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STARK BROADENING OF CARBON AND OXYGEN LINES IN HOT DQ WHITE DWARF STARS: RECENT RESULTS AND APPLICATIONS

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Abstract. White dwarf stars are traditionally found to have surface compositions made primarily of hydrogen or helium. However, a new family has recently been uncovered, the so-called hot DQ white dwarfs, which have surface compositions dominated by carbon and oxygen with little or no trace of hydrogen and helium (Dufour et al. 2007, 2008, 2010). Deriving precise atmospheric parameters for these objects (such as the effective temperature and the surface gravity) requires detailed modeling of spectral line profiles. Stark broadening parameters are of crucial importance in that context. We present preliminary results from our new generation of model atmospheres including the latest Stark broadening calculations for C II lines and discuss the implications as well as future work that remains to be done.

Key words: stars: white dwarfs, fundamental parameters, Stark broadening

1. INTRODUCTION

A new spectral class of white dwarf stars with surface compositions dominated by carbon and oxygen, the hot DQs, has recently been discovered (Dufour et al. 2007). The first generation of model atmospheres used to analyze these stars revealed that they were both hydrogen and helium deficient and that all of them are clustered in a very narrow range of effective temperatures between 18 000 and 23 000 K (Dufour et al. 2008). Follow-up high signal-to-noise spectroscopic observations of these rare white dwarfs using the MMT (6.5 m) and the Keck (10 m) telescopes also revealed Zeeman splitted line profiles in more than half of these stars, indicating the presence of strong surface magnetic fields in the mega Gauss range (Dufour et al. 2009, 2010). Luminosity variations have also been observed in five of the 14 known hot DQ white dwarfs (Montgomery et al. 2008; Barlow et al. 2008; Dunlap et al. 2010; Dufour et al. 2011), opening up a new window through which one may study these stars by means of asteroseismology.

One of our main challenges is now to successfully explain and understand the extraordinary properties and characteristics of these stars, as well as the place they occupy in stellar evolution. In order to achieve this, atmospheric parameters (effective temperatures, surface gravities, surface chemical compositions, etc.) must be determined accurately. Of particular importance is a better determination of the surface gravity since this would severely constrain the mass of the progenitors via the initial-to-final mass relationship. For example, an extremely high surface gravity may indicate that these white dwarf stars have evolved from some of the most massive stars on the main sequence that do not explode as supernovae. As such, they could have cores made of elements much heavier than carbon and oxygen.

In the context of carbon/oxygen dominated atmosphere, it is very important to have good Stark broadening damping constants in order to derive meaningful atmospheric parameters from line profiles. However, Stark damping constants for all of the hundreds of C II lines, from UV to optical, observed in hot DQ white dwarfs, are not readily available from the literature (for example, only a few lines can be found in Griem 1974, Goly and Weniger 1982, Djenize et al. 1988, Blagojevic et al. 1999, Sreckovic et al. 2000, Mahmoudi et al. 2004 and many other references, clearly insufficient for our needs). Moreover, since the first detailed analysis of hot DQ white dwarfs presented in Dufour et al. (2007, 2008) were based on low signal-to-noise ratio SDSS observations, the first generation of hot DQ model atmospheres were built simply using the standard approximation (see Castelli 2005): $\gamma_s/N_e = 10^{-8} n_{\rm eff}^5$ where γ_s is the Stark width of the line in angular frequency units and $n_{\rm eff}$ is the effective quantum number (Kurucz line list also gives damping constants for a few C II lines, but these values are listed only for a single temperature of 10 000 K and are based on questionable approximations as well). While this approximation, which is loosely a fit by Peytremann (1972) to detailed calculations by Sahal-Bréchot & Segre (1971), was enough to reveal the basic properties of hot DQ stars. However, this method is not appropriate for a precise determination of atmospheric parameters, especially the surface gravity from the high S/N spectroscopic data now available.

In order to go beyond these limitations from the input data in our stellar modeling, we calculated widths and shifts for all the isolated lines of the C II ion due to electron collisions, recalculated model atmosphere grids for hot DQs and refitted the C II line profiles appropriately.

2. CALCULATIONS AND RESULTS

Stark broadening parameters were determined within the semi-classical perturbation method for 1002 C II lines between ∼400 and 10 000 Å in the VALD database (see Larbi-Terzi et al. 2010, Sahal-Bréchot 2010 and Sahal-Bréchot et al. 2011). The calculations were performed for an electron density of 10^{17} cm^{-3} and temperatures between 5000 K and 100 000 K. In order to facilitate the inclusion of all these calculations in our stellar atmosphere code, we fitted, for each C II line, a smooth function of the form $\log(w) = D_1 + D_2\ log(T) + D_3\ (log(T))^2$, where w is the FWHM width in angstroms. The D_i for each line can easily be implemented into our line list in order to get the correct width for the temperature and electron density at each depth of a given model atmosphere. It is noted that the

Table 1. Stark widths for the strong C II 4267 line ($N_e = 10^{17}$ cm^{-3}).

T (K)	Width (Å)
5000	2.08
10 000	1.67
20 000	1.37
30 000	1.26
50 000	1.16

new Stark widths calculated here are significantly different than those obtained from the above approximation. Moreover, we now explicitly take into account the variation of the width with the temperature in the model atmosphere calculations, a variation that is not simply proportional to $T^{-1/2}$, the expected dependency according to simple classical calculations (Table 1 shows, for example, the result of the new Stark broadening calculations for the strong C II 4267 line). The widths are scaled linearly with electron density, a reasonable approximation that is valid for the densities of interest here (electron densities of the order of $N_e \sim 10^{18}$ cm^{-3} are reached only in the deepest layers where $\tau_R > 10$).

Using these state-of-the-art Stark broadening parameters for C II lines, we next computed a new model atmosphere grid for hot DQ stars. This new generation of model atmosphere also includes several improvements over those presented in Dufour et al. (2008). The numerous modifications made to our code will be reported in details in a forthcoming publication. Our grid covers a range from $T_{\rm eff}$ = 16 000 to 25 000 K in steps of 1000 K, from $\log g$ = 7.5 to 10.0, in steps of 0.5 dex, and from log (C/H) = +3.0 to 0.0, in steps of 1.0 dex. This grid has been calculated with a fixed value of C/O = 1.0 for this exploratory study, a value appropriate for SDSS J1153+0056 according to a preliminary inquiry. Proper navigation in the C/O dimension will be done in due time.

We first focus on the simpler objects which do not show signs of magnetic line splitting (limits of about 300–400 kG given the spectral resolution of our observations). Our spectroscopic fitting procedure relies on the standard nonlinear least-squares method of Levenberg-Marquardt, and is similar to that described in Dufour et al. (2008). Figure 1 shows an example of our best fit solution for SDSS J1153+0056. We refrain, however, from giving final atmospheric parameters at this point since, in this preliminary study, we calculated only one grid with a fixed oxygen abundance. Moreover, new oxygen line Stark width calculations, which are currently underway, will also need to be included to replace the approximation used in our grid. As a consequence, it is expected that the atmospheric parameters that we derive here will change slightly when all the correct ingredients are put together and the parameter space explored appropriately.

Nevertheless, we can already notice significant improvements in the quality of our fits compared to our first generation of models (see Fig. 2 of Dufour et al. 2009, for example). Quantitatively, we also observe significant difference between the parameters determined in Dufour et al. (2008) and those found with our new model atmosphere grid. For egzample, we find surface gravities much higher than $\log g \sim 8$ reported in Dufour et al. (2008), with our values in the vicinity of $\log g \sim 9$. Such differences are due to a combination of several factors: better S/N ratio spectroscopic observations, improved continuum opacities, new Stark

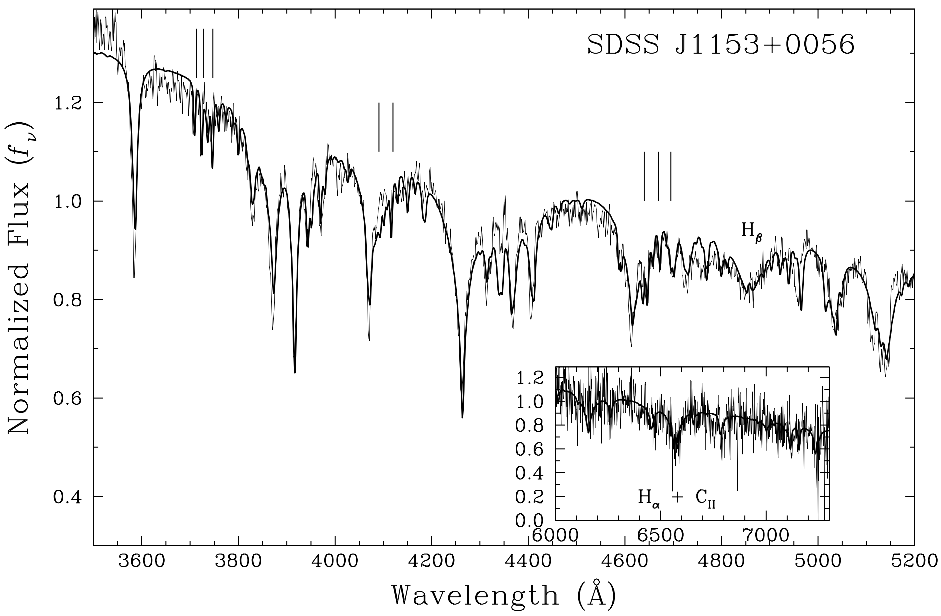

Fig. 1. Fit of a model to the carbon lines for the hot DQ SDSS J1153+0056. Oxygen lines, which are not fitted, are indicated by tick marks. The thick line is the best solution obtained by fitting the optical (MMT) data. The insert shows the Hα region (SDSS spectroscopic observations). The C/O ratio is fixed to 1 in this preliminary analysis. This represent a significant improvement over the 'first generation' fits of Dufour et al. (2009, see their Fig. 2).

broadening parameters and the presence of large amount of oxygen that was previously unnoticed. It thus appear that hot DQ stars are among the most massive white dwarfs known. Unfortunately, as noted above, there are still more calculations that remain to be completed before we can provide a better quantitative assessment of this affirmation. We must, however, remain cautious about such interpretation since it is possible that the line profile appears broader as a result of unresolved components of lines slightly split by a weak magnetic field. Further high resolution spectropolarimetric observations, which we hope to obtain soon, should alleviate this issue.

3. CONCLUSIONS

A new generation of model atmospheres, including state-of-the-art C II Stark broadening data, is used for a detailed modeling of hot DQ white dwarfs. The new Stark broadening data calculated specifically for this work will soon be available in the STARK-B database (http://stark-b.obspm.fr/).

Fits of the modeled line profiles to high S/N spectroscopic data yield atmospheric parameters that are significantly different from those presented in Dufour et al. (2008). As a consequence, it is now believed that the hot DQ stars might be among the most massive isolated white dwarfs that can be formed by standard stellar evolutionary channels. However, further calculations are still required before more precise atmospheric parameters can be published with confidence. For instance, O I, O II and C I Stark broadening data also need to be incorporated in our model atmosphere calculations.

Future work will also focus on modeling of the UV region (spectroscopic data from HST/COS are now available for 5 hot DQs, see Dufour et al. (2010). For such hot stars, most of the flux is emitted in that part of the electromagnetic spectrum. Furthermore, model atmospheres including magnetic fields with different geometry will need to be developed for the analysis of the majority of hot DQs. As the spectroscopic modeling of the hot DQ stars gains in maturity, and more accurate atmospheric parameters become available, a better understanding of the origin and evolution of these strange stars should soon emerge.

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