the development of white dwarf interior structure models, and in our ability to fit them to the available observations. This rapid improvement in our understanding has been most evident for the DBV white dwarfs, where the physical conditions are ripe for asteroseismic investigation. Our models for these stars have evolved from a simple parameterization of a single surface He layer above a pure C core to the double-layered envelope structure expected from diffusion calculations surrounding a physically motivated C/O profile in the core. We have finally been able to demonstrate that these structural ingredients, when taken together, lead to significant improvements in our ability to match the observations of CBS 114.

It is now clear that the detailed core C/O profile is the most
important feature for quantitative asteroseismology of DBV white dwarfs. The most dramatic improvements in our ability to match the observations came from the addition of C/O cores, even when using relatively crude approximations for the structure in the envelope. The generic C/O profiles developed by Metcalfe et al. (2001) seemed to reproduce the most important asteroseismic features, but the physically motivated profiles introduced here appear to be necessary for a reliable determination of the composition deep in the core. Disentangling the roles of the $^{12}\text{C} (\alpha, \gamma)^{16}\text{O}$ reaction and mixing processes such as convective overshoot should be possible using the derived value of $\gamma$ from Straniero et al. (2003). New simulations of white dwarf interior chemical profiles that attempt to match the asteroseismic C/O profile will help to calibrate these processes.

Without a C/O profile, the double-layered envelope structure expected from diffusion actually diminishes the ability of the models to match the observations, compared to simpler envelopes. We can now understand this to be a natural outcome of the relative importance of various regions of the interior: C/O profiles leave the largest imprint on the pulsation periods, followed by the base of the envelope ($M_{\text{env}}$) and the surface layer ($M_{\text{He}}$). In the absence of core structure, models that maximize the imprint of $M_{\text{env}}$ provide better fits. Since double-layered models effectively split the He transition zone between two separate locations in the envelope, the imprint of $M_{\text{env}}$ is reduced relative to single-layered models. With the C/O core included, the fine tuning made possible by the double-layered models produces a significant improvement and leads to a credible envelope structure. Future time-dependent diffusion calculations should attempt to reproduce these asteroseismic measurements.

We can instill greater confidence in these results by applying our physically motivated structural models to additional white dwarf stars. Imposing the requirement that our model must be able to explain two independent sets of observations—from stars operating under slightly different physical conditions—is a very powerful constraint. Unfortunately, GD 358 may not be the best choice for such an experiment because the intrinsic core-envelope symmetry in this case appears to create an intractable ambiguity between the locations of the surface He layer and the core C/O profile, even when using physically motivated shapes for the chemical transitions. A better candidate might be found among DBV stars that are hotter than CBS 114 (e.g. EC 20058–5234) or cooler than GD 358 (e.g. PG 1456+103). Many new DBV stars have recently been identified in the Sloan Digital Sky Survey (Nitta et al. 2005), but most of them are considerably fainter than the previously known sample. Extensive follow-up observations to identify the most promising multi-mode pulsators will require 2-m class telescopes equipped with time-series optimized frame-transfer CCD cameras (Nather & Mukadam 2004). With the computational tools in place, we should quickly be able to refine our understanding of the forces that shape white dwarf interiors.

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