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Numerical simulations of the convective dilution process in helium-rich white dwarfs

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Abstract

DB and DBA white dwarfs are generally believed to be the result of a process by which a thin radiative hydrogen atmosphere floating in diffusive equilibrium on top of a helium envelope is eventually completely diluted in the underlying more massive helium convection zone that develops with cooling. However, the observed hydrogen abundances in these objects exceed by several orders of magnitude the predictions obtained from such a scenario invoking diffusive equilibrium, thus currently leaving the very existence of DB and DBA white dwarfs unaccounted for in any satisfactory way. We present here the results of new numerical simulations aimed at improving the modeling of this convective dilution process. In particular, we show how DA white dwarfs can be transformed into DB stars below 20,000 K, and more importantly, we propose a model that predicts the correct amount of hydrogen observed in DBA stars without invoking any accretion mechanism, an alternative model that has been proposed over the years to account qualitatively for the presence of hydrogen in the atmospheres of DBA stars.

1 Introduction

Rolland et al. (2018) presented a detailed analysis of a sample composed of 115 helium-line (DB) and 28 cool, He-rich hydrogen-line (DA) white dwarfs based on model atmosphere fits to optical spectroscopy and photometry. Hydrogen lines were detected in 63% of our DB subsample, making these objects DBA stars. Using state-of-the art envelope models, we found that the values of $M_{\rm H}$ inferred for the bulk of our sample were incompatible with the convective dilution scenario in which a thin superficial hydrogen layer is diluted with the more massive underlying helium convective envelope. We also concluded that the measured hydrogen abundances in these white dwarfs could not be accounted for by any kind of non-transient accretion mechanism. In the light of the absence of a satisfactory paradigm to explain the existence of DB and DBA stars, we report here the results of our ongoing numerical simulations. Our main goal is to improve the modeling of the convective dilution process and to provide a better understanding of the presence of hydrogen in the atmospheres of DBA white dwarfs.

2 Modeling Scheme

In our calculations, the hydrogen observed in DBA white dwarfs is assumed to have a fossil origin. Any kind of accretion from the interstellar medium or from other bodies, such as comets, is neglected throughout our simulations. As a result, the total hydrogen content is constant at every effective temperature of a given sequence of envelope models. In the outer layers of a white dwarf, typical hydrogen diffusion timescales are much smaller than cooling times. As such, the abundance profile above the mixed hydrogen/helium convection zone is assumed to be in complete diffusive equilibrium. On the other hand, full evolutionary computations (see below) tend to demonstrate that the diffusion of hydrogen in the deeper layers is an extremely slow process with respect to cooling time. In order to approximate this behavior in our simulations, the hydrogen profile below the convection zone is set to be independent of time (i.e., static).

We begin at an effective temperature high enough ($T_{\rm eff} \sim 60,000$ K) that the atmosphere and envelope are purely radiative and in full diffusive equilibrium, and we assume a given value for the total mass of hydrogen, $M_{\rm H}$, present in the star. At each temperature step, we redistribute appropriately the total amount of hydrogen within the stellar envelope and atmosphere. In particular, when convection sets in, the hydrogen abundance is assumed to be constant within the convection zone. We thus iterate on the envelope structure until the same initial amount of hydrogen is distributed below, within, and above the convection zone.

Sample abundance profiles for our $\log M_{\rm H}/M_\odot$ =

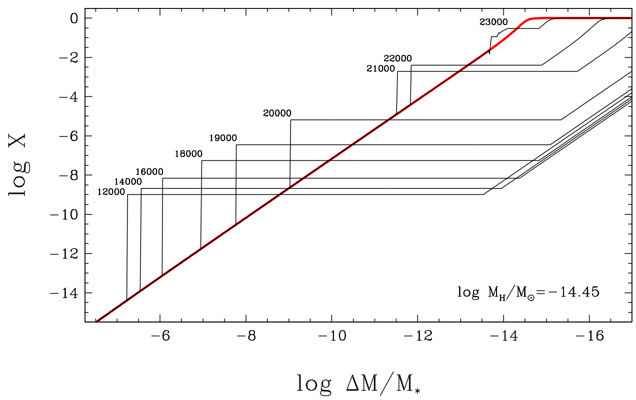

Figure 1: Sequence of envelope models at different effective temperatures for a 0.6 $M_\odot$ white dwarf with a total hydrogen content of $\log M_{\rm H}/M_\odot = -14.45$. The hydrogen mass fraction is shown as of function of depth, expressed as the fractional mass above the point of interest. The thick red line represents our reference abundance profile in diffusive equilibrium at 60,000 K. As the star cools off, the helium convective zone — seen here as the flat part of each model where the hydrogen abundance is homogeneous — becomes increasingly larger and deeper.

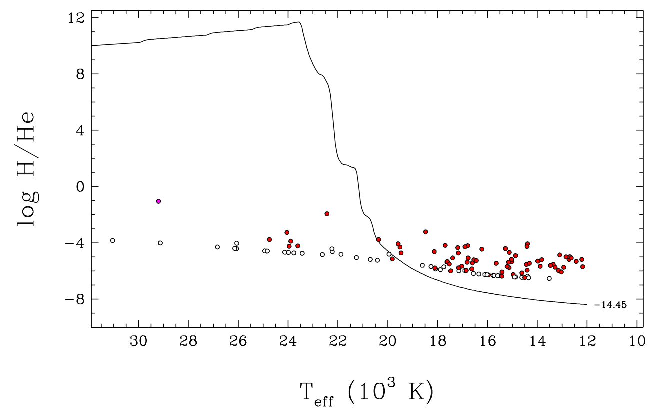

Figure 2: Hydrogen-to-helium abundance ratio (in number) predicted at the photosphere of our 0.6 $M_\odot$ white dwarf sequence with a total mass of $\log M_{\rm H}/M_\odot = -14.45$, subject to the convective dilution process. Also displayed are the results of Rolland et al. (2018) for a sample of relatively bright DB (white symbols) and DBA (red symbols) white dwarfs.

-14.45 sequence are displayed in Figure 1. With these newly computed envelope models, the helium convection zone becomes increasingly larger and deeper as the white dwarf cools off. Since these simulations assume that hydrogen is in diffusive equilibrium above the convection zone, the mass conservation of hydrogen imposed in our simulations leads to a gradual depletion of the hydrogen abundance in the outer layers. This process will eventually turn a DA white dwarf into a DB star.

3 Surface Abundance Evolution

In Figure 2, we show the predicted photospheric ($\tau_R \sim 1$) hydrogen-to-helium abundance ratio as a function of effective temperature for our sequence with a total hydrogen content of $\log M_{\rm H}/M_\odot = -14.45$. The spectroscopic determinations of Rolland et al. (2018) are also reproduced for comparison; the values for DB white dwarfs represent only upper limits set by the absence of Hα feature. While the convective dilution process occurs at $T_{\rm eff} \sim 21,000$ K, an effective temperature around which the number of DBA white dwarfs increases significantly, the predicted H/He abundance ratios are 10^2 to 10^3 smaller than the typical values observed in DBA stars, a conclusion also reached by MacDonald & Vennes (1991).

4 A Different Paradigm

We now consider a different evolution process while keeping the hypothesis that the hydrogen has a primordial origin. The starting point of this scenario is an extremely hot PG 1159 progenitor that has depleted most of its hydrogen after late thermal flashes, producing an almost completely homogeneous envelope from the surface to the C/O core. With time, diffusion will push the hydrogen distributed throughout the stellar envelope to the surface. In Figure 3, we show a snapshot at $T_{\rm eff} \sim 20,000$ K of a full set of evolutionary calculations for a stellar hydrogen mass fraction of $X({\rm H}) = 10^{-6}$, which corresponds to a total hydrogen mass of $\log M_{\rm H}/M_\odot = -7.84$. These time-dependent calculations (discussed in a future publication) reveal that even if hydrogen is a trace element in the envelope, its abundance profile is far from equilibrium because of the extremely large diffusion timescales in the deeper layers. This offers the possibility that substantial amounts of hydrogen can still be located in the deeper layers of a white dwarf. Furthermore, since the photosphere is usually close to the surface at these effective temperatures ($\log \Delta M/M_\star \sim -15.5$), the majority of the hydrogen in the envelope thus sits in a deep reservoir and is invisible to spectroscopic observations.

5 Convective Dredge-up

In order to take into account that large amounts of hydrogen might be hidden in the deeper layers of the envelope, we replaced our equilibrium profile (see Figure 1) with

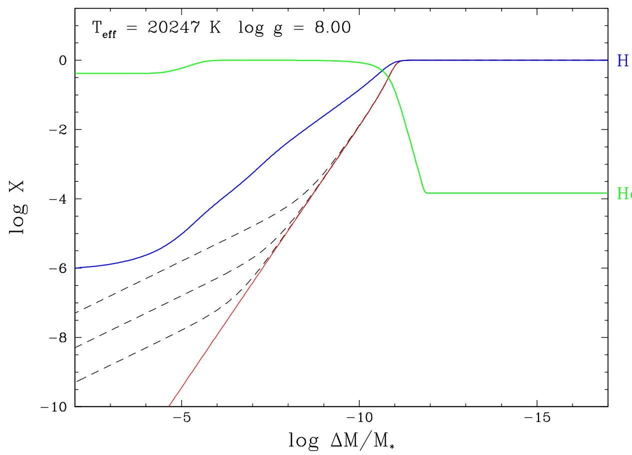

Figure 3: Snapshot of the hydrogen (blue) and helium (green) mass fractions as a function of depth taken from time-dependent calculations of a 0.6 $M_\odot$ white dwarf with a total hydrogen mass fraction of $X(\mathrm{H}) = 10^{-6}$. Also displayed in red is a diffusive equilibrium profile containing $\sim 10^{-11}\ M_\star$ of hydrogen. Three examples of our approximate power law profiles (see text) are represented by dashed lines.

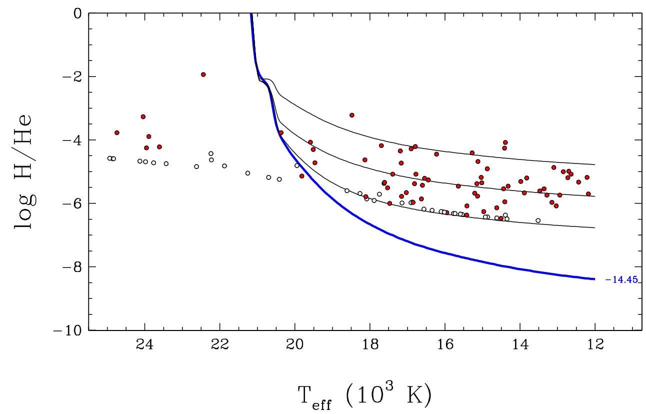

Figure 4: Hydrogen-to-helium abundance ratio (in number) predicted at the photosphere by our simulations including dredge-up for a 0.6 $M_\odot$ white dwarf. Also shown is our original sequence reproduced from Figure 2 with a total mass of $\log M_\mathrm{H}/M_\odot = -14.45$ (blue), as well as the results of Rolland et al. (2018) for DB (white symbols) and DBA (red symbols) white dwarfs.

a more appropriate empirical function of the form

$$\frac{n_\mathrm{H}}{n_\mathrm{He}} = \gamma_{eq} + \gamma_0 \left(\frac{p}{p_0}\right)^{-\frac{1}{2}} \tag{1}$$

where γ_{eq} represents our original equilibrium profile, and the second term is the contribution of the hydrogen reservoir for which p is the total pressure, and γ_0 and p_0 are scaling constants. The choice of a power law is inspired by the analytical calculations of Vennes et al. (1988) for a binary plasma without radiative levitation. For a trace H II in a background of He III, the theoretical exponent should be $-5/4$ at diffusive equilibrium. Since a homogeneous profile is implicitly a zeroth order function, we settled for a midway exponent $(-1/2)$ to characterize the ongoing upward diffusion. Three examples of this composite abundance profile are displayed in Figure 3 for an equilibrium contribution with a hydrogen content of $\log M_\mathrm{H}/M_\star = -11$, which resemble the true time-dependent hydrogen profile. In Figure 4, we present our new sequence of envelope models using equation 1.

Our simulations clearly show that hydrogen dredge-up can easily explain the observed abundance in DBA stars. Our calculations also indicate that, in this context, the hydrogen layer at the surface only represents 0.07% of the total hydrogen mass present in the white dwarf, a value smaller than in most standard evolutionary scenarios.

6 Discussion

Our calculations indicate that the dilution process of a thin, superficial hydrogen radiative layer by the underlying and more massive convective helium envelope can occur near $T_\mathrm{eff} \sim 20,000$ K if the superficial hydrogen layer mass is of the order of $\log M_\mathrm{H}/M_\odot = -14.45$. Despite the concordance of this result with the temperature range where DBA white dwarfs are found, all the scenarios where hydrogen is in diffusive equilibrium yield photospheric abundances that are up to 3 orders of magnitude below the values observed in these objects. Instead, our exploratory calculations of a different paradigm, where hydrogen is initially diluted in the deeper layers of the stellar envelope and slowly diffuses upward, showed that its abundance profile is far from equilibrium when the convective dilution process occurs. As a consequence, as the convection zone grows, large amounts of hydrogen are dredged-up to the surface, a phenomenon similar to that invoked in the context of DQ white dwarfs (Pelletier et al., 1986). This new approach reproduces very well the hydrogen-to-helium abundance ratios observed in DBA stars without the need for any kind of accretion mechanism. However, more detailed and rigorous calculations are needed to confirm that this new process is actually occurring in DBA white dwarfs.

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