White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
Proceedings IAU Symposium No. 357, 2019
M. A. Barstow, S. J. Kleinman, J. L. Provencal & L. Ferrario, eds.
doi:10.1017/S1743921320000289

The spectral evolution of hot white dwarfs

Antoine Bédard, Pierre Bergeron and Gilles Fontaine

Département de Physique, Université de Montréal, Montréal, QC H3C 3J7, Canada
emails: bedard@astro.umontreal.ca, bergeron@astro.umontreal.ca

Abstract. As they evolve, white dwarfs undergo major changes in their atmospheric composition, a phenomenon known as spectral evolution. In particular, most hot He-rich (DO) stars transform into H-rich (DA) stars as they cool off, most likely as a result of the float-up of residual H. We investigate this DO-to-DA transition by taking advantage of the extensive spectroscopic dataset provided by the Sloan Digital Sky Survey (SDSS). Using our new state-of-the-art non-LTE model atmospheres, we perform a spectroscopic analysis of 1882 hot ($T_{\rm eff} > 30,000$ K) white dwarfs identified in the SDSS. We find that at least 15% of all white dwarfs are born with a He-dominated atmosphere. Among these, ∼2/3 turn into H-rich stars before they reach $T_{\rm eff} \sim 40,000$ K, while the remaining ∼1/3 maintain their He-rich surface throughout their entire evolution. We speculate on the origin of these two groups of objects.

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

1. Introduction

White dwarf stars can be divided into two main groups based on their atmospheric composition, either H-rich or He-rich. In both cases, the atmosphere usually displays a high degree of chemical purity, resulting from the high efficiency of gravitational settling in the strong gravitational field of white dwarfs. The corresponding optical spectra are thus dominated either by H lines (spectral class DA) or by He lines (spectral classes DO for $T_{\rm eff} \gtrsim 45,000$ K and DB for $T_{\rm eff} \lesssim 45,000$ K).

Interestingly, the distribution of spectral types along the white dwarf cooling sequence is far from uniform. In particular, the hot ($T_{\rm eff} > 30,000$ K) white dwarf population exhibit two striking features: a deficiency of DA stars at the very hot end of the cooling sequence ($T_{\rm eff} > 90,000$ K), and a deficiency of DB stars within the so-called DB gap ($45,000 \text{ K} > T_{\rm eff} > 30,000$ K). Between the two regimes, the fraction of He-rich objects is observed to decrease monotonously (Fontaine & Wesemael 1987). This suggests that the main atmospheric constituent of a white dwarf can change radically as it cools, a phenomenon referred to as spectral evolution. More specifically, the above-mentioned trend is best explained by a scenario in which most white dwarfs are born with a He-dominated atmosphere, but eventually develop a H-dominated atmosphere.

The physical mechanism most likely responsible for such a transformation is described by the so-called float-up model. It is generally believed that hot He-rich white dwarfs descend from stars that experience a late He-shell flash, following which the outer H layer is mixed deeply into the He envelope and hence burned (Werner & Herwig 2006). According to the float-up model, a small amount of H survives this evolutionary episode, but initially remains invisible (since it is thoroughly diluted within the He envelope). However, under the influence of gravitational settling, this residual H gradually diffuses upward and accumulates at the surface, ultimately causing a DO star to turn into a DA star (Fontaine & Wesemael 1987).

The float-up model, while qualitatively accounting for the spectral evolution of hot white dwarfs, has seldom been quantitatively investigated. Most notably, it is still unclear what fraction of white dwarfs undergo the DO-to-DA transition, and what fraction retain a H-rich or He-rich atmosphere throughout their life. As the spectral evolution of a degenerate star depends sensitively on its total H content, such measurements can provide global constraints on the amount of H inherited from previous evolutionary phases. We propose to tackle this issue by studying the statistical variations of atmospheric composition with effective temperature for a large sample of hot stars.

2. Sample

The largest spectroscopic sample of white dwarfs is provided by the Sloan Digital Sky Survey (SDSS). Starting from the available SDSS white dwarf catalogs (Kleinman *et al.* 2013; Kepler *et al.* 2015, 2016), we first defined a color-selected ($u-g<0$) sample of 6270 objects, whose optical spectra were then retrieved from the SDSS database. For classification purposes, we performed preliminary fits to all spectra with both our pure-H and pure-He model atmospheres (see below). All fits were visually inspected, and stars with $T_{\rm eff}<30,000$ K or $\log g<6.5$ were rejected. Our final sample contains 1882 white dwarfs, including 1713 DA, 95 DO, and 74 DB stars. Also, note that 128 objects show a hybrid spectrum with both H and He lines (spectral type DAO, DAB, DOA, or DBA).

3. Model Atmospheres

We employed the codes TLUSTY and SYNSPEC (Hubeny & Lanz 1995) to compute non-LTE H+He model atmospheres and synthetic spectra. We constructed two sets of models differing by the assumed chemical configuration, which we refer to as homogeneous and stratified. In our chemically homogeneous models, H and He are distributed uniformly throughout the atmosphere, in which case the He-to-H number ratio (He/H) is a free parameter. Our homogeneous grid covers $30,000\ {\rm K}<T_{\rm eff}<150,000$ K, $6.5<\log g<9.5$, and $-6.0<\log {\rm He/H}<6.0$. In our chemically stratified models, a thin H layer floats on top of a He envelope in diffusive equilibrium, in which case the mass of the H layer ($M_{\rm H}/M_*$) is a free parameter. The equilibrium chemical profile is obtained from the formalism of Vennes *et al.* (1988). Our motivation for calculating these models arises from the float-up model: as the float-up process builds a thin H layer at the surface, a chemically stratified atmosphere is indeed expected. Our stratified grid covers $30,000\ {\rm K}<T_{\rm eff}<60,000$ K, $6.5<\log g<9.5$, and $-13.0<Q<-5.0$ where $Q\equiv 3\log g+2\log M_{\rm H}/M_*$. Note that models at the composition boundaries of our grids are practically identical to pure-H and pure-He atmospheres. Finally, it is worth mentioning that we implemented in TLUSTY and SYNSPEC the state-of-the-art treatment of Stark broadening of He I lines from Beauchamp *et al.* (1997), which is essential to properly reproduce the observed spectrum of He-rich white dwarfs.

4. Spectroscopic Analysis

For each star in our sample, we fitted the optical spectrum with our model atmosphere grids in order to derive the effective temperature, the surface gravity, and the atmospheric composition. We relied on our usual two-step fitting procedure: we first normalized the observed and synthetic spectra to a continuum set to unity, and then minimized the difference between these normalized spectra using the non-linear least-square Levenberg-Marquardt algorithm. Objects showing only H lines or only He lines were simply analyzed with pure-H or pure-He models, respectively. Hybrid white dwarfs were analyzed with both our homogeneous and stratified grids, and we adopted the best-fitting solution.

https://doi.org/10.1017/S1743921320000289 Published online by Cambridge University Press

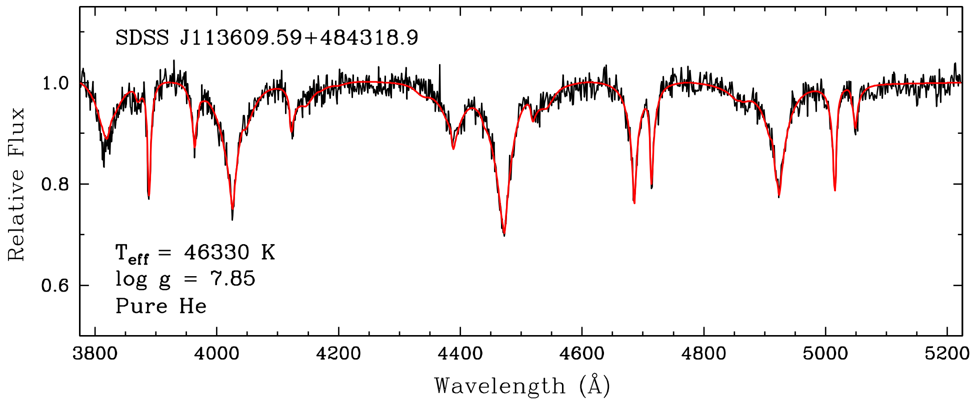

Figure 1. Example of a spectroscopic fit for a DO star in our sample. The observed and synthetic spectra are shown as the black and red lines, respectively, and the best-fitting atmospheric parameters are given in the figure.

Indeed, the H and He line profiles can be quite sensitive to the outer chemical configuration, which could thus be determined unambiguously in most cases (Manseau *et al.* 2016). Figure 1 displays an example of a fit for a DO star in our sample.

5. Results and Discussion

The left panel of Figure 2 presents the fraction of He-dominated white dwarfs as a function of decreasing effective temperature for our sample. The fraction of He-rich stars falls between 55 and 70% at the beginning of the cooling sequence, but drops sharply to ∼15% at ∼90,000 K. Taken at face value, this result seems to imply that between 40 and 55% of all white dwarfs are born with a He-rich atmosphere and then develop a H-rich atmosphere very early in their evolution, perhaps because they contain a relatively large amount of residual H (say, $M_{\rm H}/M_{*} \sim 10^{-6}$) that rapidly floats to the surface. Nevertheless, the large proportion of He-rich objects observed at very high temperatures might also be an artifact of the difference in evolutionary timescales between H-atmosphere and He-atmosphere white dwarfs. As discussed in recent studies, DA stars evolve faster than their DO counterparts at the beginning of the cooling sequence, hence the apparent lack of very hot DA white dwarfs (Werner *et al.* 2019).

Going down the temperature scale, we find that the fraction of He-rich objects is roughly constant between 90,000 and 60,000 K, and then decreases gradually from ∼15% at ∼60,000 K to ∼5% at ∼40,000 K. This suggests that, among the ∼15% of stars whose atmosphere is still He-dominated at ∼60,000 K, ∼2/3 contain a small amount of residual H (say, $M_{\rm H}/M_{*} \sim 10^{-10}$) that slowly floats to the surface, while ∼1/3 contain no H whatsoever. Therefore, below ∼40,000 K, the former become DA white dwarfs, while the latter remain DB white dwarfs. This interpretation is fairly robust, contrary to the case of hotter objects discussed in the previous paragraph, since the cooling ages of H-rich and He-rich stars become similar at lower temperatures. Thus, we can confidently assert the following: *at least* 15% of all white dwarfs are born with a He-dominated atmosphere, and those comprise two distinct groups, namely, H-deficient objects and H-free objects. Interestingly enough, this is somewhat reminiscent of the two known evolutionary channels feeding the He-rich white dwarf population, each associated with a different progenitor: the He-, C- and O-rich PG 1159 stars produced by a late He-shell flash, and the He-rich O(He) stars formed through a merger process (Reindl *et al.* 2014). We speculate that these two channels produce the two groups of hot He-rich white dwarfs that we have identified. More specifically, we propose that white dwarfs descending from

https://doi.org/10.1017/S1743921320000289 Published online by Cambridge University Press

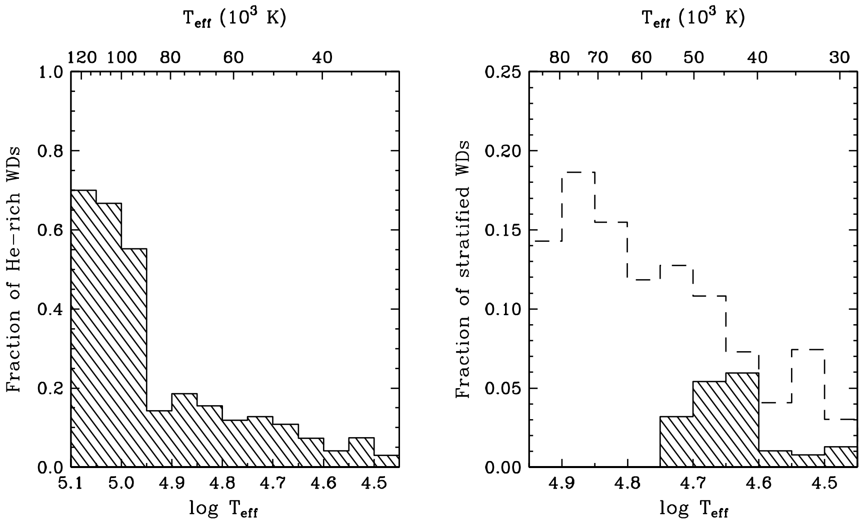

Figure 2. *Left panel:* Fraction of He-rich white dwarfs as a function of effective temperature. *Right panel:* Fraction of chemically stratified white dwarfs as a function of effective temperature. The histogram from the left panel is shown as the dashed line for comparison.

PG 1159 stars initially are He-rich but eventually become H-rich through the float-up of residual H, while white dwarfs descending from O(He) stars retain a He-dominated atmosphere throughout their entire evolution (perhaps because the whole H content was lost in the merger event). According to our results, these two evolutionary channels account for ∼10% and ∼5% of the total white dwarf population, respectively.

Finally, our spectroscopic analysis allowed us to identify 27 white dwarfs with a chemically stratified atmosphere. The right panel of Figure 2 displays the fraction of stratified objects as a function of decreasing effective temperature. The fraction of He-rich stars (the histogram from the left panel) is also reproduced for comparison. It is interesting to note that the stratified white dwarfs are found mainly in the temperature range where the fraction of He-rich white dwarfs decreases, just above the DB gap ($55,000$ K $> T_{\rm eff} > 40,000$ K). This confirms the idea that they are transitional objects currently undergoing the DO-to-DA conversion, and consequently lends strong support to the float-up model.

References

Beauchamp, A., Wesemael, F., & Bergeron, P. 1997, *ApJS*, 108, 559
Fontaine, G. & Wesemael, F. 1987, *IAU Colloq. 95: 2nd Conference on Faint Blue Stars*, 319
Hubeny, I. & Lanz, T. 1995, *ApJ*, 439, 875
Kepler, S. O., Pelisoli, I., Koester, D., *et al.* 2015, *MNRAS*, 446, 4078
Kepler, S. O., Pelisoli, I., Koester, D., *et al.* 2016, *MNRAS*, 455, 3413
Kleinman, S. J., Kepler, S. O., Koester, D., *et al.* 2013, *ApJS*, 204, 5
Manseau, P. M., Bergeron, P., & Green, E. M. 2016, *ApJ*, 833, 127
Reindl, N., Rauch, T., Werner, K., *et al.* 2014, *A&A*, 572, A117
Vennes, S., Pelletier, C., Fontaine, G., *et al.* 1988, *ApJ*, 331, 876
Werner, K. & Herwig, F. 2006, *PASP*, 118, 183
Werner, K., Rauch, T., & Reindl, N. 2019, *MNRAS*, 483, 5291

https://doi.org/10.1017/S1743921320000289 Published online by Cambridge University Press