

## 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 atmosphere including the latest Stark broadening calculations for CII lines and discuss the implications as well as future work that remains to be done.

**Key words:** stars: atmospheric parameters – broadening: Stark

### 1. INTRODUCTION

A new spectral class of white dwarf stars with surface compositions dominated by carbon and oxygen, the Hot DQs, has recently been uncovered about 4 years ago (Dufour et al. 2007). The first generation of model atmosphere used to analyze these Hot DQ stars revealed that they were both hydrogen and helium deficient and that they all clustered in a very narrow range of effective temperature between 18,000 to 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 asteroseismological studies.

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 temperature, surface gravity, 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-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 of utmost importance 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 CII 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 atmosphere were built simply using the standard approximation (see Castelli 2005):  $\gamma_s/N_e = 10^{-8}n_{eff}^5$  where  $\gamma_s$  is the Stark width of the line in angular frequency units and  $n_{eff}$  is the effective quantum number (Kurucz linelist also gives damping constants for a few CII lines, but these values are only listed 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-Br  chot & Segre (1971), was enough to reveal the basic properties of Hot DQ stars, it is certainly not appropriate for a precise determination of atmospheric parameters, specially the surface gravity, now that high S/N spectroscopic data are available.

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

## 2. CALCULATIONS AND RESULTS

Stark broadening parameters were determined within the semi-classical perturbation method for 1002 CII lines between  $\sim 400$  and  $10,000 \text{ \AA}$  in the VALD database (see Larbi-Terzi et al. 2010, Sahal-Br  chot 2010 and Sahal-Br  chot et al. 2011). The calculations were performed for an electron density of  $10^{17} \text{ cm}^{-3}$  and temperatures between 5,000 K and 100,000 K. In order to facilitate the inclusion of all these calculations in our stellar atmosphere code, we fitted, for each CII 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 angstrom. The  $D_i$  for each line can then easily be imple-

**Table 1.** Stark widths for the strong CII 4267 line ( $N_e = 10^{17} \text{ cm}^{-3}$ ).

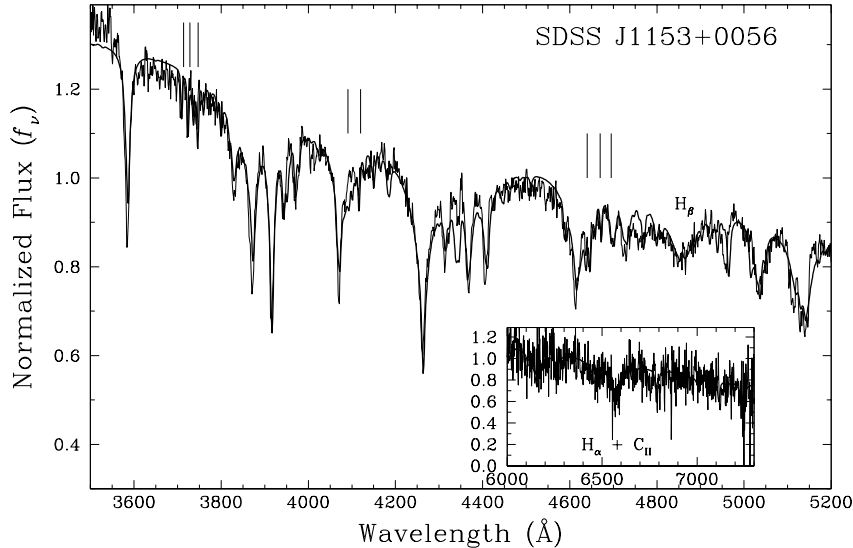
T (K)	Width (Å)
5,000	2.08
10,000	1.67
20,000	1.37
30,000	1.26
50,000	1.16

mented into our linelist 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 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 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 CII  $\lambda 4267$  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  $N_e \sim 10^{18} \text{ cm}^{-3}$  are reached only in the deepest layers where  $\tau_R > 10$ ).

Using these state-of-the-art Stark broadening parameters for CII lines, we next computed a new model atmosphere grid for Hot DQ stars. This new generation of model atmosphere also include 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  $T_{\text{eff}} = 16,000$  to  $25,000$  K in steps of  $1,000$  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 approximately appropriate for SDSS J1153+0056 according to 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 sign of magnetic line splitting (limits of about  $\sim 300$ - $400$  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 widths calculations, which are currently underway, will also need to be included in replacement of 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 instance, we find surface gravities much higher than the  $\log g \sim 8$  reported in Dufour et al. (2008), with values now 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 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



**Fig. 1.** Fit 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  $H_\alpha$  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 figure 2).

white dwarfs known. Unfortunately, as noted above, there are still more calculations that remain to be completed before we can provide a more quantitative assessment of this affirmation. We must, however, remain cautious about such an interpretation since it is possible that the line profile appear 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 atmosphere including state-of-the-art CII Stark broadening data is presented 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 to high S/N spectroscopic data using these new models yield atmospheric parameters that are significantly different to 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 form from standard stellar evolutionary channels. However, further calculations are still required before precise and final atmospheric parameters can be published with confidence. For instance, OI, OII and CI Stark broadening data also need to be incorporated in our model atmosphere calculations.

Future work will also focus on the modelisation of the UV region (spectroscopic data from HST/COS are now available for 5 Hot DQ, see Dufour et al. 2010) since, for such hot stars, most of the flux is emitted in that part of the electromagnetic spectrum. Furthermore, model atmosphere including magnetic fields with different geometry will need to be developed for the analysis of the majority of Hot DQ white dwarfs. 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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