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New theories of convection in the context of a recent analysis of the DBV white dwarf GD 358

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ABSTRACT

We present updated evolutionary calculations for carbon–oxygen DB white dwarfs using the self-consistent model for turbulent convection recently developed by Canuto, Goldman & Mazzitelli (CGM). To this end, we employ a detailed stellar evolutionary code in which we include a new equation of state for helium plasmas computed by Saumon, Chabrier & Van Horn as well as new OPAL radiative opacities. The present study is aimed at assessing the compatibility of the CGM model with the recent effective temperature redetermination of the pulsating DB white dwarf star GD 358. This star defines the blue edge of the DB white dwarf instability strip. Using thermal time-scale arguments, we find that the DB blue edges given by the CGM fit to the effective temperature of GD 358 are much better than those given by the previous Canuto & Mazzitelli model.

Key words: convection – stars: individual: GD 358 – white dwarfs.

1 INTRODUCTION

Since the existence of pulsation in some cool white dwarf (WD) stars was established, our understanding of both the structure and evolution of these stars has greatly improved. Pulsating WDs, which are restricted to narrow instability strips, represent a powerful tool for providing a view on the innermost structure that would be inaccessible otherwise. In particular, the asteroseismological analysis of pulsating WDs gives us the possibility of probing the thermal structure of the partial ionization zone where pulsation driving occurs. In this context, numerous past studies have shown that the theoretical determination of the location of the hot (blue) edge of instability strips is mostly sensitive to the treatment of convection. Accordingly, a match to the observed blue edge would yield a way of constraining the convective efficiency assumed in the theoretical models (see, e.g., Winget et al. 1982; Winget et al. 1983; Tassoul, Fontaine & Winget 1990; Wesemael et al. 1991; Bradley & Winget 1994; and further references cited therein).

With regard to pulsating WDs with helium-rich outer layers (DBV), the hottest of the observed objects belonging to this group, GD 358, has been the subject of many discussions. In particular, its effective temperature provides an upper temperature limit for the DB WD instability strip. Very recently, Provencal et al. (1996) presented a new analysis of the ultraviolet spectrum of GD 358 confirming the C II and He II detections of Sion et al. (1988). Provencal et al. derived for GD 358 an effective temperature of 27 000 ± 1000 K, which is close to the value determined much earlier by Liebert et al. (1986). The determination by Provencal et al. is somewhat higher than that derived by Thejll, Vennes & Shipman (1991), who found a temperature of 24 000 ± 1000 K. This higher effective temperature derived for GD 358 implies larger convective efficiencies than previously assumed in order to obtain a fit between theoretical predictions of the location of the instability strip and observations.

It is worth mentioning that the majority of theoretical studies in the WD investigation employ the mixing length theory (Böhm-Vitense 1958) to deal with the convective energy transport, which undoubtedly represents one of the weakest points in the theoretical description of the models. In recent years, there has been considerable progress in the formulation of alternative theories of convection. In particular, the model for stellar turbulent convection developed by Canuto & Mazzitelli (CM) (1991, 1992), which has been successfully tested in different stellar con-

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texts, is a significant improvement over the mixing length since it includes the full spectrum of turbulent eddies. Another advantage of the CM model is that it does not have adjustable parameters. In particular, the convective turbulent length is given by the geometrical depth inside the convective zone. Using thermal time-scale arguments, Althaus & Benvenuto (1996) have recently shown that the CM model predicts blue edges for the DB WD instability strip in good agreement with the observations of Thejll et al. (1991).

Very recently, Canuto, Goldman & Mazzitelli (CGM) (1996) have refined the CM model by developing a self-consistent model for convection, which, like the CM model, includes the full spectrum of eddies but computes the rate of energy input self-consistently. That means that the energy input from the source (buoyancy) into the turbulence depends now on both the source and the turbulence itself. At low and intermediate convective efficiencies, the CGM model provides higher convective fluxes (up to a factor of 3) than those given by the CM model. Such differences in the values of the convective flux are due exclusively to the self-consistent nature of the CGM model (see Canuto et al. 1996 for details). At high convective efficiencies, the CM and CGM models yield similar results.

CGM applied the new model to compute the main-sequence evolution of a solar model as well as the evolution of low-mass Pop II stars. They found that the extent of the overshooting required to fit the solar radius is smaller than that given by the CM model. This is in better agreement with recent observational data. Also, the age of the globular cluster M68 is ≈ 1 Gyr smaller than that derived from the CM model.

In this letter, we present the first results of the evolution of carbon–oxygen DB WD configurations considering the new model for stellar convection of CGM with the aim of evaluating the compatibility of this model with the recent effective temperature determination of GD 358. To this end, we evolved DB WD models with masses ranging from 0.4 to 1.0 $\mathrm{M}_\odot$ at intervals of 0.1 $\mathrm{M}_\odot$ by means of a detailed and updated WD evolutionary code. A more extensive exploration of our results is presented in Benvenuto & Althaus (1997).

2 INPUT PHYSICS

The calculations were performed by means of a well-tested WD evolutionary code. The code has been written following the method of triangles to derive the surface boundary conditions as described in Kippenhahn, Weigert & Hofmeister (1967). The fitting mass fraction between the base of the envelope and the first Henyey mass shell is $\approx 10^{-15} M_*$. For a correct evaluation of the temperature gradient in the outer layers, the value of the fitting mass fraction is allowed to vary in the course of evolution. The interior integration is treated according to the standard Henyey technique and the Schwarzschild criterion is used for the occurrence of convection. For numerical details of our code as well as for a description of the initial models, we refer the reader to Benvenuto & Althaus (1995), and Althaus & Benvenuto (1997). In particular, we have adopted WD models with the same chemical stratification, consisting of a carbon–oxygen core plus a $10^{-6} M_*$ helium-rich envelope and metal abundances (by mass) of 0.001 and 0.00. The thickness of the helium layer is of the order of that found by Winget et al. (1994) ($1.5 \times 10^{-6} M_*$). As we will show later, this is not a critical value.

In the present work we included the new equation of state for helium plasma presented by Saumon, Chabrier & Van Horn (1995). This treatment was used in the low-density and low-temperature regime. Outside the range covered by Saumon et al.'s tables, we considered partially degenerate electrons, Coulomb interactions, quantum corrections for the ions, and electron exchange and Thomas–Fermi contributions at finite temperature (see Althaus & Benvenuto 1997 for details).

The latest OPAL radiative opacities (Iglesias & Rogers 1993) were also included in our calculations. Except for very high densities, where total opacity is controlled by degenerate electrons, the OPAL data covers the whole temperature and density regime of our models. Conductive opacities were taken from Itoh et al. (1983, 1984) and from Itoh & Kohyama (1993). The calculations of Itoh et al. were complemented with the older data of Hubbard & Lampe (1969) (as fitted by Fontaine & Van Horn 1976) for the low-density regime.

Finally, we take into account the different mechanisms of neutrino emission that are relevant in the WD context (see Althaus & Benvenuto 1997 for details). It is worthwhile to emphasize that, even at the effective temperatures characteristic of the DBV WDs, neutrino losses are not completely negligible in the case of low-mass objects.

3 DISCUSSION OF THE RESULTS

As a comparison between the various parametrizations of the mixing length model usually employed in WD calculations and the CM model has already been performed (see Althaus & Benvenuto 1996), we shall not repeat such an analysis here.

In Fig. 1, we show the behaviour of the evolving outer convective zone for the 0.6-$\mathrm{M}_\odot$ DB WD model according to the CGM and CM models for the case of $Z = 10^{-3}$. We plot the top and the base of the convective zone in terms of the mass fraction q ($q = 1 - M_r/M_*$) as a function of effective temperature. The shape of the convective profile is the same in both models, but at intermediate effective temperatures the CGM model provides deeper convective zones than does the CM model. This is exactly what is expected to happen since, for low and intermediate convective efficiencies, the CGM convective fluxes are substantially higher than those of the CM model. The resulting temperature profiles throughout the entire convective zone at the effective temperature of 26 400 K are depicted in Fig. 2 for the 0.6-$\mathrm{M}_\odot$ DB WD model for the same metallicity as in Fig. 1.

It is worthwhile to note that the discontinuity at the top of the convective zone in Fig. 1 by $T_{\mathrm{eff}} \approx 30\,000$ K is due exclusively to our employment of the Saumon et al. (1995) equation of state (see their fig. 20). In fact, at these conditions the departure from thermodynamical consistency of Saumon et al.'s equation of state is larger than elsewhere. Such a problem precludes us from avoiding such discontinuity. However, fortunately, at $T_{\mathrm{eff}} \approx 27\,000$ K we do not find such

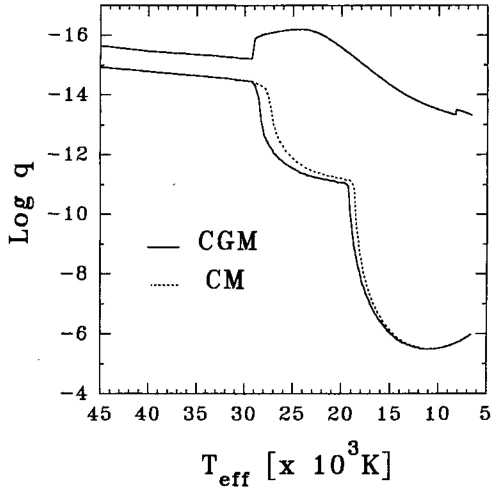

Figure 1. The extent of the outer convective zone for the 0.6-$M_\odot$ DB WD model according to the CGM (solid line) and CM (dotted line) models of convection. The location of the top (almost coinciding with the location of the photosphere) and the base of the convective zone is expressed in terms of the mass fraction q as a function of the effective temperature.

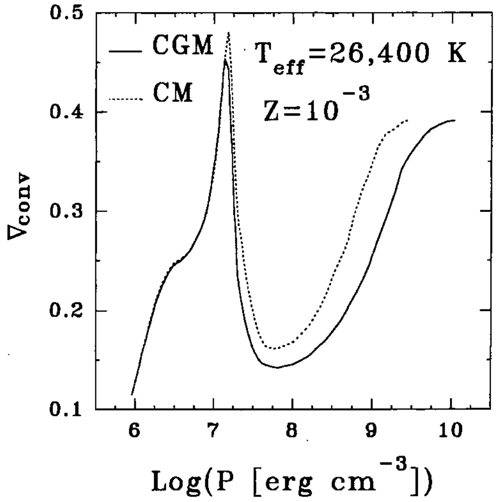

Figure 2. The dimensionless convective temperature gradient as a function of the pressure throughout the entire convective zone. The results correspond to the 0.6-$M_\odot$ DB WD model at the effective temperature of 26 400 K according to the CGM (solid line) and CM (dotted line) models. The higher convective fluxes characterizing the CGM model yield lower internal temperatures than those given by the CM model.

Table 1. Theoretical blue edge temperatures for DB WDs computed with the CGM and CM models.

Theory of Convection	Mass ($M/M_\odot$)	T_{eff} (K) ($Z = 10^{-3}$)	T_{eff} (K) ($Z = 0.0$)
CGM	0.40	25,410	25,692
CM	0.40	24,250	24,508
CGM	0.50	26,090	26,349
CM	0.50	24,910	25,194
CGM	0.60	26,590	26,902
CM	0.60	25,400	25,659
CGM	0.70	26,970	27,206
CM	0.70	25,770	26,039
CGM	0.80	27,210	27,465
CM	0.80	26,010	26,275
CGM	0.90	27,360	27,611
CM	0.90	26,220	26,418
CGM	1.00	27,440	27,653
CM	1.00	26,310	26,466

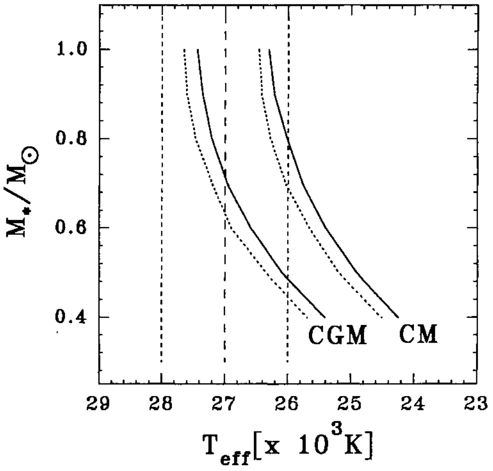

Figure 3. The dependence of theoretical blue edge temperature on the stellar mass for the CGM and CM models of convection. Solid and dotted lines represent the results for $Z = 10^{-3}$ and $Z = 0.00$, respectively. The Provencal et al. recent determination of the effective temperature of DBV GD 358 (27 000 ± 1000 K) is also shown. The agreement with observations is much better in the CGM model than in the CM model.

a difficulty. Thus, it does not affect the conclusions of this work.

The recombination of helium in a cooling DB WD causes the outer layers to become unstable against convection. As cooling proceeds, the region of partial ionization moves deeper into the star, thus increasing the thermal time-scale τ_{TH} at the base of the outer convective zone. The blue edge of the instability strip can be identified by determining the effective temperature at which τ_{TH} becomes comparable with the shortest observable g-mode periods, which for a WD are of the order of 100 s (Winget et al. 1983; Tassoul et al. 1990). In this connection, we show in Table 1 the blue edge effective temperature of the DB WD instability strip according to the CGM and CM models and for the different stellar masses and metallicities we have considered. The blue edge temperatures in the CGM model are systematically hotter (by more than 1000 K) than those obtained with the CM model. We have verified that, as claimed by Bradley & Winget (1994) on the basis of detailed pulsation computations, the theoretical blue edge is relatively insensitive to the helium layer mass, at least in the range of 10^{-2}–$10^{-6} M_*$.

The dependence of the theoretical blue edge temperature on the stellar mass together with Provencal et al.'s recent determination of the effective temperature of DBV GD 358 are shown in Fig. 3. It is worth mentioning in the present context that GD 358 has a stellar mass of ≈0.58 $M_\odot$ (see Provencal et al. 1996 for details). It is clear that, with respect to the CM model, the results given by CGM model are in better agreement with the new observational data. A lower effective temperature for GD 358, such as that reported by Thejll et al. (1991), would be in strong discrepancy with the new CGM self-consistent model.

Provencal et al. have determined a carbon abundance of $-5.75 < \log n(\mathrm{C})/n(\mathrm{He}) < -5.55$ for GD 358. It seems very difficult to measure the metallicity of GD 358 observationally, but according to Provencal et al.'s result it should be lower than 10^{-3}. Consequently, the actual metallicity of GD 358 should be bracketed by the two values employed here. From the results shown in Fig. 3, it is clear that the effective temperature of the blue edge of the instability strip is more sensitive to the theory of convection than to the metallicity. Thus, it provides a good test for convection theories.

We note that both theory and observations tend to indicate a hotter blue edge of the DB instability strip than that derived by Thejll et al. (1991). This should be considered as a strong indication that, in accounting for the observational position of the DB instability strip, the CGM model is a significant improvement in the treatment of stellar convection, especially when compared to the popular mixing length theory also in the white dwarf domain.

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