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EVOLUTION OF WHITE DWARF STARS

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RESUMEN

El objetivo del presente trabajo es presentar los principales resultados que hemos obtenido acerca del estudio de la evolución de las estrellas enanas blancas. Los cálculos se realizaron mediante un código evolutivo detallado, el cual está basado en una descripción física actualizada. En particular, discutimos brevemente los resultados sobre la evolución de enanas blancas de diferentes masas y composiciones químicas como así también la evolución de enanas blancas en el contexto de una constante de gravitación variable en el tiempo.

ABSTRACT

This paper is aimed at presenting the main results we have obtained for the study of the evoution of white dwarf stars. The calculations are carried out by means of a detailed evolutionary code based on an updated physical description. In particular, we briefly discuss the results for the evolution of white dwarfs of different stellar masses and chemical composition, and the evolution of white dwarfs in the framework of a varying gravitational constant G scenario as well.

Key Words: **CONVECTION — GRAVITATION — PULSARS: GENERAL — STARS: EVOLUTION — STARS: WHITE DWARFS**

1. INTRODUCTION

White dwarf (WD) is the most common fate for stars. Typically, WDs have stellar masses $M_* \approx 0.6 M_\odot$, central densities of $\sim 10^6$ g cm^{-3}, sizes of the order of the Earth and core compositions of ^{12}C and ^{16}O. The mechanical structure of these objects is primarily specified by degenerate electron pressure (Chandrasekhar 1939), whereas the non-degenerate ions provide the star's luminosity. In particular, their evolution, which can be basically described as a cooling process, has been the subject of numerous studies such as, e.g., Iben & Tutukov (1984), D'Antona & Mazzitelli (1989) and Wood (1992) among others. Since many WDs are very old, they contain information about the early phases of our galaxy. In particular, their observed luminosity function (Liebert, Dahn, & Monet 1988; Leggett, Ruiz, & Bergeron 1998; hereafter WDLF), combined with WD cooling times, constitutes a powerful tool for constraining the age of the disk of the Galaxy (Wood 1992; Legget et al. 1998).

The interest in cool WDs has greatly increased since the existence of pulsations in some of them was established. Indeed, pulsating WDs, restricted to narrow instability strips, represent a powerful tool for providing a view on the innermost WD structure that would be otherwise inaccessible. In particular, WD seismology allows us to derive fundamental parameters of these stars, such as the stellar mass, chemical composition, and stratification of the outer layers (Winget et al. 1994; Bradley, & Winget 1994; Bradley 1996). In addition, the efficiency of convection in the outer layers of these stars can be estimated from the observed location in the Herstzprung-Russell diagram of the blue edge (the onset of pulsations) of the instability strips (see Bradley 1996 and references therein).

Considerable attention has also been devoted in the last few years to low-mass helium WDs. In this context, strong observational evidence has been accumulated in favour of the idea that helium WDs would be the result

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of the evolution of certain close binary systems. Indeed, Marsch (1995), Marsch, Dhillon, & Duck (1995), Lundgreen et al. (1996), Moran, Marsch, & Bragaglia (1997), among others, detected low-mass WDs in binary systems containing another WD or a millisecond pulsar. Very recently, Edmonds et al. (1999) have reported the presence of a candidate helium WD in the globular cluster NGC 6397. Needless to say, detailed evolutionary models of low-mass WDs may provide valuable information not only on the WD itself but also on the companion object and even on the past evolution of the system.

In the context of the preceeding discussion, we perform detailed eovlutionary calculations of WD models for a wide range of stellar masses. Emphasis is placed mainly on low-mass WDs, the study of which has recently been undertaken. Likewise, we compare our cooling sequences with recent improvements in the observed WDLF in order to assess the age of the Galactic disk.

2. EVOLUTIONARY CODE AND INPUT PHYSICS

The calculations are carried out by means of a WD evolutionary code developed by us independently of other researchers. The code is based on the technique proposed by Kippenhahn, Weigert, & Hofmeister (1967) for calculating stellar evolution. Magnetic fields and rotation are not considered. The independent variables are the time t and the mass M_r. The set of equation describing the evolution of our WD models is

$$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho}, \tag{1}$$

$$\frac{\partial P}{\partial M_r} = -\frac{G M_r}{4\pi r^4}, \tag{2}$$

$$\frac{\partial T}{\partial M_r} = -\frac{T\, G M_r \nabla}{4\pi P r^4}, \tag{3}$$

$$\frac{\partial L_r}{\partial M_r} = \epsilon_{nuc} - \epsilon_\nu - C_p \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} + \frac{\partial q_{lh}}{\partial m}\dot{m}, \tag{4}$$

where L_r is the local luminosity, ϵ_ν the neutrino energy losses, ϵ_{nuc} the nuclear energy release and the other symbols have their usual meanings (see Kippenhahn & Weigert 1990). The last term in eq.4 measures the rate at which latent heat is released during the propagation of the crystallization front, and in eq.3, $\nabla \equiv d\ln T/d\ln P$, the value of which, in the case of convection, is given by a theory of convective energy transport. The outer boundary conditions are provided by three envelope integrations (at constant luminosity) starting from a grey atmosphere. The fitting mass fraction between the base of the envelope and the first mass shell is $q_F \approx 10^{-15}$ ($q = 1 - M_r/M_*$). For solving eqs. 1–4, we employ the standard Henyey technique.

The constitutive physics of our code is as detailed as possible. Briefly, for the low-mass density regime we consider the equation of state of Saumon, Chabrier, & van Horn (1995) for hydrogen and helium plasmas. The treatment for the high density regime appropiate for the WD interior includes ionic contributions, Coulomb interactions, partially degenerate electrons, quantum corrections for the ions and electron exchange, and Thomas-Fermi contributions at finite temperature. Radiative opacities for the high temperature regime are those of OPAL (Iglesias & Rogers 1993), whilst for lower temperatures we use the Alexander & Fergusson (1994) molecular opacities. We also include convective mixing and the complete network of thermonuclear reaction rates for hydrogen burning corresponding to the proton-proton chain and the CNO bi-cycle (Caughlan & Fowler 1998). We use an implicit method of integration to compute the change of the following chemical species: ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{7}Li, ^{7}Be, ^{8}B, ^{12}C, ^{13}C, ^{13}N, ^{14}N, ^{15}N, ^{15}O, ^{16}O, ^{17}O and ^{17}F. Conductive opacities for the crystalline and liquid phases and the various mechanisms of neutrino emission are taken from the work of Itoh and collaborators (for details see Althaus & Benvenuto 1997a). Finally, we consider the model for stellar turbulent convection developed by Canuto & Mazzitelli (1991; hereafter CM91). This model, which has been successfully tested in different stellar contexts, is a significant improvement over the mixing length theory (MLT) used thus far in most WD studies. Indeed, the CM91 model includes the full spectrum of turbulent eddies and does not have parameters requiring calibration.

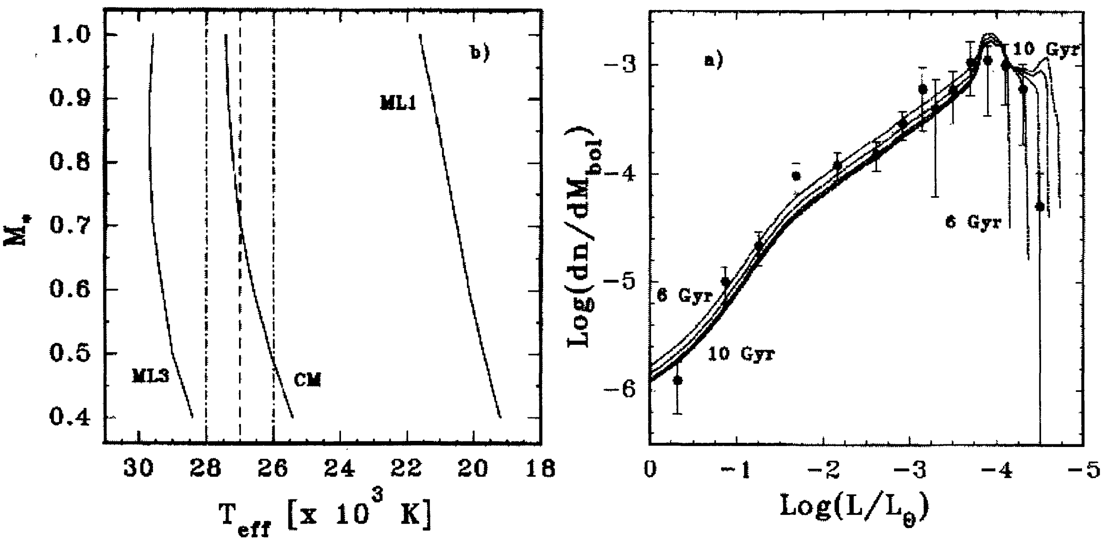

Fig. 1. *a)* Theoretical WDLFs (dashed lines) corresponding to our carbon-oxygen models with a hydrogen envelope mass $M_H/M_* = 10^{-4}$. The curves which correspond to assumed disk ages of 6–10 Gyr (at intervals of 1 Gyr) are compared with the observational data of Leggett et al. (1998) (from Benvenuto & Althaus 1999). *b)* The dependence of theoretical blue edge temperature on the stellar mass for the CM91, and for the ML1 and ML3 versions of MLT. We also show the Provencal et al. (1996) determination of the DBV GD 358 effective temperature, $27,000 \pm 10,000\,^{\circ}$K. Note the agreement between the CM91 predictions and observations (from Benvenuto & Althaus 1997).

3. EVOLUTIONARY RESULTS

We employed our code to study the evolution of WDs with stellar masses ranging from 0.1 to 1.2 $M_{\odot}$, and hydrogen envelope in the range $10^{-12} \leq M_H/M_* \leq 4 \times 10^{-3}$. The sequences were evolved down to $\log(l/L_{\odot}) = -5$. We also studied the evolution of strange dwarf stars composed of a strange matter core (Benvenuto & Althaus 1996). In what follows, we shall briefly discuss the results we obtained for WDs of different stellar masses and chemical compositions, and the evolution of WDs in the framework of a varying gravitational constant scenario as well.

3.1. *Carbon - oxygen WD models*

From the point of view of an age determination of the disk of the Galaxy from the observed space density of WDs, the evolutionary times of WDs as a function of stellar mass obviously represents an important issue. In this connection, we have constructed integrated WDLFs from our evolutionary sequences and we have compared them with the observed ones (Leggett et al. 1998). The results are shown in Fig.1*a*, in which the WDLFs have been converted into intervals of bolometric magnitude M_{bol}. Note that the best fit to the coolest WDs observed is obtained for an assumed disk age ~ 8 Gyrs (see details in Benvenuto & Althaus 1999).

To compare the predictions of our models with observations of pulsating WDs, we derive effective temperatures (T_{eff}) for the theoretical blue edge of instability strips by using thermal time-scale arguments for our evolving models. Specifically, the theoretical blue edge corresponds approximately to the T_{eff} at which the thermal time-scale at the base of the outer convection zone becomes comparable to 100 s, which for a WD is of the order of the shortest observable g-mode periods. At intermediate T_{eff}, where pulsating WDs are observed, convection treatment plays a significant role in fixing the structure of the outer zone of the models (Tassoul,

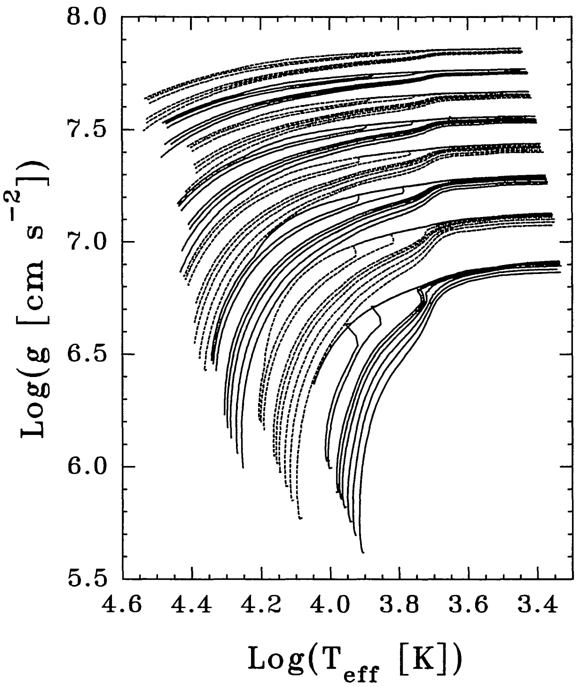

Fig. 2. Surface gravity versus effective temperature relation for helium WD models with (top to bottom) $M_*/M_\odot = 0.50, 0.45, 0.40, 0.35, 0.25, 0.20$ and 0.15, in an alternate sequence of short-dashed and solid lines. Different hydrogen envelope values are considered for each stellar mass (from Benvenuto & Althaus 1998).

Fontaine, & Winget 1990). In Fig 1*b* we show the dependence of the theoretical blue edge temperature on the stellar mass together with a recent determination of the T_{eff} of DBV GD 358 (Provencal et al. 1996). This WD definesd the blue edge of the DB instability strip (pulsating WDs without hydrogen envelope). The results correspond to the CM91 model as well as to different parametrizations of MLT. Note that in the case of the CM91 model, the agreement between theory and observation is quite natural (Althaus & Benvenuto 1997b), strongly suggesting that the description of convection provided by models based on the full turbulence spectrum theory is definitively better than that provided by the MLT in its different guises.

3.2. *Low-Mass Helium WD Models*

Low-mass helium WDs, which would be the result of the evolution of close binary systems (Iben & Tutukov 1986), have recently begun to be detected in numerous binary configurations. It is clear that, in order to make an adequate interpretation of observational data, we need models of helium WDs as accurate and detailed as possible. For this purpose, we calculate a grid of evolutionary tracks for low-mass WDs with helium cores in the mass range from 0.1 to 0.5 $M_\odot$. In Fig.2, we show the surface gravity g in terms of T_{eff} for models with different stellar masses and hydrogen envelopes. As T_{eff} decreases, g gradually becomes larger, ultimately reaching an almost constant value as expected for a strongly degenerate configuration. Note that the effects of finite temperature and hydrogen envelopes are clearly noticeable, particularly for less massive models. Note also that, at low T_{eff}, convective mixing between hydrogen and helium layers increases the g values of models with thin hydrogen envelopes. It is worth mentioning that the age of helium WD models depends not only on the stellar mass but also on the mass of the hydrogen envelope (Althaus & Benvenuto 1997a; Benvenuto & Althaus 1998). This is particularly true for models with thick hydrogen envelopes, for which hydrogen burning may contribute substantially to the total luminosity of the star, thus leading to a delay in cooling even down to very low T_{eff}.

It is clear that detailed models of low-mass WDs such as the presented in this study should be carefully taken into account, should the mass of a WD be measured by applying the surface gravity versus T_{eff} relation.

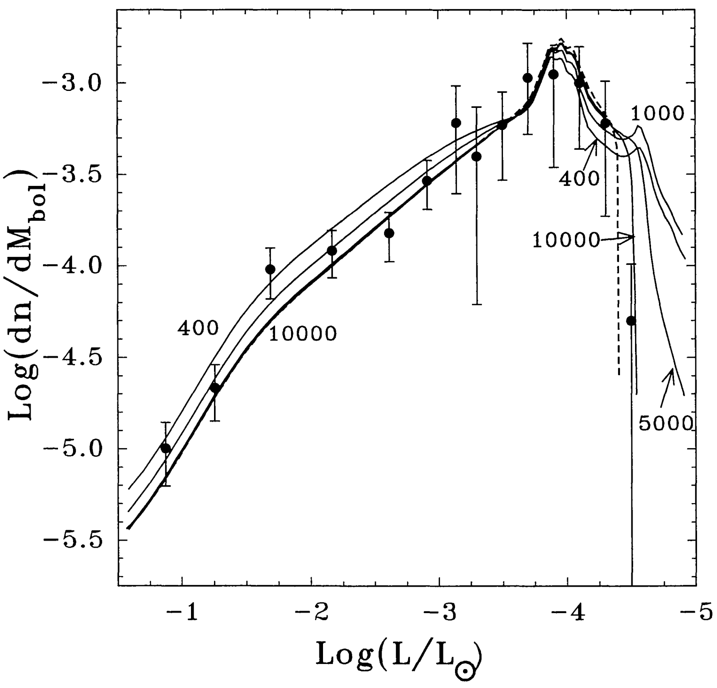

Fig. 3. Theoretical WDLFs corresponding to our WD models with varying G for the set of ω values: 400, 1000, 5000 and 10000, assuming a disk age of 7 Gyr. At high luminosities curves are ordered from top to bottom for increasing ω values. We also depict the WDLF corresponding to $G = 0$ (dashed lines). Note that the dimmest WDs observed can be fitted only by curves corresponding to $\omega > 5000$ (from Benvenuto et al. 1998).

This is particularly true regarding, for instance, the possibility of constraining the equation of state at neutron star densities as inferred from observations of low-mass WD companions to millisecond pulsars (van Kerkwijk, Bergeron, & Kulkarni 1996).

3.3. *WD Stars with Varying G*

Over the years, the study of theories with varying gravitational constant G has captured the attention of numerous investigators. In particular, the most promising candidates as alternatives of the standard General Relativity are known as scalar-tensor theories. WD stars in particular provide an independent method for measuring a change of G. This is so because they are long lived objects ($\approx 10^{10}$ Gyr) and also because their energy is basically of gravitational and thermal origin; therefore a change of G will modify the energy balance. In addition, their observed WDLF is relatively well-known.

Here, we study the evolution of WDs in the framework of the simplest model of scalar-tensor theory: Brans-Dicke gravity (Brans & Dicke 1961), which predicts a very slow decrese in G ($G(t) \propto t^{-n}$, where $n = 2/(4+3\omega)$ and ω is the free parameter of the theory). To this end, we modified our evolutionary code in order to include the effects induced by a varying G. We assume that the star is able to *see* the cosmological evolution of G (obtained from relativistic equations). Attempts of ascertaining the evolution of WDs in varying G theories were started by García-Berro et al. (1995). They were the firsts in establishing upper bounds to the rate of change in G by employing the observed WDLF. However, they employed a very simplified (semi-analytic) treatment for the WD by describing its evolution in terms of an isothermal interior, and by neglecting the effect of the variations of G in the structure of the stellar envelopes they considered.

It can be show that (see García-Berro et al. 1995; and Benvenuto, Althaus, & Torres 1998a), in the case of a varying G, an additional term of the form $\dot{G}M_r/r$ appears in eq.4. We found that the process of cooling is strongly accelerated, particularly for massive stars and low luminosities, even if the ω parameter of Brans-Dicke is big enough as to accord well with any other test of gravitation (see Benvenuto et al. 1998a for more details). This uncommon cooling process translates into several distinct features of WD evolution like: a) a new profile of luminosity versus fractional mass and age; b) different central temperature versus surface luminosity (the interior strongly departs from an isothermic description in spite of the extremely low conductivity of the degenerate plasma in the deep interior); and, most important, c) an appreciable variation in the theoretical WDLF. In this connection, we show in Fig.3 the observed WDLF (Leggett et al., 1998) together with the predictions of our models for different values of ω, thus implying a powerful test of gravitation. In particular, it is possible to constrain the variation of the value of G with a far greater degree of sensitivity than that provided by the existing experiments. In this sense, we derive a value for $|\dot{G}/G|$ of the order of 10^{-14} (see Benvenuto, Althaus, & Torres 1998b), which is between 1 and 3 orders of magnitude more restrictive than previous bounds.

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