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An overview of white dwarf stars

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Abstract. We present a brief summary of what is currently known about white dwarf stars, with an emphasis on their evolutionary and internal properties. As is well known, white dwarfs represent the end products of stellar evolution for the vast majority of stars and, as such, bear the signatures of past events (such as mass loss, mixing phases, loss and redistribution of angular momentum, and thermonuclear burning) that are of essential importance in the evolution of stars in general. In addition, white dwarf stars represent ideal testbeds for our understanding of matter under extreme conditions, and work on their constitutive physics (neutrino production rates, conductive and radiative opacities, interior liquid/solid equations of state, partially ionized and partially degenerate envelope equations of state, diffusion coefficients, line broadening mechanisms) is still being actively pursued. Given a set of constitutive physics, cooling white dwarfs can be used advantageously as cosmochronometers. Moreover, the field has been blessed by the existence of four distinct families of pulsating white dwarfs, each mapping a different evolutionary phase, and this allows the application of the asteroseismological method to probe and test their internal structure and evolutionary state. We set the stage for the reviews that follow on cooling white dwarfs as cosmochronometers and physics laboratories, as well as on the properties of pulsating white dwarfs and the asteroseismological results that can be inferred.

1. BASIC FACTS ABOUT WHITE DWARFS

- White dwarfs are the end products of stellar evolution for the vast ($\gtrsim$95%) majority of stars. They have run out of thermonuclear fuel, and most of them have burned H and He in their interiors.
- Most *observable* white dwarfs are isolated or part of non-interacting binaries. They are believed to have C-O cores and to descend from main sequence stars with masses in the range from slightly less than 1 $M_\odot$ to $\sim$8 $M_\odot$. This maps into a narrow range of final masses centered around $\sim$0.6 $M_\odot$. This implies important mass loss in previous evolutionary (red giant) phases.
- White dwarfs have a stratified structure (see Fig. 1). Most have a C-O core (containing $\sim$99% of the total mass M) surrounded by a thin He mantle ($\sim$1% M at most), itself surrounded by a thinner but opaque H envelope ($\sim$0.01% M at most).
- White dwarfs are compact cooling bodies in hydrostatic equilibrium; gravity is balanced by degenerate electron pressure. This implies an evolution at almost constant radius. From a pulsation point of view, white dwarfs have a mechanical structure radically different from those of non-degenerate stars (see Fig. 2).

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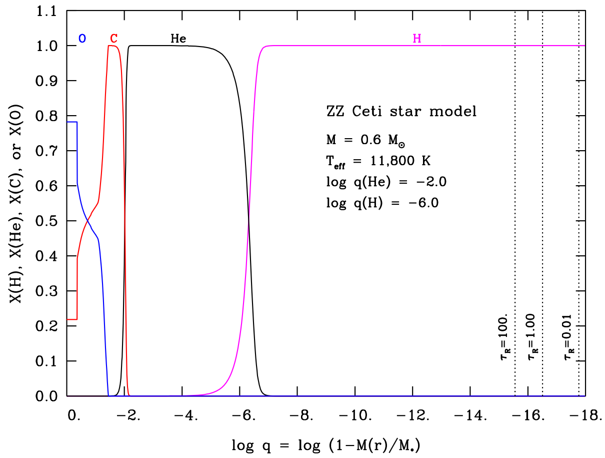

Figure 1. Chemical layering in a representative model of a DA white dwarf (a ZZ Ceti pulsator). The location of the atmospheric layers is indicated through the values of the Rosseland optical depth. The He mantle and the H envelope contain relatively very little mass, but they play a key role in the evolution of a white dwarf because they regulate, through their large opacity, the rate of energy outflow. Except for the fact that the mass of the He (H) envelope has to be less than ∼1% (∼0.01%) of the total mass – otherwise there would be thermonuclear runaways – we do not know exactly how much He and H are leftover. These are among the major uncertainties about white dwarf internal structure, along with the uncertain proportions of C and O in the core.

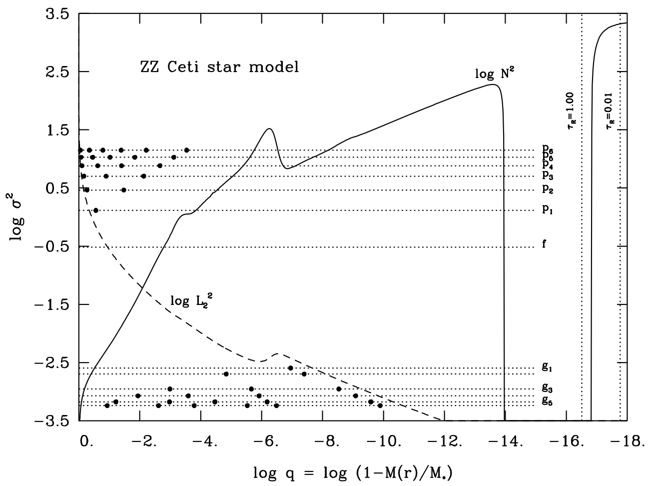

Figure 2. Propagation diagram for quadrupole ($l = 2$) modes computed using a representative model of a ZZ Ceti pulsator. The solid curve shows the profile of the logarithm of the square of the Brunt-Väisälä frequency as a function of fractional mass depth. The value of log $q = 0$ corresponds to the center of the stellar model. The locations of two atmospheric layers, those with $\tau_R = 10^{-2}$ and $\tau_R = 1$, are also indicated by the vertical dotted lines on that scale. Likewise, the dashed curve gives the logarithmic profile of the square of the Lamb frequency for modes with $l = 2$. The labelled horizontal dotted lines show the low-order frequency spectrum, again on a scale involving the logarithm of the square of the frequency. The dots give the locations of the nodes of the (radial) eigenfunction $\xi_r(r)$ for the different modes illustrated. Contrary to non-degenerate stars, the low-order p-modes probe much deeper than the low-order g-modes.

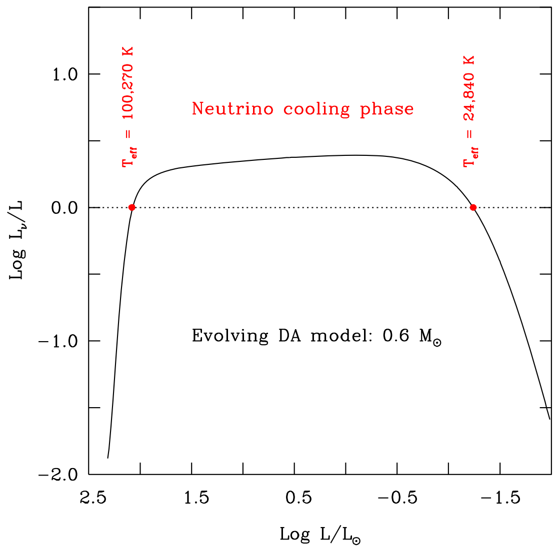

Figure 3. Cooling track illustrating the behavior of the neutrino luminosity in relation to the photon luminosity in a representative model.

- Cooling white dwarfs shine through the slow leakage of thermal energy of the ionic plasma. The latter behaves initially as a gas, then, with cooling, as a fluid, and ultimately undergoes a first-order phase transition to the solid phase. In the early, short-lived phase of their evolution, white dwarfs lose copious amounts of energy via neutrino processes (see Fig. 3).

2. SPECTRAL TYPES AND SPECTRAL EVOLUTION

White dwarfs are all chemically peculiar. About 75% of post-AGB stars enter the white dwarf domain with H-rich atmospheres. Element sedimentation – very efficient in stars with log $g \sim 8$ – then leads quickly to the formation of almost pure H atmosphere stars, the DA stars. The latter have Balmer lines detectable in the full range of effective temperature covered in the HR diagram.

The rest of post-AGB stars undergoes a very late helium flash that pushes them back temporarily to the AGB again (the so-called "born-again scenario"). This produces a violent mixing episode during which the residual H is burned away. The post-born-again stars then exhibit atmospheres made of a mixture dominated by He, C, and O in roughly comparable proportions. These are very hot objects, called the PG1159 stars, showing a very characteristic spectral signature.

Residual stellar winds compete for a while with gravitational settling to maintain the PG1159 composition but, with cooling, the winds subside and sedimentation takes over, producing He-atmosphere white dwarfs (C and O sink out of sight below the photosphere). Depending on the effective temperature and the possible presence of traces of polluting elements, those are known as DO, DB, DQ, DZ, and DC stars.

Below an effective temperature of ~80,000 K, white dwarfs come in two main flavors: those with H-dominated atmospheres, and those with He-dominated atmospheres. However, there is spectral evolution in that a non-DA white dwarf may become a DA (and vice-versa) during certain evolutionary phases. This is observed as the DB gap (a dearth of He-rich atmosphere white dwarfs between ~45,000 K and ~30,000 K in effective temperature), and also in the changing ratio of non-DA's to DA's as a function of T_{eff}. Convective dilution and mixing, along with diffusion are the suspected culprits for that. Fig. 4 depicts the spectroscopic HR diagram for white dwarfs and hot subdwarfs.

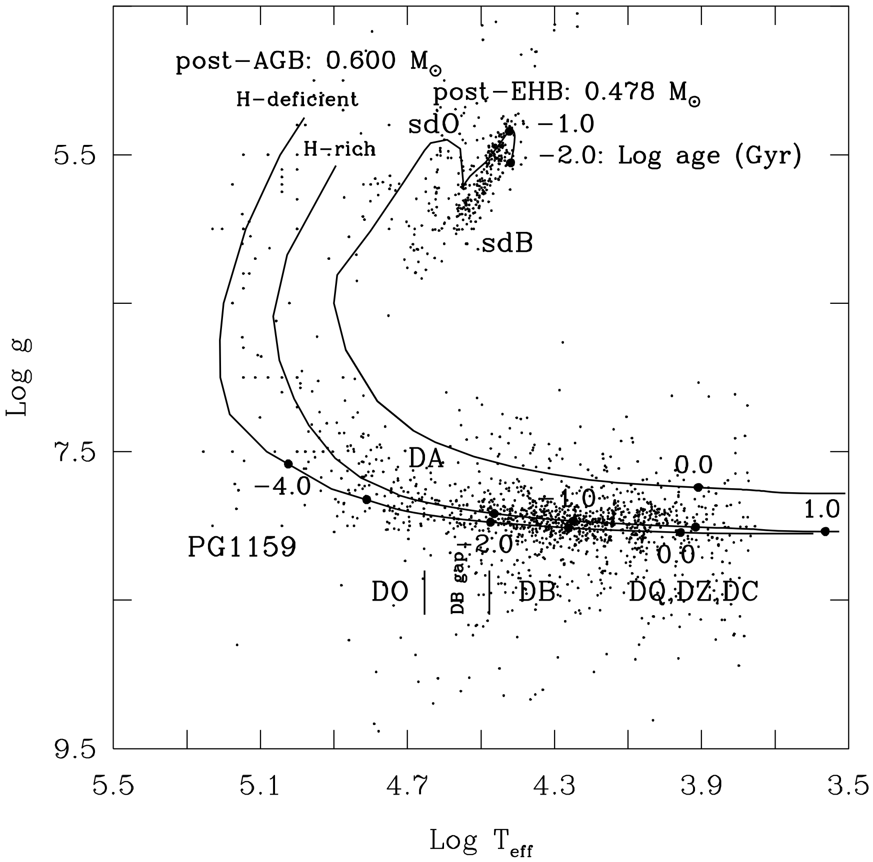

Figure 4. White dwarfs and hot subdwarfs in the spectroscopic HR diagram. Typical evolutionary tracks are plotted showing 1) the track followed by a 0.6 $M_{\odot}$ post-AGB, H-rich star which becomes a H-atmosphere white dwarf (*middle curve*), 2) the path followed by a 0.6 $M_{\odot}$ post-AGB, H-deficient star which becomes a He-atmosphere white dwarf (*left curve*), and 3) the path followed by a 0.478 $M_{\odot}$ post-EHB model which leads to the formation of a low-mass H-atmosphere white dwarf (*right curve*). The latter channel contributes only a small ($\sim 2\%$) fraction of the white dwarf population. Along each track, the small filled circles correspond to specific ages with respect to some reference epoch. The numbers shown indicate the logarithmic value of the age expressed in Gyr. For instance, along the left track, the small circle labelled −4.0 gives the location of the model after 10^5 yr of evolution from the end of the AGB phase. The next circles correspond to a cooling age of 10^6 yr, 10^7 yr, 10^8 yr, 10^9 yr, and so on.

Despite the relatively high degree of purity found in the atmospheres of white dwarfs (H or He), traces of heavy elements often pollute them. This is particularly true at high effective temperatures where residual winds and selective radiative levitation compete against gravitational settling. An example is provided in Fig. 5.

Heavy elements can also pollute the atmospheres of cool white dwarfs. The cause may be intrinsic (such as convective dredge-up bringing back to the surface settling atoms of C and O) or extrinsic (such as accretion of planetary debris via tidal disruption). Although only traces of metals are found in the atmospheres of cool white dwarfs, their opacity may dominate the spectra.

An extremely rare type of white dwarfs, the so-called Hot DQ white dwarfs, characterized by atmospheres dominated by C and found in a narrow range of effective temperature around 20,000 K has been discovered in 2007. Their very existence presents a challenge to current stellar evolution theory.

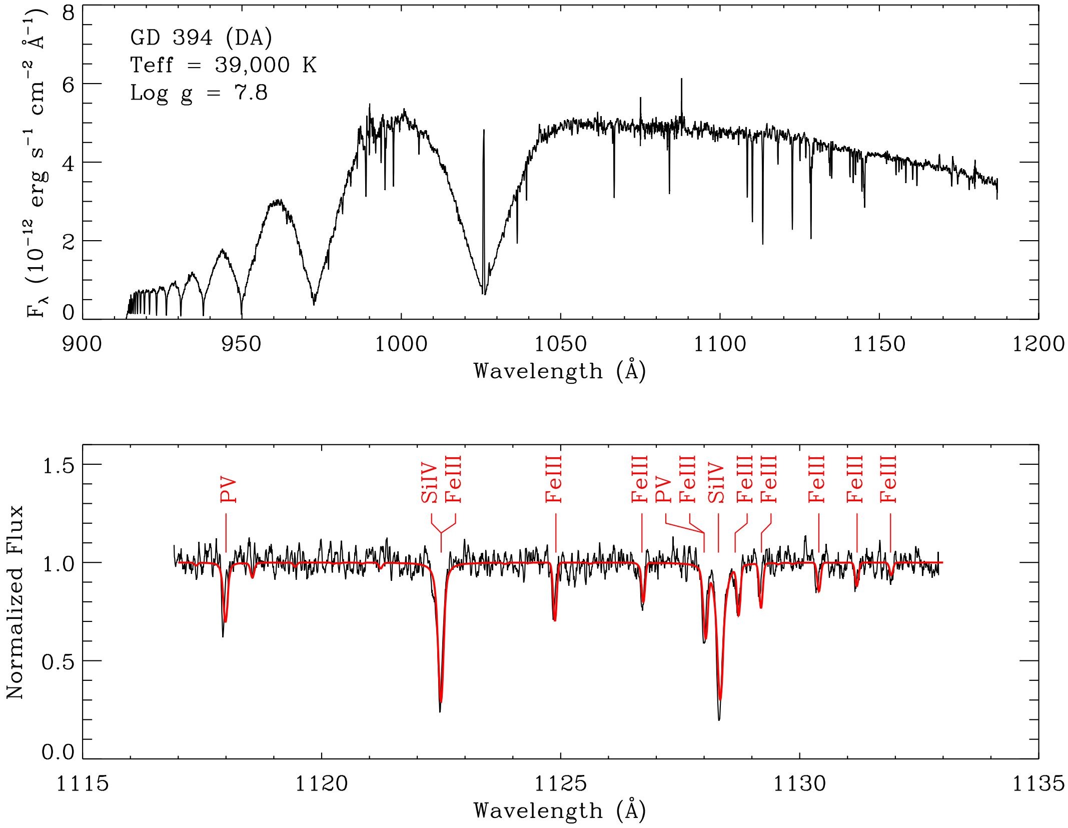

Figure 5. *Upper panel*: FUSE spectrum of the bright (V = 13.08) hot DA white dwarf GD 394 showing the domination of the Lyman lines of neutral hydrogen. *Lower panel*: zoom on a spectral region showing the presence of several heavy element pollutants.

3. CENSUS AND OTHER PROPERTIES OF WHITE DWARFS

A total of about 2200 relatively bright field white dwarfs are listed in the 1999 McCook and Sion Catalog of Spectroscopically Identified White Dwarfs. The average visual magnitude of the stars in that catalog is $\langle V \rangle \sim 15.5$. The bulk of this sample well resides within $\sim$1 kpc from the Sun. With the advent of the Sloan Digital Sky Survey, the number of spectroscopically known white dwarfs has sky-rocketed in the last decade, having reached more than 25,000 after data release DR7.

Most of what we know about white dwarfs results from the application of quantitative spectroscopy to the bright sample. Hence, white dwarfs are found in the following domains,

- $200,000\,\mathrm{K} \gtrsim T_{\mathrm{eff}} \gtrsim 3,000\,\mathrm{K}$
- $10^7 \lesssim g(\mathrm{cm\,s^{-2}}) \lesssim 10^9$, $< \log g > \simeq 8.0$
- $0.3 \lesssim M/M_\odot \lesssim 1.2$, $< M > \simeq 0.6\,M_\odot$
- $0.025 \gtrsim R/R_\odot \gtrsim 0.006$, $< R > \simeq 0.012\,R_\odot$
- $< \rho > \simeq 10^6\,\mathrm{g\,cm^{-3}}$, $< \rho > \simeq 1\,\mathrm{g\,cm^{-3}}$ for a normal star
- $-4.6 \lesssim \log L/L_\odot \lesssim 2.5$

In addition, some $10 - 15\%$ of the known white dwarfs exhibit huge large scale magnetic fields in the range 10^6–10^9 G. Furthermore, isolated white dwarfs appear to be slow rotators, at least at their surfaces. Four (perhaps five, as discussed by H. Shibahashi in these proceedings) distinct families of pulsating

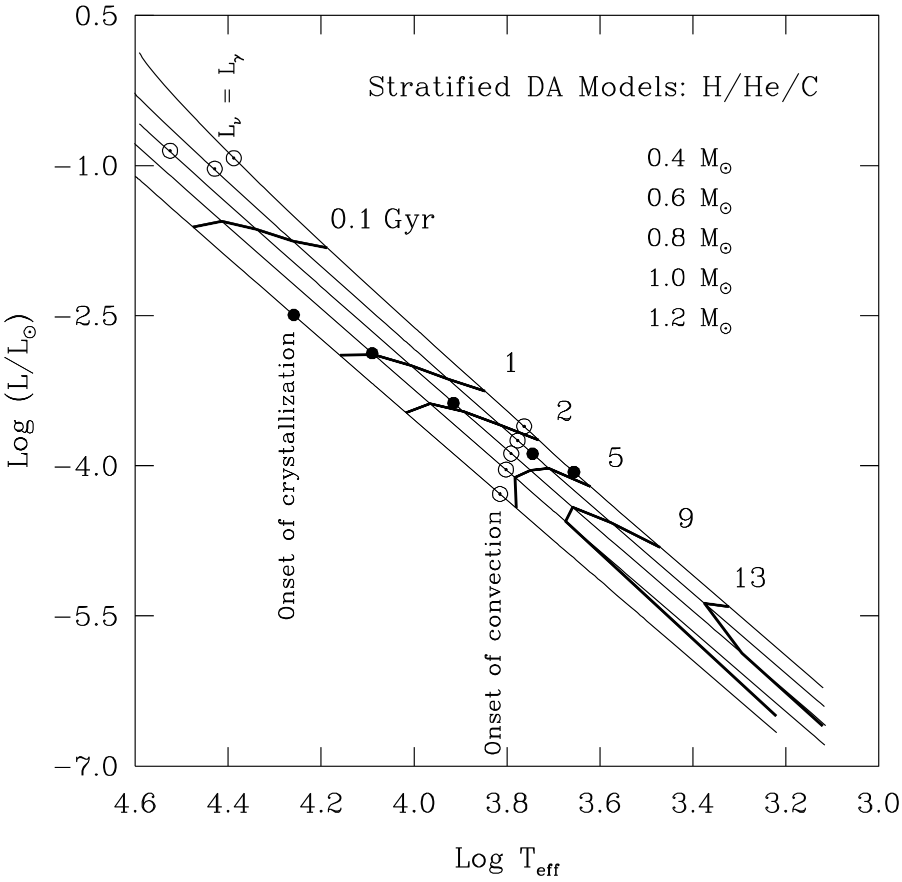

Figure 6. Evolutionary tracks (*solid curves*) of five ($M = 0.4$, 0.6, 0.8, 1.0, and 1.2 $M_{\odot}$, from top to bottom) representative models of DA white dwarfs in the theoretical Hertzsprung-Russell diagram. The thick solid curves are isochrones. The number next to each isochrone gives the cooling time in units of Gyr. The small filled circles indicate the onset of crystallization at the center of each evolving model. The larger open circles at high luminosities indicate the transition between the neutrino cooling phase (which dominates at higher luminosities) and the thermal cooling phase (which becomes relevant at lower luminosities). The other set of open circles at lower luminosities indicates the onset of convective coupling between the surface and the thermal core.

white dwarfs are currently known. The properties of these fascinating stars are reviewed by H. Saio in these proceedings. Finally, to be complete, we point out that distant populations of white dwarfs in open and globular clusters are now routinely detected and studied on large telescopes.

4. MODELS OF COOLING WHITE DWARFS

An instructive view of the properties of cooling white dwarfs is provided by Fig. 6 which illustrates the evolutionary tracks of five idealized models of DA stars (differing only by mass) in the theoretical HR diagram, as well as representative isochrones. Because of the peculiar mass-radius relation characterizing degenerate stars, the more massive white dwarfs are also smaller, and this is clearly shown by the evolutionary tracks. It is also obvious that these paths nearly follow curves of constant radii (straight lines with a slope of −4 in this log-log version of the HR diagram). This is particularly true for the more massive, collapsed objects, and also at low luminosities where residual gravitational contraction has practically ceased. We have indicated, along each track, three important epochs in the cooling history of a white dwarf. First, the open circles at high luminosities (two of which are offscale and, therefore, not shown) loosely define the transition between the neutrino cooling phase at higher luminosities and the thermal cooling phase at lower luminosities. The circles correspond to the epoch when the neutrino luminosity, previously dominant, becomes equal to the photon luminosity. In the early, short-lived phase of evolution immediately following the planetary nebula phase, white dwarf interiors are still hot enough for neutrinos to be formed there in great quantities through a number of processes involving the electroweak interaction. The vast majority of the neutrinos escape directly from the central regions where they are created to outer space, thus contributing to an important stellar energy sink (Fig. 3). The evolution of a very hot, young white dwarf is thus dominated by neutrino cooling. Neutrino processes largely specify the cooling timescale of a very hot white dwarf, and also lead to a temperature reversal in the stellar core. By the time a $\sim$0.6 $M_{\odot}$ white dwarf has cooled down to $T_{\rm eff}$ $\sim$25,000 K, however, the star has lost its memory of the neutrino cooling phase, and enters the thermal cooling phase proper. Its subsequent evolution and structure depend exclusively on the properties of its degenerate electrons and thermal ions.

The second set of open circles attached to the evolutionary tracks at much lower luminosities indicate the onset of convective coupling, i.e., the epoch when the base of the superficial H convection zone in these models first reaches the upper boundary of the degenerate core. From that point on convection directly affects the rate of cooling of a model since it transports energy through the outermost insulating layers more efficiently than would be possible through radiative-conductive transfer alone. The third epoch of interest is the onset of crystallization at the center of each evolving model, and this is indicated by the small filled circles on the tracks. We note that because of their larger masses *and* smaller radii, more massive white dwarfs have larger internal densities (for comparable temperatures) and, therefore, develop a crystallized core earlier, at higher luminosities or, equivalently, higher effective temperatures. Figure 6 also shows that more massive models undergo a relatively rapid and final phase of cooling toward the black dwarf state at the cool end of the sequence. This produces the dramatic bending of the later isochrones in the figure. This is due to the fact that more massive stars also reach the state where the specific heat in the solid regime plunges to very small values earlier, a phenomenon well understood within the framework of the simple Debye theory of solids in quantum statistical mechanics. In effect, matter under these conditions has lost much of its ability to store thermal energy, the energy reservoir of a white dwarf has become nearly empty, and the star must then disappear from sight in a relatively rapid phase often referred to as "Debye cooling". Crystallization and subsequent Debye cooling are responsible for the "accelerated" evolution of the more massive models at low luminosities. In contrast, at much higher luminosities, before crystallization has set in, but after neutrino cooling has subsided, Fig. 6 illustrates a more "normal" behavior: A more massive white dwarf takes longer to cool to a given effective temperature than a less massive object. This is simply because the more massive star has a larger energy reservoir, with more C ions with energy kT (in these idealized pure C-core models). Overall, the isochrones shown in Fig. 6 clearly demonstrate that the cooling time of a white dwarf is a strong function of both its luminosity (effective temperature) and its mass. Figure 7 provides a complementary view of an evolving model structure in a phase diagram.

Given the available pieces of constitutive physics for building white dwarf models (radiative and conductive opacities, equations of state, neutrino rates, diffusion coefficients), the computations of cooling ages suffer from two main uncertainties, both of which are related to our incomplete understanding of stellar evolution in phases leading to the white dwarf state. Indeed, the cooling rate of a white dwarf depends on 1) how much thermal energy is stored in the interior of the star, and 2) how rapidly this energy is transferred from the hot degenerate core to the outside through the thin but opaque outer layers. In a first approximation,

$$t_{cool} \simeq -\int_0^M C_V\, dm \times \int_{L_1}^{L_2} \frac{\partial T_c}{\partial L} \frac{dL}{L}\ . \qquad (1)$$

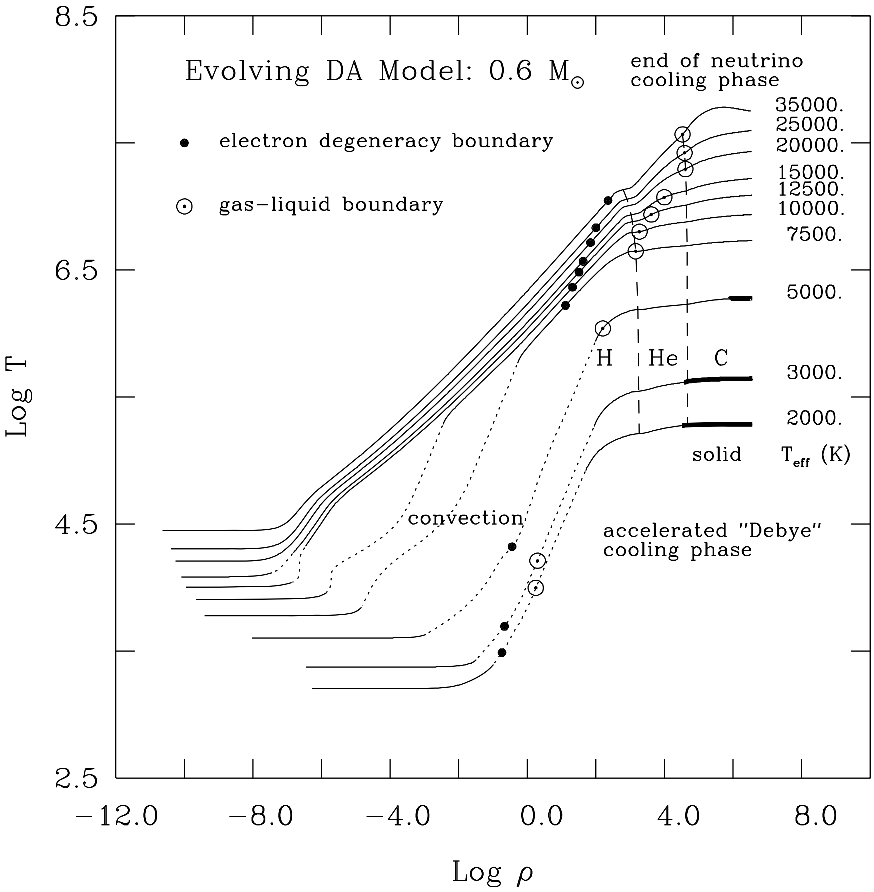

Figure 7. Evolving structure of a representative model of a DA white dwarf in a phase diagram. This model has a mass of 0.6 $M_{\odot}$ and belongs to our family of 5 reference models presented in Fig. 6. Each curve corresponds to the density-temperature distribution from the surface (defined here by the location of optical depth $\tau_R = 10^{-8}$) to the center of the model at an effective temperature given by the number alongside. The solid, dotted, and thick solid (for the 3 cooler epochs) portions of each curve indicate the radiative-conductive, convective, and crystallized regions. The top of the convection zone is always located in the photospheric layers. Electrons become degenerate to the right of the small filled circle on each curve. Likewise, the bigger open circle on each curve indicates the location to the right of which the ions become strongly correlated (fluid phase). The dashed curves define the composition transition zones, H/He at lower densities, and He/C at higher densities.

The first integral on the right-hand side, the integrated specific heat, is clearly related to the thermal energy content of the star (item 1 above). Its value depends directly on the *core composition*, which is largely unknown because of uncertainties in the rate of thermonuclear burning of He in stars. Likewise, the second integral involves the relation between the core temperature and the surface luminosity, which is given by the solution of the heat transfer problem through the envelope, from the core to the surface (item 2). That problem is specifically dependent on the *chemical stratification* in the envelope, which is largely unknown because of remaining and persistent uncertainties in AGB physics. Fortunately, pulsating white dwarfs do exist, and the power of asteroseismology can potentially be used to infer both the core composition and the envelope layering in such stars (see, e.g., the paper of N. Giammichele in these proceedings). This should go a long way toward establishing white dwarf cosmochronology on much firmer grounds than is currently possible. J. Isern reviews the potential of white dwarfs as cosmochronometers in the next paper.

5. CONVECTION AND WHITE DWARF STARS

We end this brief overview with a few remarks on the phenomenon of convection, which plays a major role in the evolution of white dwarfs in their cooler phases. Although the cooling times of white dwarf models are not affected by the usual uncertainties associated with the mixing-length theory (because convective coupling between the thermal reservoir and the surface layers occurs only in the adiabatic regime), the modeling of their atmospheres in certain temperature ranges as well as the non-adiabatic properties of the ZZ Ceti, Hot DQV's, and V777 Her pulsating white dwarfs depend sensitively on the physical treatment of convection.

It should not be surprising that cooler white dwarfs are intimately connected with convection. This is because the envelope material, initially highly ionized in the hot phases, recombines as the result of cooling. As a consequence, partial ionization zones develop, leading to the formation of very large opacity peaks. In the cooler pulsators, the opacity bumps due to the recombination of He (in the V777 Her stars), of C (in the Hot DQV stars), and H (in the ZZ Ceti stars) become so large that

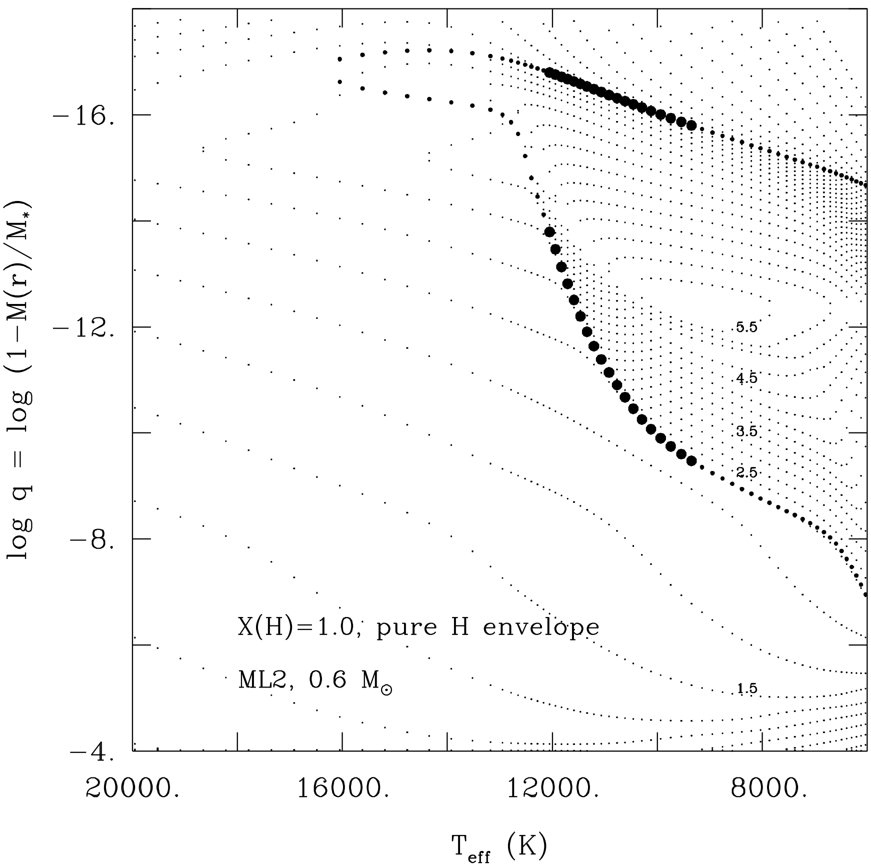

Figure 8. Structure of the envelope of a representative evolving model of a DA white dwarf. The ordinate gives the fractional mass depth in logarithmic units. On this scale, the center of the star is at log q = 0; only the outermost layers are depicted here. The small dots define "isocontours" of opacity, and some are labelled by their value of log κ. The small filled circles indicate the boundaries of the superficial convection zone that develops due to H recombination. It should be pointed out that the top of the convection zone always resides in the photospheric layers, while the base sinks into the star as it cools. The large filled circles identify the pulsationally unstable models along the evolutionary sequence.

convection sets in and modes are driven mostly through the convective driving mechanism. Given that the driving/damping zone in these stars is rather confined near the base of the superficial convection zone, and given that this location depends on the assumed mixing-length convective efficiency, the exact location of the instability strip (and other non-adiabatic properties of the pulsators) also depend on this particular choice. Figure 8 provides an example of the outer structure of an evolving DA white dwarf model computed with the so-called ML2 version of the mixing-length theory. It illustrates quite well the relationship between the opacity bump (due to recombination of the envelope constituent with cooling, H in this case) and the existence of pulsational instability phases.

P.-E. Tremblay, in these proceedings, provides us with a fresh view of convection in white dwarfs through the use of 3D hydrodynamic simulations. It is hoped that this avenue will eventually free modelers of the atmospheric layers and of the cooler pulsating white dwarfs from the uncertainties associated with mixing-length theory.