Towards an Understanding of the Atmospheres of Cool White Dwarfs

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Abstract. Cool white dwarfs with $T_{\text{eff}} \lesssim 6000$ K are the remnants of the oldest stars that existed in our Galaxy. Their atmospheres, when properly characterized, can provide valuable information on white dwarf evolution and ultimately star formation through the history of the Milky Way. Understanding the atmospheres of these stars requires joined observational effort and reliable atmosphere modeling. We discuss and analyze recent observations of the near-ultraviolet (UV) and near-infrared (IR) spectrum of several cool white dwarfs including DQ/DQp stars showing carbon in their spectra. We present fits to the entire spectral energy distribution (SED) of selected cool stars, showing that the current pure-hydrogen atmosphere models are quite reliable, especially in the near-UV spectral region. Recently, we also performed an analysis of the coolest known DQ/DQp stars investigating further the origin of the C$_2$ Swan bands-like spectral features that characterize the DQp stars. We show that the carbon abundances derived for DQp stars fit the trend of carbon abundance with $T_{\text{eff}}$ seen in normal cool DQ stars. This further supports the recent conclusion of Kowalski (2010a) that DQp stars are DQ stars with pressure distorted Swan bands. However, we encounter some difficulties in reproducing the IR part of the SED of stars having a mixed He/H atmosphere. This indicates limitations in current models of the opacity in dense He/H fluids.

1. Introduction

Being billions of years old, cool white dwarfs (WD) represent the last stage of the evolution of most stars. When properly understood these stellar remnants may be used to investigate stellar evolution, cosmochronometry [Fontaine et al. 2001; Richer et al. 2006] and even to determine the bulk composition of exoplanetary material thought to be accreting on the surfaces of many WD (e.g. Farihi et al. 2010). In order to extract the valuable information contained in the spectra of cool WD, we have to properly understand their atmospheres (Kowalski 2010b) where more extreme physical conditions are encountered than in normal stars. In particular, He-dominated atmospheres have
fluid-like densities (up to a few g/cm$^3$, Kowalski & Kilic (2010)). Over the last decade many dense-medium effects were introduced into the modeling, substantially increasing the fidelity of the atmosphere models. This has resulted in significant improvements in our understanding of these stars (see Kowalski & Kilic (2010) and Kowalski (2010b)). Here we briefly discuss the current state of understanding of cool white dwarfs and the results of our most recent studies.

2. Atmospheres of hydrogen and helium

2.1. Test of pure-hydrogen models

With the inclusion of the red wing of the Ly-$\alpha$ line and improvements in the description of the physics of He-rich atmospheres, we obtained a qualitatively different set of atmosphere models whose application in the analysis of data has resulted in better determinations of the surface composition of cool H/He WD (Kowalski & Kilic 2010). The inclusion of Ly-$\alpha$ absorption (Kowalski & Saumon 2006) led to a successful reproduction of the entire spectral energy distribution (SED) of many cool white dwarfs (from the near-UV to the IR, e.g. Kilic et al. (2009), Kowalski & Saumon (2006)). However, until recently the spectra in UV region, where the Ly-$\alpha$ is the dominant opacity, had been measured for only two stars with hydrogen-rich atmospheres, which we successfully reproduced with our models (Kowalski & Saumon 2006; Durant et al. 2012). To further test the reliability of the Ly-$\alpha$ line profile model of Kowalski & Saumon (2006) over a broader range of conditions, we obtained near-UV spectra of eight cool white dwarfs with the STIS instrument on the Hubble Space Telescope. Two examples of our fits to the SED are given in Fig. 1 using the parameters derived by Kilic et al. (2009) without the benefit of the near-UV data. Nonetheless, the models fits of Kilic et al. (2009) reproduce the near-UV flux of all eight stars reasonably well with pure-H models, including three stars to which Bergeron et al. (2001) assigned a He-rich composition. The presence of hydrogen is clearly visible in the near-UV as strong Ly-$\alpha$ absorption from...
atomic H shortward of \(~ 4000 \AA\) is absent in pure-He models. This result indicates that the pure H models can be relied upon for accurate determinations of the parameters of cool WD with H-rich atmospheres.

2.2. The atmospheric composition of cool white dwarfs

Our studies of different samples of cool white dwarfs have shown that most of the stars with \(T_{\text{eff}} < 6000 \text{ K}\) have hydrogen-rich atmospheres and that the amount of hydrogen increases with the age of a star (decrease of \(T_{\text{eff}}\), e.g. Kilic et al. (2009), Kowalski (2006)). This result was confirmed recently by Giammichele et al. (2012), who revised the atmospheric parameters of very cool WD (Bergeron et al. 1997, 2001; Kilic et al. 2010) after including the Ly-\(\alpha\) profiles of Kowalski & Saumon (2006) in their models. Figure 2 compares \(T_{\text{eff}}\) and gravity determinations by Giammichele et al. (2012) and Kilic et al. (2009) for a common sample of stars. The excellent agreement between the two studies shows the reliability of state-of-the-art models for H-rich atmospheres of cool WD.

2.3. He-rich atmospheres

Although we are able to describe well the SED of H-rich stars (Fig. 1), He-rich atmospheres remain challenging. In Fig. 3 we present the spectra of two He-rich stars, LHS 1126 (DQp) and LHS 3250 (DC). The presence of significant amount of hydrogen in the atmosphere of these stars is evident from the strong IR flux depletion caused by \(\text{H}_2 - \text{He}\) collision-induced absorption (CIA) when comparing with the synthetic spectrum of a pure-He atmosphere. Although from the optical fluxes we are able to estimate that \(T_{\text{eff}} \sim 5300 \text{ K}\) for both stars, their IR spectra can not be well reproduced by the current models. For instance, good fits of the near-IR overestimate the IR flux beyond 3 \(\mu\text{m}\). In LHS 1126, the near-UV spectrum suggests a different composition where He is more dominant than indicated by the IR flux. The overall strength and frequency dependence of the IR opacity is not well reproduced by the models. Notably, the models predict a pronounced dip at \(\sim 2.3 \mu\text{m}\) from the first overtone band of \(\text{H}_2\) CIA, which is not
Figure 3. Comparison of the SED of the He-rich stars LHS 1126 and LHS 3250 with models of different H/He atmosphere composition. $T_{\text{eff}} = 5300$ K and $\log g = 8$. The photometric fluxes are from Bergeron et al. (2001), Kilic et al. (2008) and Kilic et al. (2009). For LHS 1126 the UV flux is from Wolf et al. (2002) and the near-IR flux is our new data (Kowalski et al. 2012). All the spectra are normalized to the $V$ band flux.

observed. This suggest a deficiency in the H$_2$-He CIA under the high densities found in these He-rich atmospheres. Another possibility is the presence of CIA from carbon species in the atmosphere of LHS 1126. Nevertheless, until the models are able to correctly and consistently reproduce the entire SED of WD with He-rich atmospheres, one can not draw solid conclusions regarding their atmospheric parameters, particularly the H/He ratio. More theoretical and experimental effort is required to correctly describe the properties of matter in these extreme atmospheres.

3. Cool DQ/DQp white dwarfs

Cool DQ stars have atmospheres dominated by helium with traces of carbon revealed by C$_2$ Swan bands in their spectra. The extreme character of the coolest known examples manifests itself through the appearance of peculiar DQ stars (“DQp”) at $T_{\text{eff}} \lesssim 6000$ K with distorted C$_2$-like bands (Schmidt et al. 1995; Bergeron et al. 1997; Kowalski 2010a). The peculiar appearance of these bands has been attributed to a new molecular species: C$_2$H (Schmidt et al. 1995; Bergeron et al. 1997, 2001). However, Hall & Maxwell (2008) rejected this interpretation and Kowalski (2010a) showed that the observed features are pressure-shifted C$_2$ bands. In order to investigate further the nature of DQp stars we collected and analyzed near-IR spectra of four DQ and four DQp stars (Kowalski et al. 2012). The spectra are featureless, which essentially rules out significant absorption from carbon-bearing molecules other than C$_2$. We found that all DQ/DQp stars with $T_{\text{eff}} \lesssim 5500$ K have some hydrogen in their atmospheres, revealed by a pronounced IR flux suppression, believed to be caused by H$_2$ – He CIA (Kowalski et al. 2012). Such a flux deficit is clearly visible in the spectrum of the DQp LHS 1126 (Fig. 3). However,
Figure 4. Carbon abundance in the atmospheres of cool DQ (circles) and DQp (squares) stars as a function of $T_{\text{eff}}$, derived by assuming atmospheres without hydrogen. Open symbols show our results (Kowalski et al. 2012) and the filled symbols represent the values derived by Koester & Knist (2005).

as we already discussed in the previous section, we are not able to fit the entire SED of this star with a single model and derive a definitive hydrogen abundance. Nevertheless, we can determine the abundance of C in DQp stars by fitting the depth of the distorted Swan bands in the optical with hydrogen-free models. The C/He ratios derived for DQp stars follow the trends reported by Dufour et al. (2005) and Koester & Knist (2005) for DQ stars, as shown in Fig. 4. Bergeron et al. (2001), Bergeron et al. (1997) and Dufour et al. (2005) noticed that the DQ sequence terminates abruptly at $T_{\text{eff}} \sim 6000$ K and cooler stars with C/He $\sim 10^{-8} \text{--} 10^{-7}$ are not observed, although such a carbon abundances should be easily detectable. The results presented in figure 4 suggest that these “missing” DQ stars are the DQp stars. Note however that the C abundances derived for both DQ and DQp stars would substantially increase should hydrogen be present in their atmospheres (Kowalski et al. 2012). This is because even trace amounts of hydrogen increase the continuum opacity and veils the C$_2$ bands. Therefore, in mixed He/H atmospheres, more carbon is needed to produce bands of a given strength than in a hydrogen-free atmosphere.

4. Conclusions

In this contribution, we gave a short overview of the current state of understanding of the atmospheres of cool white dwarfs and discussed some results of our recent observations and application of our models. Having analyzed the near-UV spectra of several cool white dwarfs in conjunction with their full SED, we conclude that hydrogen-rich atmosphere models of very cool WD are quite reliable. The initial claim of Kowalski & Saumon (2006) that the nearly all of the coolest DC white dwarfs have
hydrogen-rich if not pure-H atmospheres is strengthened by our analysis of near-UV spectra and confirmed by an independent analysis (Giammichele et al. 2012). Our investigation of the IR fluxes of cool DQp stars have revealed that in addition to helium and carbon, hydrogen is also present in their atmospheres. However, the discrepancy between the observed and modeled fluxes in the IR and an inability to fully reproduce the entire SED of WD with mixed H/He composition dominated by He reveals a persistent deficiency in the modeled opacities. This prevents the derivation of reliable H abundances for the stars with mixed H/He atmospheric composition, including the DQ and DQp white dwarfs. Nevertheless, the carbon abundances we have derived for DQp stars support the recent claim of Kowalski (2010a) that DQp stars are just DQ stars showing pressure-distorted C\textsubscript{2} bands in their optical spectra. We are addressing these difficulties by pursuing theoretical modeling of the relevant opacities in the exotic conditions found in these atmospheres.

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