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An asteroseismic test of diffusion theory

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Abstract. The helium-atmosphere (DB) white dwarfs are commonly thought to be the descendants of the hotter PG 1159 stars, which initially have uniform He/C/O atmospheres. In this evolutionary scenario, diffusion builds a pure He surface layer which gradually thickens as the star cools. In the temperature range of the pulsating DB white dwarfs ($T_{\rm eff} \sim 25,000$ K) this transformation is still taking place, allowing asteroseismic tests of the theory. Objective global fitting of our updated double-layered envelope models to recent observations of the pulsating DB star CBS 114, and to existing observations of the slightly cooler star GD 358, lead to determinations of the envelope masses and pure He surface layers that qualitatively agree with the expectations of diffusion theory. These results provide new asteroseismic evidence supporting one of the central assumptions of spectral evolution theory, linking the DB white dwarfs to PG 1159 stars.

Key words. Stars: evolution – Stars: interiors – Stars: oscillations – white dwarfs

1. Introduction

In January 2002, the star V838 Mon suddenly became 600,000 times more luminous than our Sun, sending a spectacular echo of light through the surrounding interstellar medium (Bond et al., 2004). One model for this event suggested that we were witnessing a Very Late Thermal Pulse (VLTP), leading to the creation of a born-again AGB star (Lawlor, 2005). I don't know if this is the correct model for V838 Mon, but in this paper I will discuss the born-again phenomenon, and how it relates to the evolution of H-deficient post-AGB stars, diffusion theory, and asteroseismology.

2. Theoretical Background

2.1. Post-AGB Evolution

As post-asymptotic-giant-branch (post-AGB) stars begin to descend the white dwarf cooling track, about 20% will experience a Very Late Thermal Pulse (VLTP; Iben et al., 1983). In the process, most of the residual H in the envelope will be burned, but traces ($\sim 10^{-11}\ M_*$) are expected to remain (Herwig et al., 1999). The VLTP also forces the outer $\sim\ 10^{-2}\ M_*$ to become a uniform mixture of the remaining elements, mostly He, C, and O. The resulting H-deficient object becomes a born-again AGB star, and then continues its evolution as a hot DO white dwarf, or PG 1159 star.

2.2. Spectral Evolution

According to the spectral evolution theory of Fontaine & Wesemael (1987, 1997), DO stars are the progenitors of the cooler DB white dwarfs. The primary difficulty with this scenario is the paucity of non-DA stars with effective temperatures between 45,000 K and 30,000 K, the so-called "DB gap" (Liebert

Table 1. Optimal model parameters for CBS 114 and GD 358

Parameter	CBS 114	GD 358	Uncertainty
$T_{\rm eff}$ (K)	25 800	23 100	±100
M_* ($M_\odot$)	0.630	0.630	±0.005
$\log(M_{\rm env}/M_*)$ . . .	−2.42	−2.92	±0.02
$\log(M_{\rm He}/M_*)$ . . .	−5.96	−5.90	±0.02
$\sigma_{\rm P}$ (s)	2.33	2.26	· · ·

et al., 1986). If there is an evolutionary connection between the hot DO stars and the cooler DB white dwarfs, how do we explain the missing H-deficient objects at intermediate temperatures? The proposed answer is that as a DO star cools, the small traces of H left over from the VLTP float to the surface through diffusion. By the time it reaches 45,000 K this surface H layer is thick enough to disguise the star as a DA white dwarf. Inside the DB gap it continues to cool as an apparent DA until a growing He convection zone eventually dilutes the thin surface H layer, and at 30,000 K the star reveals itself to be a DB. A possible relative overabundance of DA stars inside the DB gap supports this hypothesis (see Kleinman et al., 2004, their Fig. 11), though other problems with the theory may still remain (Provencal et al., 2000).

2.3. Diffusion Theory

If we assume that there is an evolutionary connection between DO stars and DB white dwarfs, we can ask: how do the envelopes of DB stars evolve? Several groups have investigated this question, and they all find that diffusion slowly builds a pure He surface layer above the initially-uniform envelopes of DO stars, creating a characteristic double-layered structure (Dehner & Kawaler, 1995; Fontaine & Brassard, 2002; Althaus & Córsico, 2004). Such models lead to a specific prediction: at a given mass, *hotter* DB stars should have *thinner* surface He layers.

3. Observations

Fortunately, the DB stars pulsate in a range of temperatures just below the DB gap, allowing an asteroseismic test of this prediction. The two most extensively studied DB variables are GD 358 (Winget et al., 1994; Vuille et al., 2000; Kepler et al., 2003) and CBS 114 (Handler et al., 2002; Metcalfe et al., 2005). According to the spectroscopic estimates of Beauchamp et al. (1999) CBS 114 is up to 1500 K hotter than GD 358, so it should have a thinner He layer.

4. Model-Fitting

Metcalfe et al. (2005) used a parallel genetic algorithm (Metcalfe & Charbonneau, 2003) to optimize the match between the observed and calculated periods ($\sigma_{\rm P}$) using models with 4 adjustable parameters. They searched stellar masses (M_*) between 0.45 and 0.95 $M_\odot$ (Napiwotzki et al., 1999), effective temperatures ($T_{\rm eff}$) between 20,000 and 30,000 K (Beauchamp et al., 1999), envelope masses ($M_{\rm env}$) between 10^{-2} and 10^{-4} M_* (Dantona & Mazzitelli, 1979), and surface He layer masses ($M_{\rm He}$) between 10^{-5} and 10^{-7} M_* (Dehner & Kawaler, 1995). For this initial experiment, they used pure C cores out to the 0.95 fractional mass point.

4.1. Initial Results

The resulting optimal model parameters for the two stars are listed in Table 1, along with statistical uncertainties set by the resolution of the search. The derived mass and temperature of CBS 114 both agree with the spectroscopic estimates of Beauchamp et al. (1999). The mass of GD 358 is consistent with spectroscopy, but the derived temperature is about 1000 K too low. CBS 114 has a larger total envelope mass than GD 358 and a marginally thinner surface He layer, just as predicted. Secondary minima

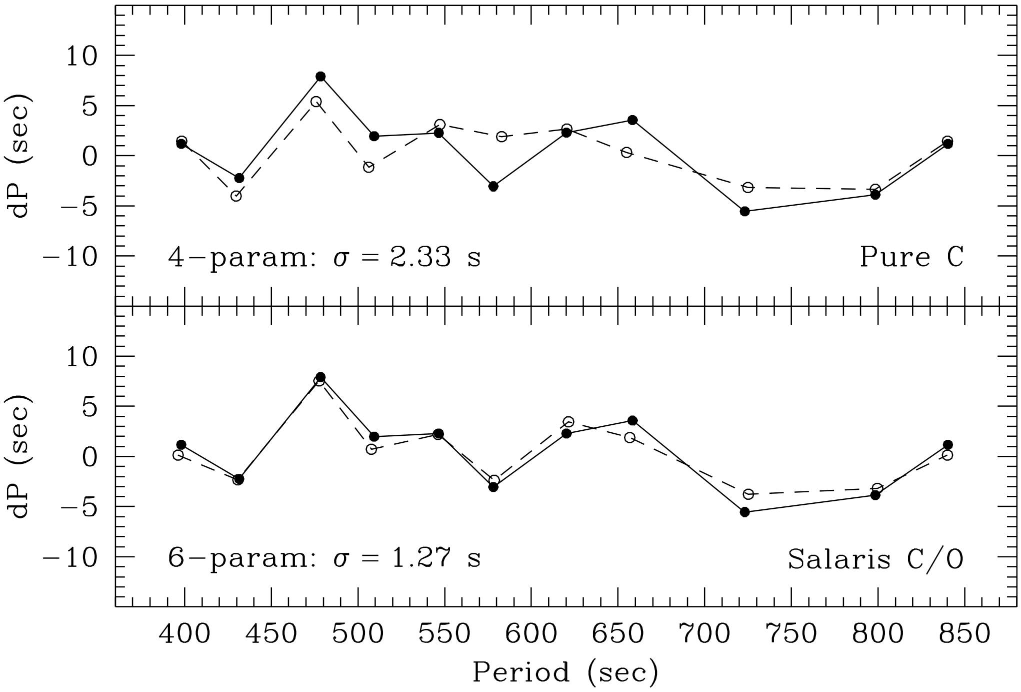

Fig. 1. A comparison of the optimal match (open points) to the observed periods of CBS 114 (solid points) for double-layered envelope models with a pure C core (top panel) and an adjustable C/O core motivated by the calculations of Salaris et al. (1997, bottom panel). The addition of two free parameters is expected to improve the fit from σ_P = 2.33 s to 1.87 s, but the fit actually improves by more than twice this amount.

in the search space hint that the models are inadequate, and that additional structure in the interior may be needed to explain the observations completely. This additional structure is most likely located in the core.

4.2. Latest Results

To explore this possibility, I added an adjustable C/O profile to the cores of the models. The original parameterization (Metcalfe et al., 2001) fixed the oxygen mass fraction (X_O) to its central value out to some fractional mass (q) where it then decreased linearly in mass to zero oxygen at 0.95 M_r/M_*. A new version uses the same parameterization, but includes a physically motivated shape for the outer C/O profile, based on the calculations of Salaris et al. (1997). The optimal model for CBS 114 from this new version leads to a significant improvement in the fit to the observations (see Fig. 1). Metcalfe (2005) presents a new series of model-fits using these same observations to illustrate the relative importance of various interior structures, and discusses the implications of this asteroseismic model which agrees with both diffusion theory and the expected nuclear burning history of the progenitor.

5. Conclusions

Let me summarize the main points I hope you will take away with you:

– Asteroseismic fits to two DBV white dwarfs are in qualitative agreement with diffusion theory
– These results support a central assumption of spectral evolution theory, linking the DB white dwarfs to PG 1159 stars

– Addition of a realistic C/O core profile significantly improves the fit to CBS 114
– Further tests will be possible using additional DBVs from the Sloan Digital Sky Survey (SDSS; Nitta et al., 2005)

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