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# Spectral analyses of DO white dwarfs and PG 1159 stars from the Sloan Digital Sky Survey

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**ABSTRACT**

We present a model atmosphere analysis of ten new DO white dwarfs and five new PG 1159 stars discovered in the Sloan Digital Sky Survey DR⋆1, DR2 and DR3. This is a significant increase in the number of known DOs and PG 1159 stars. DO white dwarfs are situated on the white dwarf cooling sequence from the upper hot end ($T_{\rm eff} \approx$ 120 000 K) down to the DB gap ($T_{\rm eff} \approx$ 45 000 K). PG 1159 stars on the other hand feature effective temperatures which exceed $T_{\rm eff}$ = 65 000 K with an upper limit of $T_{\rm eff}$ = 200 000 K and are the proposed precursors of DO white dwarfs. Improved statistics are necessary to investigate the evolutionary link between these two types of stars. From optical SDSS spectra effective temperatures, surface gravities and element abundances are determined by means of non-LTE model atmospheres.

**Key words.** stars: abundances – stars: fundamental parameters – stars: evolution – stars: AGB and post-AGB – stars: white dwarfs

## 1. Introduction

White dwarfs (WDs) represent the final evolutionary stage for 90% of all stars (initial mass $M_i < 8\,M_\odot$). Due to very high mass loss at the hot end of the Asymptotic Giant Branch (AGB), these objects lose part of their envelope forming a planetary nebula in their subsequent evolution. The remaining core of the star rapidly evolves toward high effective temperatures ($T_{\rm eff}$ > 100 000 K). When H- and He-shell burning ceases, the star enters the WD cooling sequence. The evolution of these post-AGB objects is separated into a H-rich and H-deficient sequence, the latter one occurs with a commonness of 20%. Following the first spectral classification of Krzesiński et al. (2004), we present a spectral analysis of two types of hot He-rich objects from the Sloan Digital Sky Survey (SDSS).

### 1.1. PG 1159 stars

PG 1159 stars are transition objects between the hottest post-AGB and the WD phase. The prototype of this spectroscopic class, PG 1159-035, was found in the Palomar Green (PG) survey (Green et al. 1986). It shows a spectrum without detectable H-absorption lines. In fact, it is dominated by He II and highly ionised carbon and oxygen lines. PG 1159 stars are characterised by a broad absorption trough around 4760 Å composed by He II 4686 Å and several C IV lines, suggesting high effective temperatures. Spectral analyses reveal $T_{\rm eff}$ = 65 000–200 000 K and gravities of log $g$ = 5.5–8.0 (Werner et al. 1991; Dreizler et al. 1994; Werner et al. 1996). From the 28 currently (prior to SDSS) known PG 1159 stars, ten are low-gravity (subtype lgE, Werner 1992) stars in the region of hot central stars of planetary nebulae (CSPNe) while the others are more compact objects with surface gravities of WDs (subtype A or E). The majority of the PG 1159 stars was discovered in large surveys (Palomar Green, Hamburg Schmidt (HS), Hagen et al. 1995). The most recent and only discovery (Werner et al. 2004) within the last 10 years was an object from the Hamburg ESO (HE) survey (Wisotzki et al. 1996). Currently, the SDSS (York et al. 2000) offers a new opportunity to increase the number of known PG 1159 stars.

PG 1159-035 (=GW Vir) also defines a new class of variable stars. McGraw et al. (1979) discovered low-amplitude non-radial g-mode pulsations. About one third of the PG 1159 stars show this variability driven by cyclic ionisation of carbon and oxygen (Cox 1986; Starrfield 1987). Analyses of HST spectra indicate that stars with high carbon and oxygen abundance are more likely to pulsate (Dreizler & Heber 1998) which is corroborated by theoretical calculations of Quirion et al. (2004).

The PG 1159 region in the Hertzsprung-Russell-Diagram (HRD) overlaps with that of DO white dwarfs. Therefore it is

⋆ DR = Data Release.

assumed that gravitational settling of the heavier elements in the atmosphere of PG 1159 stars leads to the transition towards DO white dwarfs.

### 1.2. DO white dwarfs

White dwarfs can be separated into two distinct spectroscopic classes, DA and non-DA white dwarfs. The former ones show a pure hydrogen spectrum and can be found on the entire WD cooling sequence. The latter ones fall into three subclasses. DO dwarfs with 45 000 K < $T_{\rm eff}$ < 120 000 K, DB stars (11 000 K < $T_{\rm eff}$ < 30 000 K) and DCs ($T_{\rm eff}$ < 11 000 K). The spectroscopic appearance of each class is determined by the ionisation balance of He I and He II. DO white dwarfs show a pure He II spectrum at the hot end and a mixed He I/II spectrum at the cool end. The transition to the cooler DB dwarfs, characterised by pure He I spectra, is interrupted by the so-called "DB gap" (Liebert et al. 1986). In the HRD region of stars with 30 000 K < $T_{\rm eff}$ < 45 000 K no objects with H-deficient atmospheres have been observed to date. This phenomenon is a fundamental problem in the understanding of WD spectral evolution.

As in the case of PG 1159 stars, the most recent discovery of a DO white dwarf is due to the HE survey (Werner et al. 2004), while the PG and HS surveys contributed the majority in time steps of decades with 19 DOs known prior to the SDSS.

## 2. SDSS Observations

The SDSS is a photometric and spectroscopic survey covering 7000 square degrees of the sky around the northern Galactic cap (York et al. 2000). The survey first images the sky in five passbands and uses these data to select interesting targets for spectroscopic follow-up. The survey's main goal is to study the large scale structure of the universe, therefore only a small fraction of the observed stars are targeted for spectroscopy. For spectrophotometric calibration purposes, however, certain "HOT_STD", or hot standard stars, are specifically targeted. These objects meet the following photometric criteria: $g > 14$, $g_o < 19$ (where subscript $o$ denotes a dereddened magnitude), $-1.5 < (u-g)_o < 0.0$, and $-1.5 < (g-r)_o < 0.0$. Since the number of objects which meet these criteria is relatively small, such objects are targeted nearly to completion. All but six of the DOs and PG 1159 stars in this paper were observed by the SDSS as hot standard stars and reported first by Krzesiński et al. (2004) while the remaining six come from HOT_STD spectra included in the Second and Third Data Release of the SDSS (Abazajian et al. 2004, 2005) not analysed in the Krzesiński et al. (2004) work. A detailed description of the SDSS spectrographs and spectral data can be found in Stoughton et al. (2002) and Abazajian et al. (2003, 2004, 2005). In short, the SDSS spectral data cover a wavelength range from 3800 to 9200 Å with $R \sim 1800$. They are flux calibrated to about 10% and have an average signal-to-noise ratio of ~4 at $g = 20.2$.

## 3. Spectral analysis

In order to analyse the DO and PG 1159 spectra, we calculated homogeneous, plane-parallel non-LTE model atmospheres with a code based on the Accelerated Lambda Iteration (Werner et al. 2003, and references therein). For these types of stars it is necessary to account for non-LTE effects as shown for DO white dwarfs by Dreizler & Werner (1996) and for PG 1159 stars by Werner et al. (1991). For comparison of synthetic and observed spectra, the latter ones are normalised using a third order polynomial fit through the continuum points, which are determined using the normalised theoretical spectra. Lineshifts due to radial velocities are taken into account by means of cross-correlation. This comparison procedure is performed by an `IDL` code routine in order to guarantee consistent results. For the DO white dwarfs we used a $\chi^2$-statistic to derive best-fit models and 1-$\sigma$ errors following Zhang et al. (1986). Compared to our preliminary analyses (Hügelmeyer et al. 2005) with best-fit models selected by eye, we find differences especially for the hot DO white dwarfs. The sparsely populated model grid for the PG 1159 stars does not allow a reasonable application of $\chi^2$-statistics. We therefore have to rely on best-fit models selected by eye, guided by the variance of model − observation. Error estimates are obtained from a global analysis of the goodness of fit for neighbouring parameter sets.

### 3.1. Spectral analysis of PG 1159 stars

For the PG 1159 stars we calculated atmospheres using detailed H-He-C-O model atoms (Fig. 1). The model grid ranges from $T_{\rm eff}$ = 55 000–150 000 K and $\log g$ = 5.5–7.6. A complete coverage of this parameter space is not available due to high computational time for all model atmospheres. The abundances are fixed to values He/H = 100 and C/He = 0.01, 0.03, 0.05, 0.1, 0.3, 0.6 by number. While oxygen can only be determined in the hottest PG 1159 star, the best-fit models for the rest of the PG 1159 candidates were calculated with an oxygen abundance following the typical PG 1159 abundance-scaling ratio O/C ≈ C/He. However, variations in the oxygen abundance do not show a significant effect on the other stellar parameters.

### 3.2. Spectral analysis of DO white dwarfs

Detailed H-He atomic models (Dreizler & Werner 1996) are used to calculate the model atmospheres (Fig. 2). The model grid ranges from $T_{\rm eff}$ = 42 500–120 000 K in steps of 2500 K. The $\log g$ ranges from 7.0 to 8.4 in intervals of 0.2. The helium abundance is fixed to He/H = 99.

## 4. Results and discussion

Starting from spectral classification of hydrogen-deficient white dwarfs within DR1 (Krzesiński et al. 2004), we extend this work to a spectral analysis including similar objects from DR2 and DR3. The emphasis is placed on PG 1159 stars and DO white dwarfs.

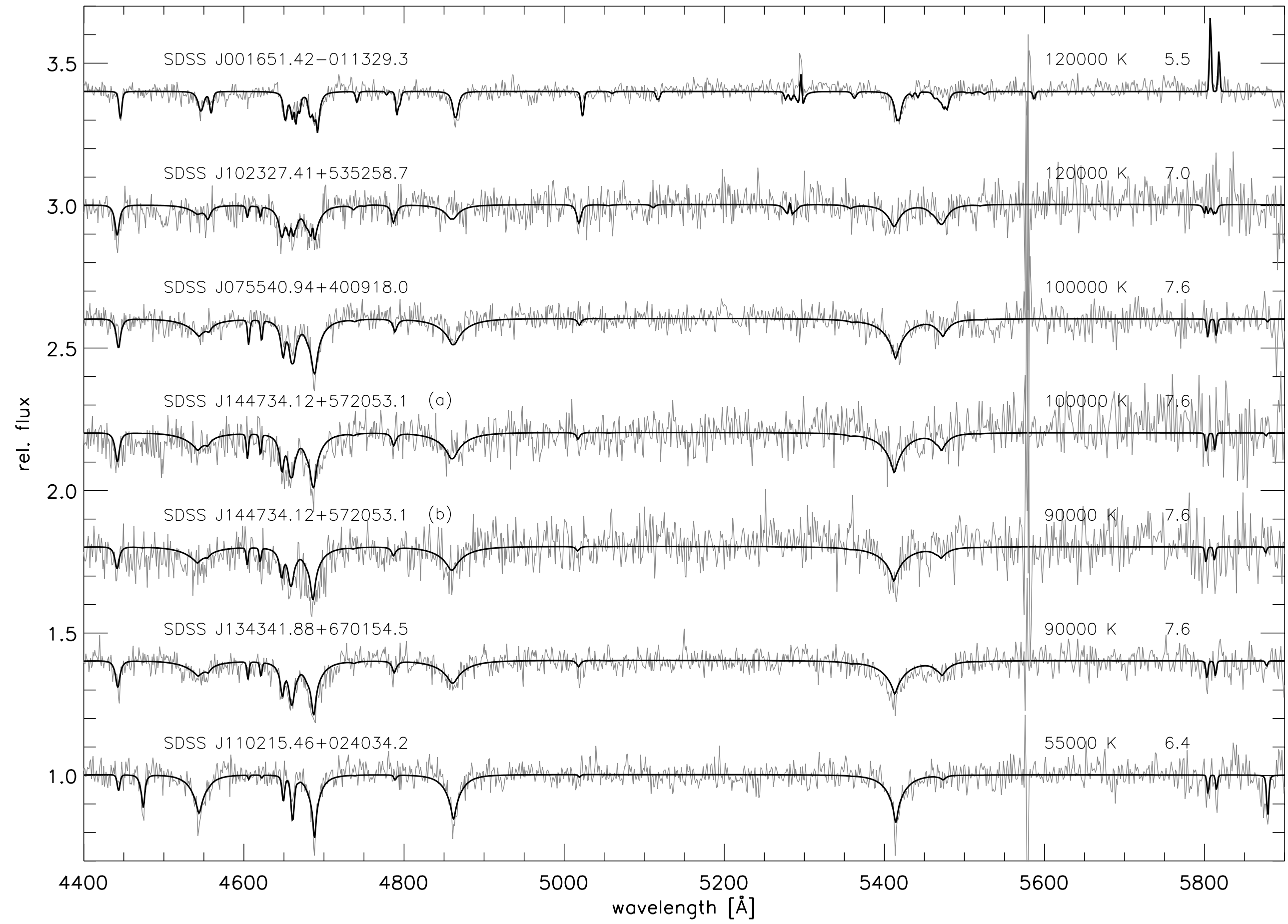


**Fig. 1.** Normalised optical spectra (grey lines) of PG 1159 stars and the sdO star (bottom-most spectrum) and model atmospheres (black lines), ordered by decreasing effective temperature. Object names are printed on the left, effective temperatures and logarithmic surface gravities on the right. SDSS J144734.12 +572053.1 was observed twice on different plates and slightly different temperatures are derived, however, within our error estimate.

### *4.1. PG 1159 stars*

From the seven spectra originally classified as PG 1159 stars, we were able to confirm five new PG 1159 stars. The results of the spectral analyses are listed in Table 1. One of the objects (SDSS J144734.12 +572053.1) has been observed twice on different plates. Both spectra are presented here (see Fig. 1). The independent analyses of the two spectra revealed parameters consistent within our error estimates. Despite strong C IV lines, one of the objects from our PG 1159 star candidates (SDSS J110215.46 +024034.2) turned out to be a sdO star according to its stellar parameters.

Compared to the number of previously known PG 1159 stars, our sample marks an increase of 18%. Following the spectroscopic subtypes scheme of Werner (1992), SDSS J001651.42 −011329.3 was classified as lgE type, SDSS J102327.41 +535258.7 as an E and the remaining three as A types The latter ones show very similar temperatures and gravities. Regarding the carbon abundance, the PG 1159 stars clearly fall into two groups: one with carbon abundances C/He $\approx$ 0.2–0.3 (by number) and the other one with C/He $\approx$ 0.03–0.05. This separation underlines earlier results of PG 1159 stars gained from HST spectra (Dreizler & Heber 1998). These previous analyses indicated a correlation between high carbon abundances and presence of pulsations, which is also corroborated by the theoretical investigations of Quirion et al. (2004). Using the above mentioned correlation, we predict that SDSS J001651.42−011329.3 and SDSS J102327.41 +535258.7 are pulsators.

While carbon and helium abundances can be derived from optical spectra of PG 1159 stars, the third most abundant element, oxygen, cannot be analysed in type A PG 1159 stars due to the lack of sufficiently strong spectral lines. O VI lines, present in hotter PG 1159 stars, are not excited while transitions of lower oxygen ionisation stages are weak in the optical range. Therefore, only the hottest object of the sample, SDSS J001651.42−011329.3, allows the determination of an oxygen abundance (O/He = 0.04). For the others, additional UV spectra would be required.

Finally, we compare the positions of the new PG 1159 stars with evolutionary tracks as well as with positions of previously known PG 1159 stars and related objects (Fig. 3). From our results SDSS J001651.42 −011329.3 marks the transition from [WC]-PG 1159 to PG 1159 stars. From its position in the $T_{\rm eff} - \log g$ diagram (Fig. 3), the sdO star did clearly not

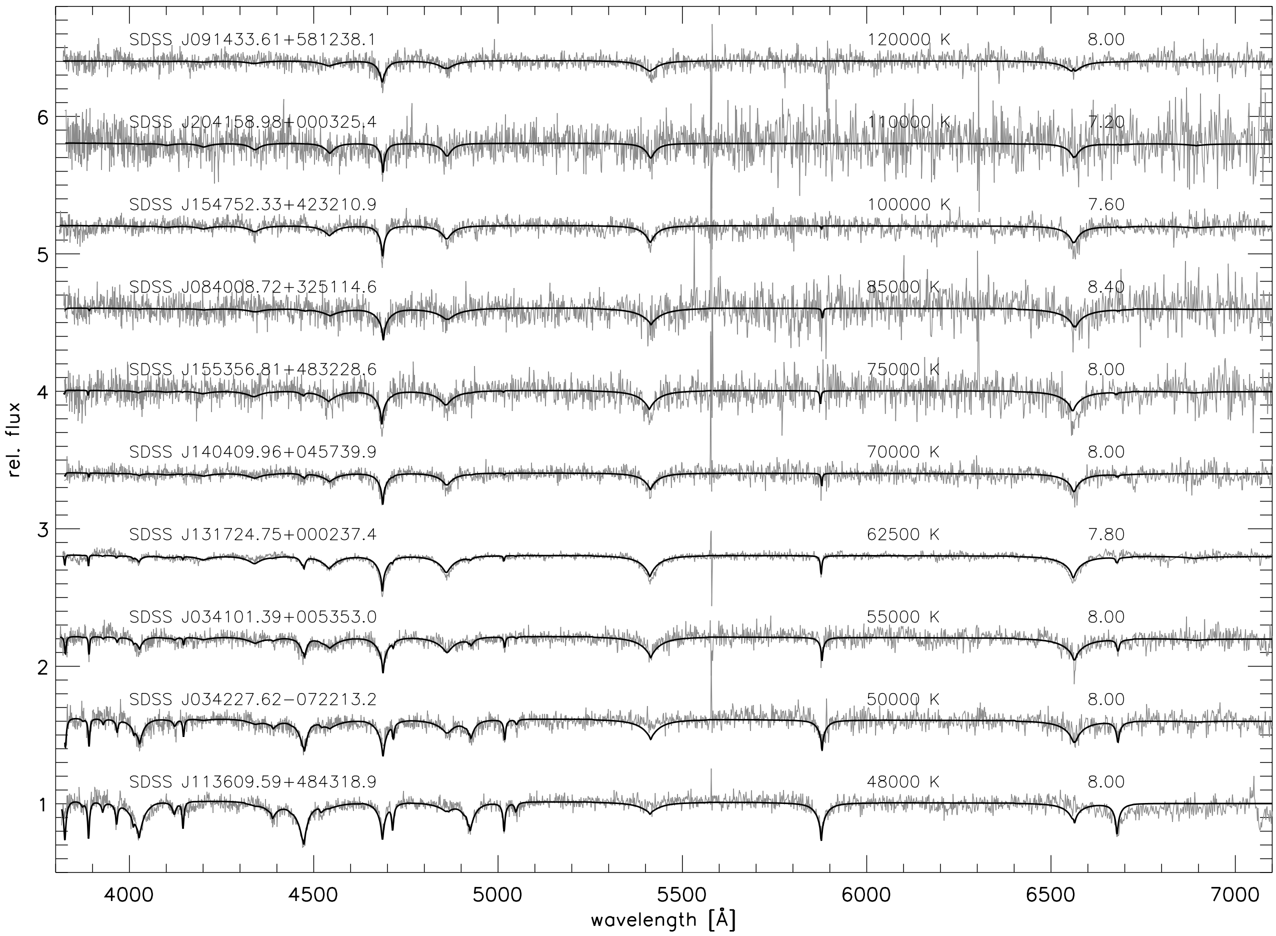


**Fig. 2.** Normalised optical spectra (grey lines) of DO white dwarfs and model atmospheres (black lines), ordered by decreasing effective temperature. Object names are printed on the left, effective temperatures and logarithmic surface gravities on the right. The spectra of the hottest stars are dominated by He II absorption lines, while increasing line strengths of He I are observed with decreasing temperature.

**Table 1.** Atmospheric parameters of PG 1159 stars and the sdO star (last entry). The C/He abundance ratio is given by number.

| Name | $T_{\rm eff}$ [kK] | $\log g$ [cgs] | C/He |
|---|---|---|---|
| SDSS J001651.42−011329.3 | 120 ± 10 | 5.5 ± 0.6 | 0.20 |
| SDSS J102327.41+535258.7 | 120 ± 10 | 7.0 ± 0.6 | 0.30 |
| SDSS J075540.94+400918.0 | 100 ± 10 | 7.6 ± 0.4 | 0.03 |
| SDSS J144734.12+572053.1 (a) | 100 ± 10 | 7.6 ± 0.4 | 0.05 |
| SDSS J144734.12+572053.1 (b) | 90 ± 5 | 7.6 ± 0.4 | 0.03 |
| SDSS J134341.88+670154.5 | 90 ± 5 | 7.6 ± 0.4 | 0.05 |
| SDSS J110215.46+024034.2 | 55 ± 5 | 6.4 ± 0.4 | 0.01 |

have an AGB history but did rather evolve directly from the Horizontal Branch.

### 4.2. DO white dwarfs

The stellar parameters are presented in Table 2. From the ten objects – an increase of 50% of known DO white dwarfs – one was previously known from the Hamburg ESO Survey (SDSS J131724.75+000237.4 = HE1314+0018, Werner et al. 2004). Comparing our results with theirs, we find similar stellar parameters. The UVES/VLT spectrum of HE1314+0018 analysed by Werner et al. (2004), however, allowed a much more detailed comparison between synthetic spectra and observation, showing discrepancies for all available models. In our low resolution spectrum, this finding can be confirmed, excluding data reduction problems as a solution for the systematic deviation between models and observation. This phenomenon has previously been observed in DO-like stars with signatures of very highly excited C, N, O, and Ne lines (Werner et al. 1995; Dreizler et al. 1995), however, no such spectral lines are present in HE1314+0018.

Two stars, SDSS J131724.75+000237.4 and SDSS J140409.96+045739.9, provide detectable C IV lines. While the carbon abundance of the former one was already determined by Werner et al. (2004) to C/He = 0.001, the latter one features a carbon abundance of C/He = 0.01 (Hügelmeyer et al. 2005). The spectra of the remaining objects do not allow to derive metal abundances due to low signal-to-noise ratios.

Stellar masses are derived from our atmospheric parameters using an interpolation program for evolutionary tracks (Wood 1995) written by D. Koester. The results are displayed in Figs. 4, 5 and Table 2. We identified the most massive DO white dwarf (0.9 $M_\odot$) known so far. In general, the mass distribution

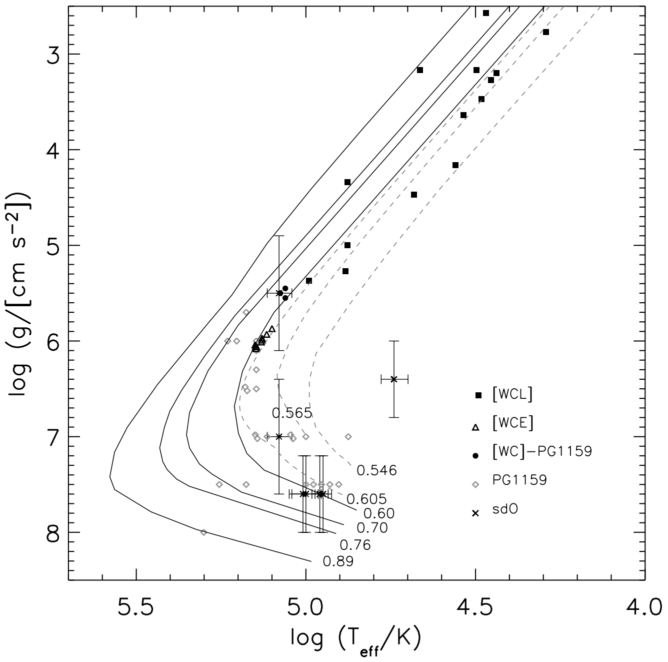


**Fig. 3.** Positions of the new PG 1159 stars (with error bars) compared to evolutionary tracks from Blöcker (1995), Schönberner (1983) (dashed lines) and Wood & Faulkner (1986). Labels: mass in $M_{\odot}$.

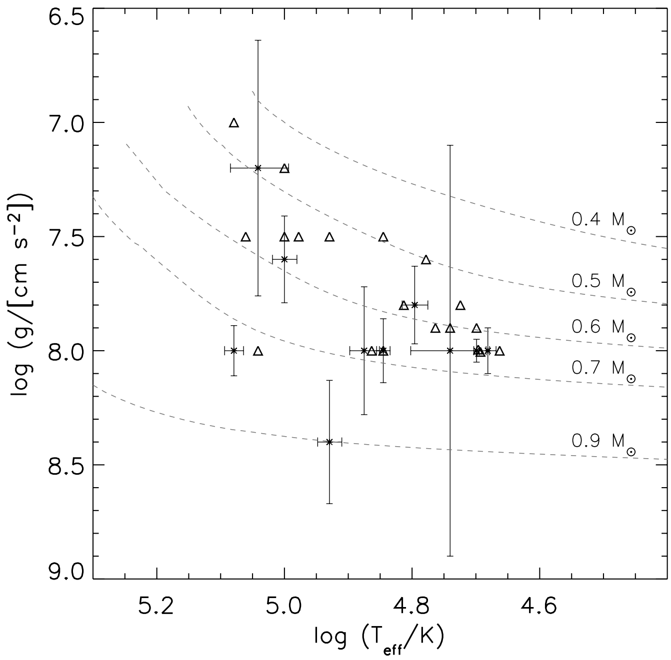


**Fig. 4.** Positions of DO white dwarfs compared with evolutionary tracks from Wood (1995). The triangles represent the 19 hitherto known DOs (see Dreizler & Werner 1996; Dreizler et al. 1997; Werner et al. 2004).

**Table 2.** Stellar parameters of DO white dwarfs.

| Name | $T_{eff}$ [kK] | log $g$ [cgs] | M [$M_{\odot}$] |
|---|---|---|---|
| SDSS J091433.61+581238.1 | 120.0 ± 4.1 | 8.00 ± 0.11 | 0.75 |
| SDSS J204158.98+000325.4 | 110.0 ± 11.5 | 7.20 ± 0.56 | 0.60 |
| SDSS J154752.33+423210.9 | 100.0 ± 4.4 | 7.60 ± 0.19 | 0.59 |
| SDSS J084008.72+325114.6 | 85.0 ± 3.7 | 8.40 ± 0.27 | 0.90 |
| SDSS J155356.81+483228.6 | 75.0 ± 4.0 | 8.00 ± 0.28 | 0.68 |
| SDSS J140409.96+045739.9 | 70.0 ± 1.7 | 8.00 ± 0.14 | 0.68 |
| SDSS J131724.75+000237.4 | 62.5 ± 2.9 | 7.80 ± 0.17 | 0.58 |
| SDSS J034101.39+005353.0 | 55.0 ± 8.4 | 8.00 ± 0.90 | 0.65 |
| SDSS J034227.62−072213.2 | 50.0 ± 0.5 | 8.00 ± 0.05 | 0.65 |
| SDSS J113609.59+484318.9 | 48.0 ± 0.3 | 8.00 ± 0.10 | 0.64 |

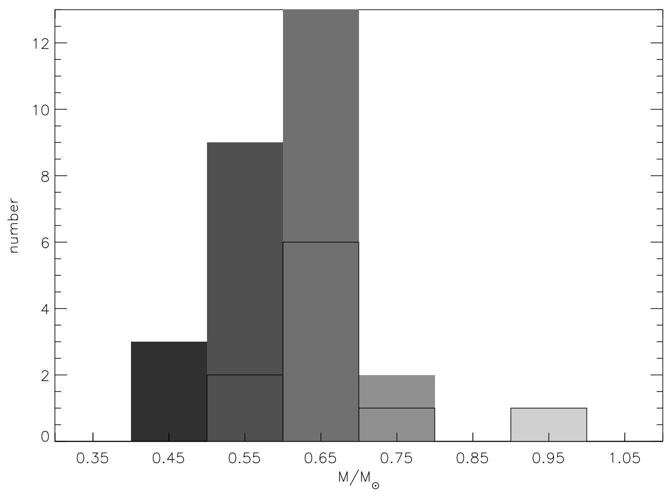


**Fig. 5.** Mass distribution (bin = 0.1 $M_{\odot}$) of all known DO white dwarfs. The region below the back line represents masses of stars from this work while the area above the line shows results from Dreizler & Werner (1996) and Dreizler et al. (1997).

of SDSS DO white dwarfs seems to be slightly shifted towards higher masses. This suggests a consistent reanalysis of the other DO stars with our current model grid and $\chi^2$-technique. Using the same program by D. Koester, we also derived cooling ages for the DO white dwarfs in the range of 145 000 to 2.500 000 years. A complete statistical analysis of DO white dwarfs is planned for presentation after the last SDSS data release.

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The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, Princeton University, the United States Naval Observatory, and the University of Washington.

## References

Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2003, AJ, 126, 2081
Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2004, AJ, 128, 502

Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2005, AJ, 129, 1755
Blöcker, T. 1995, A&A, 299, 755
Cox, A. N. 1986, Highlights in Astronomy, 7, 229
Dreizler, S., & Heber, U. 1998, A&A, 334, 618
Dreizler, S., Heber, U., Napiwotzki, R., & Hagen, H. J. 1995, A&A, 303, L53
Dreizler, S., & Werner, K. 1996, A&A, 314, 217
Dreizler, S., Werner, K., Heber, U., Reid, N., & Hagen, H. 1997, in The Third Conference on Faint Blue Stars, ed. A. G. D. Philip, J. Liebert, R. Saffer, & D. S. Hayes (Schenectady, New York: L. Davis Press), 303
Dreizler, S., Werner, K., Jordan, S., & Hagen, H. 1994, A&A, 286, 463
Green, R. F., Schmidt, M., & Liebert, J. 1986, ApJS, 61, 305
Hagen, H.-J., Groote, D., Engels, D., & Reimers, D. 1995, A&AS, 111, 195
Hügelmeyer, S. D., Dreizler, S., Werner, K., et al. 2005, in Proceedings of the 14th European Workshop on White Dwarfs, ed. D. Koester, & S. Moehler (San Francisco: ASP), ASP Conf. Ser., 334, 233
Krzesiński, J., Nitta, A., Kleinman, S. J., et al. 2004, A&A, 417, 1093
Liebert, J., Wesemael, F., Hansen, C. J., et al. 1986, ApJ, 309, 241
McGraw, J. T., Liebert, J., Starrfield, S. G., & Green, R. 1979, in White Dwarfs and Variable Degenerate Stars, ed. H. M. van Horn, & V. Weidemann (Rochester: University of Rochester), IAU Coll., 53, 377
Quirion, P.-O., Fontaine, G., & Brassard, P. 2004, ApJ, 610, 436
Schönberner, D. 1983, ApJ, 272, 708
Starrfield, S. 1987, in Second Conference on Faint Blue Stars, ed. A. G. D. Philip, D. S. Hayes, & J. Liebert (Schenectady, New York: L. Davis Press), IAU Coll., 95, 309
Stoughton, C., Lupton, R. H., Bernardi, M., et al. 2002, AJ, 123, 485
Werner, K. 1992, Lecture Notes in Physics (Berlin: Springer-Verlag), 401, 273
Werner, K., Deetjen, J. L., Dreizler, S., et al. 2003, in Stellar Atmosphere Modeling, ed. I. Hubeny, D. Mihalas, & K. Werner, (San Francisco: ASP), ASP Conf. Ser., 288, 31
Werner, K., Dreizler, S., Heber, U., & Rauch, T. 1996, in Astrophysics in the Extreme Ultraviolet, ed. S. Bowyer, & R. F. Malina (Dordrecht: Kluwer Academic Publ.), IAU Coll., 152, 229
Werner, K., Dreizler, S., Heber, U., et al. 1995, A&A, 293, L75
Werner, K., Heber, U., & Hunger, K. 1991, A&A, 244, 437
Werner, K., Rauch, T., Napiwotzki, R., et al. 2004, A&A, 424, 657
Wisotzki, L., Koehler, T., Groote, D., & Reimers, D. 1996, A&AS, 115, 227
Wood, M. A. 1995, Lecture Notes in Physics (Berlin: Springer-Verlag), 443, 41
Wood, P. R., & Faulkner, D. J. 1986, ApJ, 307, 659
York, D. G., Adelman, J., Anderson, J. E., et al. 2000, AJ, 120, 1579
Zhang, E.-H., Robinson, E. L., & Nather, R. E. 1986, ApJ, 305, 740