A Progress Report on the Carbon Dominated Atmosphere White Dwarfs

P. Dufour\textsuperscript{1}, J. Liebert\textsuperscript{1}, B. Swift\textsuperscript{1}, G. Fontaine\textsuperscript{2} and T. Sukhbold\textsuperscript{1}

\textsuperscript{1} Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721
\textsuperscript{2} Département de Physique, Université de Montréal, C.P.6128, Succ. Centre-Ville, Montréal, Québec, Canada H3C 3J7

E-mail: dufourpa@as.arizona.edu

Abstract. Recently, Dufour et al. (2007) reported the unexpected discovery that a few white dwarfs found in the Sloan Digital Sky Survey had an atmosphere dominated by carbon with little or no trace of hydrogen and helium. Here we present a progress report on these new objects based on new high signal-to-noise follow-up spectroscopic observations obtained at the 6.5m MMT telescope on Mount Hopkins, Arizona.

1. Introduction

White dwarfs have traditionally been divided into two main categories depending on the composition of the primary constituent of their atmosphere. Stars with a hydrogen rich surface composition are classified as DA white dwarfs while those with a helium dominated surface composition belong to the non-DA category (DO, DB, DC, DZ and DQ spectral type). A third category was recently uncovered by Dufour et al. (2007) when an analysis of Hot DQ white dwarfs from the Sloan Digital Sky Survey (SDSS) revealed that their surface composition was dominated by carbon and not helium as was initially assumed by Liebert et al. (2003).

These strange objects are quite rare. Only 9 were found in the SDSS DR4 catalog of spectroscopically identified white dwarfs which contained nearly 10,000 stars (Eisenstein et al. 2006). A detailed analysis of the spectroscopic and photometric data by Dufour et al. (2008) showed that the hot DQ white dwarfs are found in a rather narrow range of effective temperature centered around $\sim 20,000$ K.

No carbon dominated atmosphere white dwarfs with an effective temperature higher than $\sim 24,000$ K have been found from a careful inspection of thousands of spectra in SDSS DR6 with $u-g < -0.2$ and $g-r < -0.3$. The absence of hotter counterparts for carbon dominated atmosphere white dwarfs suggest that they probably cool as helium atmosphere stars until a convection zone develops in the underlying carbon-rich mantle due to the recombination of that element. If this scenario is correct, a subphotospheric carbon convection zone would develop around $24,000$ K and dilute the surface helium layer in the much more massive carbon envelope. This would transform a helium dominated DB star with a very thin surface helium layer into a carbon dominated Hot DQ white dwarf (see Dufour et al. 2008 for more on this scenario).

Why would some helium rich white dwarfs have thin helium layers is still not entirely understood yet. One possibility is that these stars are the result of the evolution of massive stars that have burned carbon and have an oxygen-magnesium-neon core (see Garcia-Berro et
Alternatively, they could have experienced a late thermal pulse that eliminated most of the helium, a phenomenon similar to the one that is generally believed to explain the existence of other hydrogen deficient stars (Werner & Herwig 2006). There might also be other ways to eliminate the superficial helium layers that still need to be explored. However, a scenario involving close binary interaction, as proposed to explain the variability of J1426+5752 (Montgomery et al. 2008), now appears very unlikely since i) this star has been found to show multi-periodic variations (Green et al. 2008, see also Fontaine et al. in these proceedings) ii) no radial velocity variations have been detected in J1426+5752 (see again Green et al. 2008) and iii) more importantly, it doesn’t explain why all Hot DQ’s are found within the same temperature range and none at higher or lower effective temperatures. We thus believe that the convective mixing scenario presented in Dufour et al. (2008) is the most appealing.

One essential parameter that would give important clues about the origin and evolution of these objects is the mass. The mass of a white dwarfs is generally obtained from a determination of the surface gravity by matching the observed line profiles with those of model atmosphere calculations. However, in the case of the Hot DQ white dwarfs, the surface gravity is poorly known due to several factors.

First, the atmospheric parameter determinations of Dufour et al. (2008) were based on the analysis of rather noisy optical SDSS spectra. Years of experience from analyzing DA and DB white dwarfs has taught us that high signal-to-noise ratio spectroscopic observations are required for a precise measurement of the surface gravity (and effective temperature). Rough estimates of log g were obtained by Dufour et al. (2008) but the quality of the SDSS spectra is clearly insufficient to provide the needed accuracy.

Second, most of the flux emitted by these stars is in the ultraviolet part of the electromagnetic spectrum. This region of the spectrum contains many more absorption features than there is in the optical. All these absorption lines have an important influence on the thermodynamic structure (temperature and pressure as a function of optical depth) of the atmosphere since the flux absorbed at short wavelength tends to be redistributed at longer wavelength (see Fig. 4 of Dufour et al. 2008). Hence, small errors in our modeling of the UV part of the spectrum will have an important effect on the line profiles in the optical. Unfortunately, an assessment of the quality of our modeling of the UV will only be possible by comparing UV observations (which we should obtain, if the HST repair mission goes as planned, sometime next year) with our model calculations.

Finally, any determination of the surface gravity from the line profiles must rely on a state-of-the-art theory of the broadening of the spectral lines. At the time of the Dufour et al. (2008) analysis, detailed calculations for the Stark broadening of CII lines were not available and the standard scaled classical approximation was used. Therefore, surface gravities (and effective temperatures) obtained in Dufour et al. (2008) can only be considered as preliminary approximations until new tables for the Stark broadening of CII (which are currently being calculated) are incorporated in our next generation of model atmosphere.

In summary, atmospheric parameters will only be truly reliable when each of the three issues above have been properly addressed. This paper report our development on the first of these issues.

2. New MMT Observations
As mentioned above, in order to obtain a precise determination of the atmospheric parameters, it is of utmost importance to have high signal-to-noise ratio spectroscopic observations. Due to the nature of the Sloan Digital Sky Survey acquisition procedure, spectra of faint objects such as the Hot DQ are of rather poor quality. We have thus recently undertaken a program to reobserve all the known carbon dominated atmosphere white dwarfs with the Mt. Hopkins 6.5m MMT telescope. We have obtained 7 nights of MMT time and succeeded in securing high signal-
Figure 1. Left: New spectroscopic observations from the 6.5m MMT telescope for 8 of the 10 known Hot DQ white dwarfs. Spectra are normalized to unity at 4500 Å and offset from each other for clarity. The stars are approximately ordered by increasing effective temperature from bottom to top. Right: Corresponding SDSS spectra for each of the Hot DQ that have been reobserved with MMT. Note that we have applied for clarity a three-point average window smoothing in the display of the SDSS spectroscopic data.
to-noise ratio spectra (typically S/N of 60 or more) for 8 of the 10 (9 from the DR4 WD catalog and a 10th one recently found in DR6) known Hot DQ white dwarfs (see Figure 1). We used the Blue Chanel with the 500 line mm$^{-1}$ grating with a 1” slit, resulting in a $\sim$ 3.6 Å FWHM spectral resolution at 5500 Å. The spectra were reduced with standard IRAF packages. The setup used allowed a coverage of a few hundred angstroms bluer than that of SDSS although at the expense of an equally good coverage of the redder part of the electromagnetic spectrum (our spectra cover a wavelength range of $\sim$3400-6300 Å vs $\sim$3800-9000 Å for SDSS).

In Figure 1, we present the new high signal-to-noise ratio spectrum for all the Hot DQ that have been reobserved with MMT so far. We also show, for comparison, the corresponding SDSS spectra that were used for the preliminary analysis of Dufour et al. (2008). The noise level and sharpness of the observed spectral lines are now suitable for an eventual precise spectroscopic analysis. However, it would be meaningless at this point to present updated atmospheric parameters based on these new observations since our grid does not incorporate the new tables for the Stark broadening of CII yet. We prefer to wait for the next generation of models, and also the HST observations, before sharing the results of our reanalysis for these stars. Nevertheless, even without proceeding with a full detailed analysis, several interesting observations are worth discussing.

The most remarkable concerns the fraction of Hot DQ stars that are found to be magnetic. In Figure 1, we clearly see magnetic splitting of the spectral lines for at least 4 objects. These are the 4 objects starting from the the bottom in Figure 1. The separation between the $\sigma$ and $\pi$ components indicates that the fields are of the order of 1 MG. The splitting was not observable in the noisier SDSS spectra except for the brightest Hot DQ SDSS J0005-1002. Spectropolarimetric measurement has also confirmed the magnetic nature for SDSS J0005-1002 (see Dufour et al. 2008). This is in contrast with the next 3 stars in Figure 1 that show instead very sharp CII lines where no trace of magnetic splitting is detectable. Given the spectral resolution of our observations, a limit of about 200 kG can be put on the strength of the magnetic field for these objects. The hottest stars in our sample, SDSS J0106+1513, do not show sharp and well defined lines which suggest perhaps the presence of a weak magnetic field but more precise spectropolarimetric measurements will be needed to confirm magnetism. Note also that one of the two stars that remains to be observed with MMT, SDSS J2200-0741, seems also to have lines slightly broadened by a weak magnetic field.

It thus seems that at least 4 (and perhaps 6) of the 10 known Hot DQ are magnetic. This is an incredibly high fraction considering that the fraction of magnetism of nearby white dwarfs is around 10% (Liebert et al. 2003). Is this an indication that Hot DQ have higher mass than average since magnetic white dwarfs tend to be more massive in general? The preliminary analysis of Dufour et al. (2008) indicated that most of these stars have surface gravities around log g $\sim$ 8.0 although this could possibly be revised if it is found that our approximation for the Stark broadening considerably overestimated the broadening of the lines.

This unusual high fraction could indicate that magnetism plays a significant role in the evolution of these objects. But if this is the case, why do we detect magnetism in only about 50% and not 100% of these stars? Could it be that they are indeed all magnetic but that in some cases the strength of the field is not strong enough to be detected from line splitting? More sensitive spectropolarimetric measurements, which we plan to obtain soon, should elucidate those questions.

We also detect the HeI 4471 line, indicating the presence of a significant amount of helium (C/He $\sim$0.5), in two of the coolest Hot DQ (SDSS J1426+5752 and SDSS J1402+3818). The presence of helium in SDSS J1426+5752 was also needed to explain the pulsational properties recently discovered by Montgomery et al. (2008) since pure carbon atmosphere white dwarfs are not expected to pulsate at this temperature (see Fontaine et al. 2008 and Fontaine et al., these proceedings).
Figure 2. Comparison of the fits of the SDSS (bottom) and MMT (top) spectra for SDSS J1153+0056. The solution is the same as that presented in Dufour et al. 2008, that is log =8 and $T_{\text{eff}} = 21,650$ K.

We will conclude this discussion with some remarks on our models. The solutions presented in Dufour et al. 2008 were not bad considering the level of noise of SDSS spectra. However, with the new MMT observations, it is now obvious that improvement in our models will be needed before we can claim that we know the atmospheric parameters with great accuracy. This is illustrated in Figure 2 where we show the Dufour et al. 2008 solution and a very similar fit to the MMT data for SDSS J1153+0056. While the fit to the SDSS data looks quite acceptable, there are significant discrepancies that appear when observing in detail the MMT fit. It seems that our models do not reproduce correctly the strength of many lines. This is most evident when looking at the group of lines near 4400-4500 Å (and it can also be observed at many other wavelength). Some of the lines are quite well reproduced with our models while others seem to require a different log g or $T_{\text{eff}}$ (see Figure 1 of Dufour et al. 2008 for example). This is usually symptomatic of a wrong thermodynamic structure. This could be due, as already mentioned above, to an improper modeling of the UV part of the spectrum. The treatment of the Stark broadening of CII lines might also cause such a discrepancy. The exact reason is probably a combination of both, as well as other parameters such as the abundance of other trace elements, treatment of the convective efficiency or perhaps even uncertainties in the atomic data used. Carbon dominated atmosphere modeling is relatively new and has obviously not reached yet the
level of accuracy that is attained for DA and DB stars. We hope to achieve this in a near future.

3. Conclusions
White dwarfs with a carbon dominated atmosphere represent a new challenge to stellar evolution. Their origin and evolution are very mysterious and as such, they deserve all our attention. Progress on our understanding of these objects will necessitate i) new models with state-of-the-art physics (Stark broadening) ii) observation in the UV part of the electromagnetic spectrum (HST observations are coming soon, assuming no problems with the next repair mission), and iii) high signal-to-noise ratio spectroscopic data. In this short report, we presented new optical spectra taken with MMT. Their analysis will eventually lead to a more precise measurements of the atmospheric parameters. One of the most outstanding characteristics that emerges from these new observations is the unusually high fraction of Hot DQ with a large magnetic field. Weather or not the magnetic field is intimately related to their evolution and origin remains unclear. Undoubtedly, further study of Hot DQ white dwarfs will increase our knowledge of stellar evolution. The new challenges that they bring to our field will be of the most interesting to solve.

Acknowledgments
P.D. acknowledges the financial support of NSERC. This work was also supported by the National Science Foundation through grant AST 03-07321. Support from the Reardon Foundation is also gratefully acknowledged.

References
Dufour, P., Fontaine, G., Liebert, J., Schmidt, G. D., & Behara, N. 2008, ApJ, 683, 978
Dufour, P., Liebert, J., Fontaine, G., & Behara, N. 2007, Nature, 450, 522
Eisenstein, D. J. et al. 2006, ApJ, 167, 40
Fontaine, G., Brassard, P., & Dufour, P. 2008, A&A, 483, L1
Garcia-Berro, E., Ritossa, C., Iben, I. Jr. 1997 ApJ, 485, 765
Green, E. M., Dufour, P., Fontaine, G. in preparation
Liebert, J. et . al. 2003, AJ, 126, 2521
Liebert, J., Bergeron, P., Holberg, J. B. 2003 AJ, 125, 348
Montgomery, M. H., Williams, K. A., Winget, D. E., Dufour, P., DeGennaro, S., & Liebert, J. 2008, ApJL, 678, L51
Werner, K., Herwig, F. 2006 PASP, 118, 183