White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
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The spectral evolution of cool white dwarfs

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Abstract. Empirically characterizing the spectral evolution of cool white dwarfs is a prerequisite to understanding the physical processes that shape the evolution of these old objects. However, the high photospheric densities of cool helium-rich atmospheres seriously complicate the study of those stars. We have recently developed an updated atmosphere code that is appropriate for high densities and that can model any cool white dwarf (including DZs and DQpecs). Here, we present recent advances in our understanding of the spectral evolution of cool white dwarfs that were made possible thanks to these improved models. We discuss in particular the evolution of the hydrogen-rich to helium-rich ratio at low effective temperatures as well as the DQ→DQpec transition.

Keywords. stars: abundances, stars: atmospheres, stars: evolution, white dwarfs

1. Introduction

Many different physical processes can affect the surface composition of a white dwarf throughout its evolution. These include diffusion, convective mixing, convective dilution, convective dredge-up from the core, radiative levitation, accretion from the interstellar medium and accretion of rocky debris. The competition between these mechanisms leads to the spectral evolution of white dwarfs, a topic that has been studied for decades. As larger and more accurate surveys become available, our understanding of spectral evolution and the underlying physical processes become gradually more complete (see in particular A. Bédard et al. and T. Cunningham et al. in these proceedings).

However, by lack of appropriate atmosphere models, the spectral evolution of the coolest white dwarfs has remained nebulous. Here, we describe the recent advances that were made possible thanks to our new cool white dwarf atmosphere models (see Blouin *et al.* 2018 and references therein for a complete description of the improved physics of our updated code).

2. The hydrogen-rich to helium-rich ratio

Previous attempts to constrain the ratio of H-rich to He-rich atmospheres for the coolest white dwarfs can be roughly divided into two categories. The first set of studies was based on the Montreal atmosphere code (Bergeron *et al.* 1997, 2001, Kilic *et al.* 2010) and the second set of studies relied on P. Kowalski's code (Kowalski 2006, Kilic *et al.* 2009). The major advantage of the second code is that it includes many high-density nonideal effects that need to be taken into account when modeling the fluidlike atmospheres of cool, He-rich white dwarfs. However, contrarily to the studies based on the Montreal code, studies that relied on P. Kowalski's code were limited to DA and DC stars, thus ignoring the He-rich DQs and DZs from their analyses.

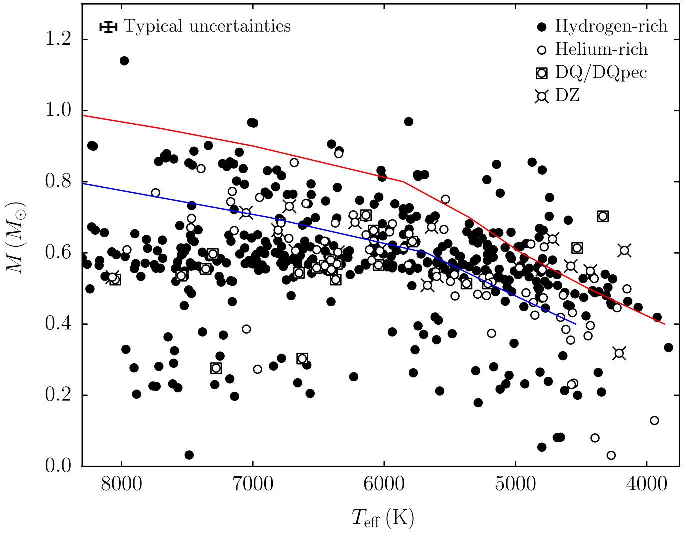

Figure 1. Mass of white dwarfs in our sample as a function of their effective temperatures. The blue and red curves indicate, respectively, the locations where 10% and 80% of the total mass has crystallized.

As we recently developed an updated atmosphere code that includes all relevant non-ideal effects and is suitable for any cool white dwarf, we were able to solve the issues that affected previous studies. We used this code to revisit the question of the H-rich to He-rich ratio of cool white dwarfs and we did so using an unbiased sample, without any discrimination on the spectral type. This section is a summary of the main results of this study, the details can be found in Blouin *et al.* (2019).

An $M - T_{\rm eff}$ diagram with all 501 objects contained in our sample is shown in Figure 1. As expected, most objects are clustered either around 0.6 $M_\odot$ or within the crystallization sequence where a pile-up is expected due to latent heat release and extra thermal energy resulting from the first phase of convective coupling (see also Bergeron *et al.* 2019 and Tremblay *et al.* 2019).

Figure 2 shows how the fraction of white dwarfs with H-rich atmospheres evolves with decreasing $T_{\rm eff}$. The first important trend that can be noticed is the decrease of the H-rich fraction between ≈ 8000 and 6000 K. This can be interpreted as the conversion of H-dominated white dwarfs into He-dominated objects due to convective mixing. Then, between ≈ 6000 and 5000 K, there seems to be an increase of the H-rich fraction. This feature is reminiscent of the non-DA gap, already described in various studies (e.g., Bergeron *et al.* 1997, 2001, Kilic *et al.* 2010). The origin of this increase remains unknown, although we note that our results allow us to eliminate the hypothesis according to which it is due to accretion of hydrogren from the interstellar medium (Kowalski 2006). If accretion of hydrogen were important, we would expect the increase of the H-rich fraction to continue down to 4000 K. On the contrary, we find that it stops at ≈ 5000 K (note that the apparent decrease of the H-rich fraction below 5000 K is probably mainly due to the faster cooling rate of He-atmosphere white dwarfs, as we find that the H-rich fraction stays approximately constant if plotted as a function of the cooling time).

While we took great care to avoid or correct any selection effect in our sample, we recognize that magnitude-limited spectroscopically identified samples can be prone to intractable biases (mainly due to complex SDSS selection effects). On the one hand, except for objects cooler than 5000 K (where differences are expected due to differences in model atmospheres), it is comforting that our results are in agreement with those of

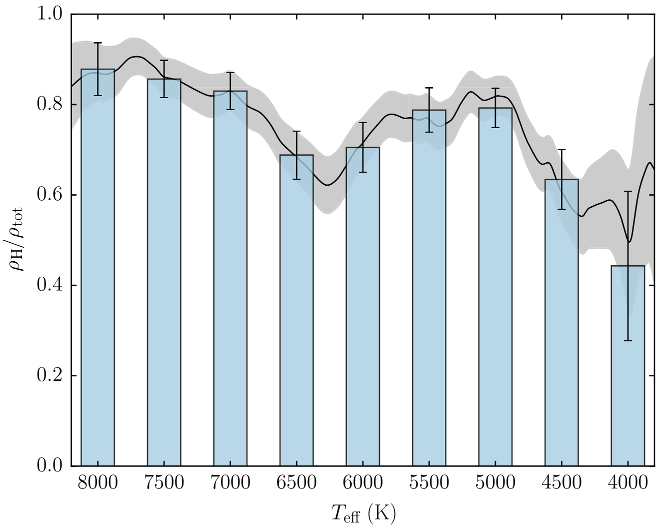

Figure 2. Fraction of H-rich white dwarfs as a function of effective temperature for fixed 500 K bins (in blue) and for a 500 K moving bin (in gray). The error bars indicate the 1σ uncertainty associated with the finite number of objects in each bin.

Limoges *et al.* (2015). Their sample was selected from reduced proper motion diagrams and is therefore not subject to biases in favor of H-rich or He-rich objects. On the other hand, the disagreement with the results of Cunningham *et al.* (2019) at the hotter hand of our sample is troubling, since their study is based on a volume-limited photometric sample for which selection effects are well understood. Hopefully, a large enough volume-complete sample of spectroscopically identified white dwarfs will soon allow us to investigate these differences.

3. Carbon-polluted white dwarfs

At low T_{eff}, the C_2 Swan bands visible in carbon-polluted white dwarfs are distorted and shifted due to high-pressure effects (Kowalski 2010), which explains the DQpec phenomenon. Our code contains all the necessary physics to obtain satisfactory fits to those objects and, in Blouin & Dufour (2019), we present the first comprehensive star-by-star analysis of DQpecs. Our results allow us to extend our understanding of the evolution of carbon-polluted white dwarfs down to very low T_{eff}.

At higher T_{eff}, DQs are clustered along two distinct evolutionary sequences (Coutu *et al.* 2009; Koester & Kepler 2019). Most of them are normal-mass white dwarfs located along a track that is well explained by the dredge-up scenario (Figure 3). The second sequence, made of more polluted and generally more massive objects, is thought to be at least partially made of the descendants of Hot DQs.

In Figure 3, we show where DQpec white dwarfs (roughly, objects cooler than 6500 K) are located with respect to the two DQ sequences in a log C/He $-$ T_{eff} diagram. The main result of this analysis is that DQpecs are simply the natural continuation of the DQ phenomenon, no matter what was the origin of carbon in the atmosphere. Most of them are the likely descendants of DQs that have dredged-up carbon from their core and a smaller fraction, located close to the second sequence, could be the descendants of Hot DQs (especially the more massive ones).

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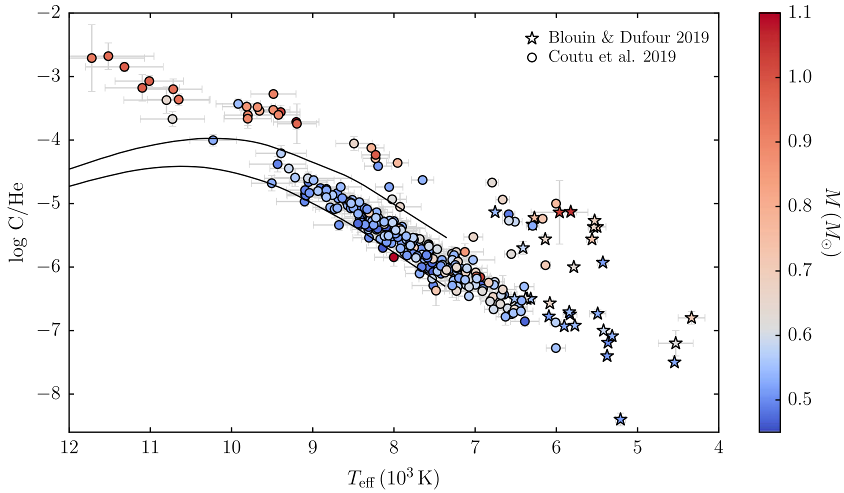

Figure 3. Carbon abundance as a function of effective temperature for white dwarfs in the Blouin & Dufour (2019, stars) and (Coutu *et al.* 2019, circles) samples. The solid lines correspond to the evolutionary models of Fontaine & Brassard (2005) assuming $M_{\rm WD} = 0.6\, M_\odot$ and $\log q({\rm He}) = -3$ (top) or $\log q({\rm He}) = -2$ (bottom).

Acknowledgments

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