He white dwarfs with large H contamination: Convective mixing or accretion?

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Abstract
White dwarfs are compact objects with atmospheres containing mainly light elements, hydrogen or helium. Because of their surface high gravitational field, heavy elements diffuse downwards in a very short timescale compared to the evolutionary timescale, leaving the lightest ones on the top of the envelope. This results in the main classification of white dwarfs as hydrogen rich or helium rich. But many helium rich white dwarfs show also the presence of hydrogen traces in their atmosphere, whose origin is still unsettled. Here we study, by means of full evolutionary calculations, the case for a representative model of the “He-H-Z” white dwarfs, a sub-group of helium rich white dwarfs showing both heavy elements and a large amount of hydrogen in their atmosphere. We find it impossible to explain its hydrogen atmospheric content by the convective mixing of a primordial hydrogen present in the star. We conclude that the most likely explanation is the accretion of hydrogen rich material, presumably water-bearing, coming from a debris disk.

1 Introduction
White dwarfs are the final evolutionary stage of most of the stars (Althaus et al., 2010). They are classified according to their spectroscopic appearance into two main classes. The more abundant type (∼ 80%) has H-rich atmospheres and are labeled as DA white dwarfs, whereas the remaining ∼ 20% corresponds to those showing He-dominated atmospheres and are referred to as DB white dwarfs (Giannicchele et al., 2012; Kleinman et al., 2013).

Spectroscopy cannot provide any constraint on the total fractional mass of the H layer and/or the He layer present in DA or DB white dwarfs. In this respect, asteroseismology is a powerful tool to determine these values. From asteroseismological studies it is founded that the hydrogen mass fraction may vary from 10^{-10} to 10^{-4} and the helium mass fraction is around 10^{-2} (see for instance Romero et al., 2012).

This picture becomes more complicated when other elements are present in their spectra. Particularly interesting is the case of cool white dwarfs showing heavy elements in their atmospheres. These heavy elements should indeed diffuse downwards, because of the high gravitational field of these compact objects, on time scales short compared to the evolutionary timescale. As many as 25 to 50 percent of the observed white dwarfs show heavy elements in their atmospheres. Some of these metallic-line white dwarfs also show an excess of radiation in the infrared. This is widely accepted as evidence of ongoing (or recent) accretion of material from debris disks.

The detection of H traces in DB white dwarfs has also modified the initial simple picture (Voss et al., 2007; Bergeron et al., 2011; Koester & Kepler, 2015). The origin of this hydrogen is still under discussion. Three different theories have been proposed to explain it:

- accretion from the interstellar medium (ISM),
- convective mixing of primordial H, and
- accretion of H-rich material from a debris disk.

Based on the largest sample of DB white dwarfs studied so far, Koester & Kepler (2015) concluded that the ISM accretion can be ruled out since there is no correlation of the number of DB with H traces with the distance above the Galactic plane and also that there is no evidence that the hydrogen abundance increases with time in these stars.

The convective mixing theory refers to the fact that white dwarfs develop a surface convective region deepening as they cool down below T_{\text{eff}} ≈ 25000 K. If hydrogen is present before convection sets in, it should float on top of helium and the white dwarf would be classified as a DA. On the other hand, if the H content is small and the star is cool enough, the convection zone may reach the H/He transition zone, dredge helium up to the surface and dilute the small amount of H into a larger (convective) region. As a result, the former DA white dwarf may become a DB with traces of hydrogen.

This seems to be a possible explanation for DBs showing small hydrogen traces (Koester & Kepler, 2015). Here we test whether it can also explain the case of the handful of DB white dwarfs showing both heavy elements and a large amount of hydrogen in their envelope (GD 16, GD 17, SDSSJ1242+5226, GD 362, PG 1225-079 referred to as He-H-Z white dwarfs, see Gentile Fusillo et al., 2017). In order to carry out this work, we perform full evolutionary simulations (which include all relevant physical processes) to test this channel of formation.

2 Method and results
All numerical experiments were done using the LPCODE stellar evolutionary code (Althaus et al., 2005, 2013). The method used in this work is similar to the one described in Wachlin et al. (2017).

We generated an initial model representative of the He-H-Z white dwarfs by adapting the 0.767 M_⊙ white dwarf model taken from Renedo et al. (2010), which was obtained from full evolutionary calculations.

The chemical composition of the accreted matter was chosen, at first, to mimic the bulk Earth composition (Allègre et al., 2001). At a second stage, we used a different chemical composition taken from Zuckerman et al. (2007).

In order to study whether convective mixing of primor-
dial hydrogen is able to explain the H/He ratio observed in the He-H-Z white dwarfs, we studied a representative model with a set of stellar parameters close to those for GD 362 (Koester, 2009), thus \( T_{\text{eff}} = 10540 \text{ K}, M_{\text{wd}} = 0.73 M_\odot \) and \( M_H = 3.51 \times 10^{-5} M_\odot \). We also chose an initial model with an amount of hydrogen as estimated from the observations of GD 362.

When no accretion is taken into account, we found that helium cannot be dredged up to the outer layers. We then included accretion of matter in our simulations with accretion rates in the range from \( 10^{-7} \) to \( 10^{-5} \text{ g/s} \), adopting the chemical distribution of the bulk Earth composition (not hydrogen or helium included). Such accretion of heavy elements on a DA white dwarf triggers fingering convection below the convective envelope which affects the photosphere’s composition (Deal et al., 2013; Wachlin et al., 2017).

Figure 1 shows the final stellar structure of our representative model for an accretion rate of \( 10^{-5} \text{ g/s} \), once a stationary state has been achieved. Hydrogen remains the most abundant element on the surface, although some helium has been dredged-up. Notice that without taking into account fingering convection, no helium would have been dredged-up at all. This clearly does not reproduce the surface composition of the He-H-Z white dwarfs, where helium is the most abundant element. Increasing the accretion rate does not change the qualitative result.

We also explored the case of initial models with less hydrogen, such that the convection (including fingering convection) be able to transform the initial DA into a DB white dwarf. Therefore, we run a new set of simulations and found that, for this \( T_{\text{eff}} \), it is not possible to attain the transformation unless we reduce the amount of primordial hydrogen by about two orders of magnitude. Then suddenly helium becomes the most abundant element on the surface, much more abundant than hydrogen (\( \log(n_{\text{He}}/n_X) \approx 3.5 \), where \( n_X \) is the density by number of element \( X \). From Koester (2009) we know that the He-H-Z white dwarfs have a significantly higher H/He abundance ratio (it is \( \log(n_{\text{He}}/n_\text{H}) \approx 1.14 \) for GD 362). Thus our experiment overestimates the amount of helium dredged-up from the inner layers. Other simulations, increasing the amount of primordial hydrogen gave similar results. None of them was able to better reproduce the surface relation between hydrogen and helium. Interestingly, the experiments show that there is no smooth transition between the two kinds of results: either hydrogen was dominant, or helium in an overwhelming proportion.

From these results we conclude that the theory of convective mixing of primordial hydrogen cannot explain the case of the He-H-Z white dwarfs. Since accretion from the ISM has been ruled out by observational arguments, this leaves us with the remaining theory that sustains that accretion of hydrogen rich material from a debris disk must be responsible for the hydrogen traces observed in those stars.

3 Conclusions

We studied the theory of convective mixing of primordial hydrogen as the explanation of the He-H-Z white dwarfs, a sub-type of DB white dwarf which show an exceptionally high amount of hydrogen in their atmosphere. By performing numerical simulations we found that, for a typical hydrogen content estimated for such star (it is \( M_H = 3.51 \times 10^{-5} M_\odot \) for instance in GD 362), it is not possible to produce the transformation from DA to DB that should take place if convective mixing would be an efficient mechanism to dredge-up helium from the interior. By lowering the amount of hydrogen we increase the chances to dredge-up helium, since the H/He transition zone becomes closer to the surface. We found that is necessary to reduce the amount of hydrogen by approximately two orders of magnitude in order to achieve the transformation of the atmosphere from hydrogen rich to helium rich. Unfortunately it is not possible to reproduce the correct proportion of H/He when the transformation is successful.

We conclude from the present work that the He-H-Z white dwarfs represent particularly interesting objects because their existence seems to require the accretion of hydrogen rich material from the surroundings. This hydrogen rich material may come from different compounds like ammonia (NH\(_3\)) or methane (CH\(_4\)), but also from water-bearing planetesimals, as suggested earlier by Farihi et al. (2013), Raddi et al. (2015) and Gentile Fusillo et al. (2017). This last possibility suggest a very appealing way of exploring the potential of planetesimals to provide water in connection with the question of exo-planets habitability. These results will be presented in more details in a forthcoming paper.

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