The cool end of the DZ sequence in the SDSS

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Abstract. We report the discovery of cool DZ white dwarfs, which lie in the SDSS (u-g) vs. (g-r) two-color diagram across and below the main sequence. These stars represent the extension of the well-known DZ sequence towards cooler temperatures.

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INTRODUCTION

Cool He-rich metal polluted white dwarfs (spectral class DZ) in the SDSS data have been analyzed by [1]. In the (u-g) vs. (g-r) diagram (Fig. 1) all but one fall in the region above the main sequence of normal stars (grey dots). Of the 147 objects discovered in the SDSS only two have $T_{\text{eff}}$ below 6600 K (at 6090 and 4660 K). This suggests that a large number of cooler DZ remains to be found. We have therefore visually checked all spectra in the region of QSO colors with borders described by the dashed lines and identified 17 as cool DZ. The location in the two-color diagram indicates that the DZ sequence might “tunnel” through the main sequence. Using a new search routine in the region bounded by the continuous lines, which checks for the characteristic features (most prominently MgI lines near 5170 Å), we found another 6 objects, 2 of which were already in the Dufour sample.

Fig. 2 shows a selection of typical spectra. SDSS1535+1247 (= NLTT40607 = G137-24) was already identified as a DZ and analyzed by [2] and [3]. It looks extremely similar to G165-7, shown by [4] to be weakly magnetic. That star is also in our sample (SDSS1330+3029). SDSS0916+2540 has the strongest features of any DZ known, whereas the remaining two show little more than the strong asymmetric feature between 5000 and 5200 Å, which is characteristic for this group. SDSS1336+3547 is magnetic, with multiple line cores in many metal lines.

Our list of extreme DZ is given here

| SDSS 0157+0033 | SDSS 0205+2155 | SDSS 0916+2540 | SDSS 0925+3130 |
|----------------|----------------|---------------|---------------|
| SDSS 0937+5228 | SDSS 0956+5912 | SDSS 1033+1809 | SDSS 1038-0036 |
| SDSS 1040+2407 | SDSS 1043+3516 | SDSS 1103+4144 | SDSS 1144+1218 |
| SDSS 1152+1605 | SDSS 1234+5208 | SDSS 1330+3029 | SDSS 1336+3547 |
| SDSS 1404+3620 | SDSS 1421+1843 | SDSS 1430-0151 | SDSS 1524+4049 |
| SDSS 1535+1247 | SDSS 1546+3009 | SDSS 1616+3303 |
FIGURE 1. SDSS Two-color diagram for objects with spectra identified as normal stars (grey S-shaped region in the middle of the figure), QSO (dots below main sequence), DZ white dwarfs analyzed by [1] (heavy black dots) and cool “extreme” DZ discovered by our search (small circles).

ANALYSIS

All spectral features can be identified with lines from Ca, Mg, Na, Fe, Ti, and Cr. The broadest lines show strongly asymmetric profiles, which were in the case of MgI 5169/5174/5185 correctly identified as due to quasistatic broadening by [2]. The width of these lines, as well as that of the CaI and CaII resonance lines is far beyond the range of validity of the impact approximation. We have used the simple and elegant method of [5], who present numerical calculations for the transition range between impact and quasistatic regime, which can in both limits be easily extended with the asymptotic formulae. These profiles are reasonable approximations in many cases. Nevertheless, the current analysis is only a first attempt and the results are a preliminary estimate of the general parameters of these objects. Among the problems which will need to be resolved are

- The CaI and CaII resonance lines between 3900 and 4250 Å are so strong that they completely cut off all the flux below 4500 Å. Our profiles assume a van der Waals $r^{-6}$ dependence for the perturbation energy, which has been shown by [6] to be a very poor approximation for the Ca-He interaction. This assumption has to be replaced by a more sophisticated potential for each individual line. The current profiles are not a satisfactory approximation.
- The u-g colors suggest that the UV flux near 3500 Å is almost totally suppressed in
all objects. We have included all expected strong lines in the UV – in particular from FeI and MgI/MgII – in our modeling, which results in a strong blanketing effect in the optical. The models qualitatively reproduce the u-g colors, and therefore also the blanketing effect. However, the MgI/II resonance lines are expected to be extremely strong, and similar caution applies to their profiles as for the CaI/II resonance lines.

- The upper limit to the H/He ratio is \( \approx 10^{-4} \) from the non-visibility of H\(\alpha\), but the exact amount is unknown. Since the broadening of Lyman \(\alpha\) by helium leads to very strong absorption even into the optical range, this is a further unknown free parameter.
Finally, the surface gravity can also not be determined from the available observations, and we have assumed $\log g = 8$.

RESULTS

For a preliminary analysis we calculated a grid of helium-rich atmosphere models with $T_{\text{eff}}$ between 7000 and 5000 K, $\log g$ fixed at 8.0, and variable metal abundances of 13 most commonly detected elements between Na and Fe, with the ratios kept at approximately solar values. The hydrogen abundance was fixed at $\log H/He = -4$. A temperature was determined from the slope of the spectrum, which is in most cases confirmed by the SDSS magnitudes. In some cases additionally the ionization balance of CaI/CaII was taken into account. The objects in the two-color diagram below the main sequence are essentially the continuation of the DZ temperature sequence down to $\approx 5400$ K.

For the most metal-rich objects individual abundances were adjusted until a reasonable fit to the spectral features was achieved. As an example we note results for two objects with the strongest features

**SDSS 1535+1247:** $T_{\text{eff}} = 5700$ K, $[\text{Mg/He}] = -7.50$, $[\text{Na/He}] = -8.90$, $[\text{Ca/He}] = -8.90$, $[\text{Fe/He}] = -7.60$

**SDSS 0916+2540:** $T_{\text{eff}} = 5500$ K, $[\text{Mg/He}] = -6.90$, $[\text{Na/He}] = -9.25$, $[\text{Ca/He}] = -7.50$, $[\text{Fe/He}] = -7.10$.

It is obvious that – while the Mg/Fe ratios are quite similar – the relative Ca and Na abundances vary significantly. Since the diffusion time scales of these elements agree within about 30%, it is quite likely that these differences have to be attributed to different compositions of the accreted material. While the Ca abundance of SDSS 0916+2540 looks exceptionally high compared to the Dufour et al. results, the other objects follow the general trend of their Fig. 9.

The total mass of observed metals in the convection zone of SDSS 0916+2540 is $\approx 5.2 \times 10^{21}$ g. Adding C, O, Si with the relative abundances as observed in GD40 [7] the total mass of metals is $\approx 1.4 \times 10^{23}$ g. If accretion really has reached diffusion equilibrium (the diffusion time scales are typically 300000 yrs) the total accreted mass is of the order of the Pallas or Vesta masses.

REFERENCES

1. P. Dufour, P. Bergeron, J. Liebert, H. C. Harris, G. R. Knapp, S. F. Anderson, P. B. Hall, M. A. Strauss, M. J. Collinge, and M. C. Edwards, *ApJ* **663**, 1291–1308 (2007).
2. A. Kawka, S. Vennes, and J. R. Thorstensen, *AJ* **127**, 1702–1711 (2004).
3. A. Kawka, and S. Vennes, *ApJ* **643**, 402–415 (2006).
4. P. Dufour, P. Bergeron, G. D. Schmidt, J. Liebert, H. C. Harris, G. R. Knapp, S. F. Anderson, and D. P. Schneider, *ApJ* **651**, 1112–1119 (2006).
5. R. Walkup, B. Stewart, and D. E. Pritchard, *Phys. Rev. A* **29**, 169–173 (1984).
6. E. Czuchaj, F. Rebentrost, H. Stoll, and H. Preuss, *Chemical Physics Letters* **182**, 191–199 (1991).
7. B. Klein, M. Jura, D. Koester, B. Zuckerman, and C. Melis, *ApJ* **709**, 950–962 (2010).