A&A 439, 317–321 (2005)
DOI: 10.1051/0004-6361:20053058

Astronomy
&
Astrophysics

HS 0146+1847 – a DAZB white dwarf of very unusual composition*

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Received 14 March 2005 / Accepted 22 April 2005

Abstract. HS 0146+1847, originally identified as a white dwarf candidate in proper motion surveys, was rediscovered as a candidate in the Hamburg Quasar Survey. Spectra obtained for the SPY (ESO Supernova Ia Progenitor) survey show strong Balmer and Ca II lines, suggesting a classification as DAZ white dwarf. Contrary to the objects known so far in this class, HS 0146+1847 has a helium-rich atmosphere at $T_{\rm eff}$ = 11 500 K. This is confirmed by very weak He lines, changing the classification to DAZB. Mg and Fe lines are also detected. We discuss the physics of Balmer line broadening by neutral helium, present a spectral analysis and note some implications for the accretion/diffusion scenario of heavy elements in cool white dwarfs.

Key words. stars: white dwarfs – stars: atmospheres – stars: abundances

1. Introduction

The mono-elemental composition of the atmospheres of most white dwarfs – either almost pure hydrogen, or equally pure helium – has been understood since a long time as a result of gravitational separation in high gravitational fields (Schatzman 1947). Some open questions remain, however, e.g. the origin of the helium-rich sequence, or the nature of mixed H-He atmospheres of spectral type DAB. Another deviation from mono-elemental composition are the traces of heavy elements (predominantly Ca) found in cooler white dwarfs below $T_{\rm eff} \approx 20\,000$ K. One of the first known white dwarfs (van Ma 2) belongs to the DZ spectral type (only metal lines visible) in a He-rich atmosphere, a well known and studied class of white dwarfs. More recently, this metal contamination has also been found in many hydrogen-rich white dwarfs (Zuckerman & Reid 1998; Zuckerman et al. 2003; Koester et al. 2005), enlarging the class DAZ originally defined by the single object G 74-4 (Lacombe et al. 1983). The most plausible explanation of the metals is accretion from interstellar matter, but some unsolved questions remain (see e.g. discussion in Zuckerman & Reid 1998; Zuckerman et al. 2003).

In this paper we report the analysis of a unique white dwarf, which at first sight looks like a DAZ with strong Ca II lines, but turns out to have a He-rich atmosphere with very strong H and metal contamination.

2. HS 0146+1847: observations and analysis

HS 0146+1847, also known as GD 16, LTT 10628, Wolf 88, was first noted as a high proper motion and blue object (Wolf 1919; Luyten 1961; Giclas et al. 1965, 1980). It was rediscovered as a white dwarf candidate in the Hamburg Quasar (HQS) survey (Hagen et al. 1995) from the objective prism plates by Homeier (2001). The object is classified as a white dwarf in the Simbad database, but to our knowledge no spectrum was ever obtained before the HQS survey and it is not in the white dwarf catalog of McCook & Sion (2003).

Two high resolution spectra were obtained as part of the search for close double degenerate binary systems in the ESO SN Ia progenitor survey (=SPY, Napiwotzki et al. 2001, 2003). The selection of the sample, the specific nature of the search as a "filler project" for mediocre weather conditions, and the reduction procedures are described in the cited papers and in Koester et al. (2001). We therefore repeat here only the most important characteristics. The spectra were obtained with the UV-Visual Echelle Spectrograph (UVES) at the Unit 2 Telescope (Kueyen) of the Very Large Telescope of ESO on

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* Based on data obtained at the Paranal Observatory of the European Southern Observatory for programs 165.H-0588 and 167.D-0407.

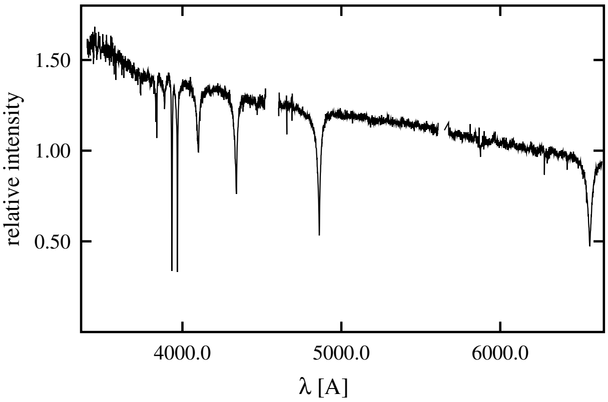

Fig. 1. UVES spectrum of HS 0146+1847, showing hydrogen Balmer lines and Ca II H and K.

Paranal. The slit width is 2.″1, leading to a resolution of about 18 500 or better, depending on the seeing. The S/N per binned pixel of 0.1 Å used in the present work is usually 15 or higher.

Both spectra show the same features, but one is of much higher quality and is the only one used for the detailed analysis presented here. The spectrum is shown in Fig. 1.

The Balmer lines and the resonance lines of Ca II are immediately obvious and we therefore included this object in our study of DAZ white dwarfs (Koester et al. 2005). The attempt to determine atmospheric parameters from the lower Balmer lines up to Hδ, however, did not produce reasonable results. The "best fit" within our normal DA model grid, resulted in $T_{\rm eff}$ = 32 100 K, log g = 7.60, and is shown in Fig. 2.

It is clear that the strong Balmer decrement of the observations is not reproduced by the models. In addition the observed line profiles seem to be asymmetric, which cannot originate from the symmetric Stark broadening of the Balmer lines. Another argument against this fit result are the Ca II lines. Photospheric lines of Ca II are not expected at such a high temperature, and the lines are much too strong to be of interstellar origin. This led us to consider the only plausible alternative – a helium-dominated atmosphere at much lower temperature – with hydrogen line broadening dominated by van der Waals interaction with neutral helium.

Very recently Gianninas et al. (2004) discovered a DAZ near $T_{\rm eff}$ = 10 000 K with equally strong Balmer and Ca II lines. This opens up the question, whether it is possible to decide upon the main atmospheric constituent in this temperature range, where He lines should be very weak or absent and hydrogen lines could theoretically be of comparable strength (although such an object has not been observed before HS 0146+1847). It is very instructive to compare their spectrum (their Fig. 2) with our spectrum in Fig. 1, which makes obvious the strong decrement and asymmetry of the Balmer lines in our object.

A number of preliminary tests with helium-rich atmospheres confirmed that this is indeed a possible solution, and led us to estimates of the H and Ca abundances. A grid of model atmospheres was then calculated with parameters in the range of these estimates. Atmosphere parameters (besides the usual $T_{\rm eff}$ and log g), were the abundances of Ca (around 2×10^{-9} by numbers, compared to He) and H (10^{-1} to 10^{-4}). The solution is not well determined when all parameters are allowed to vary, since e.g. the hydrogen lines increase in strength both with abundances, but also with $T_{\rm eff}$. For our first determinations we therefore held log g fixed at 8.0 and also the Ca abundance at 2×10^{-9}, close to the final best fit value. The solutions found with these constraints are as expected at much lower temperature, e.g. $T_{\rm eff}$ = 11 320 K, H/He = 1.8×10^{-3}. This fit is shown in Fig. 3; it is much better than the DA fit, but still far from perfect. While Hα is still somewhat too strong, the higher Balmer lines are too weak. We have repeated the fit procedure with different log g within a plausible range of 7.5–8.5, but the result does not improve significantly.

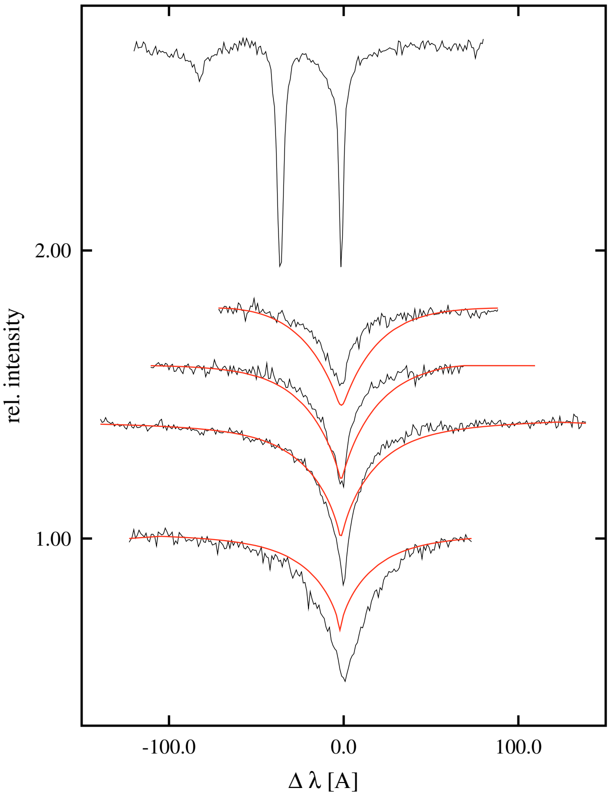

Fig. 2. Best fit of DA models to the Balmer lines Hα to Hδ from bottom. The region with the Ca II lines, which also shows Hϵ in the left wing of the K line and a weak H8, is not included in the fitting, but shown in the figure to preserve the same scale as in the following figures. The profiles have been shifted upwards by 0.4, 0.6, 0.8, 1.7 starting from Hβ.

With such an unsatisfactory fit, can we be certain to use the right range of parameters as regarding major constituent and effective temperatures? Fortunately there are strong arguments in favor. A close inspection of the observed spectrum reveals the presence of weak, but clearly identified He I lines at 5875 and 4471 Å. Figure 4 shows that our best fit model – considering the approximations in the line broadening, see below – gives a very reasonable fit for both lines (note that we show here the final model making use of the changes in input physics discussed below). This is confirmation that the dominant element is indeed helium and also excludes any temperature outside the range 11 500 ± 750 K.

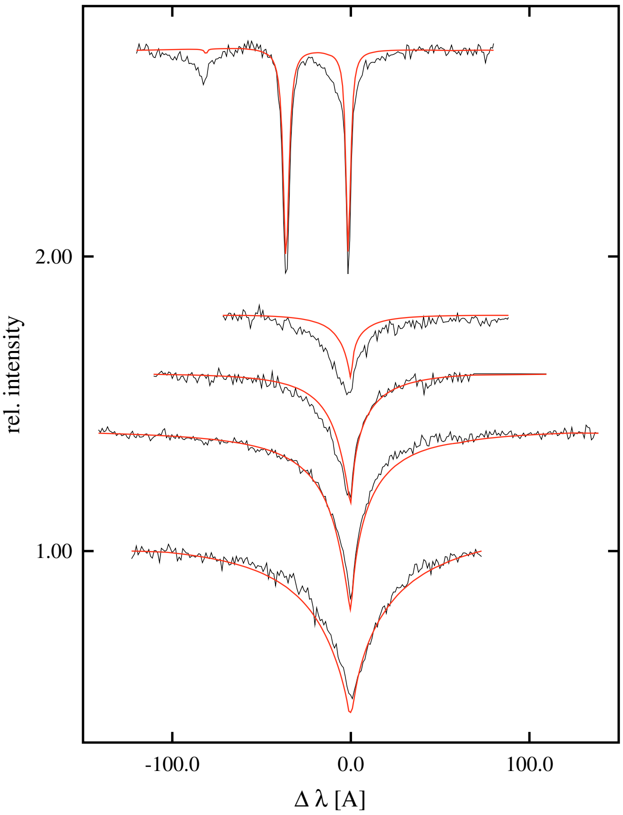

Fig. 3. Best fit with He-rich models including H and Ca. See text for further description.

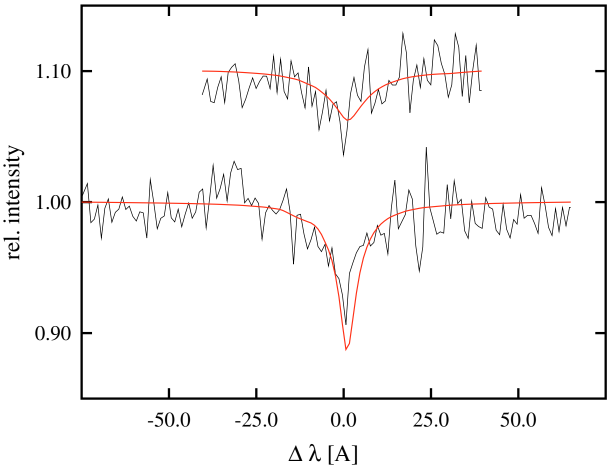

Fig. 4. He I 5875 (*bottom*) and 4471 (*top*) lines in the observed spectrum and the best fit model.

2.1. Some remarks on input physics

Line broadening for hydrogen, helium, and metal lines under these conditions is dominated by interactions with neutral He atoms. We have determined the van der Waals interaction constants C_6 (the interaction energy between emitter and perturber is approximated as $\Delta E = h\,C_6/r^6$, with Planck constant h and distance r) and the damping parameter Γ_6 following Unsöld (1968), with the improvements for hydrogen lines broadened by neutral helium as described by Bergeron et al. (1991). We use the impact approximation, which leads to a (shifted) Voigt profile. This is usually a good approximation for the line center; its range of validity can be estimated (see Unsöld 1968) as 55, 22, 15, 11 Å from the line center for Hα, Hβ, Hγ, and Hδ. Ideally we would prefer a unified theory valid for center and line wing, which to our knowledge is not available for the conditions needed here. Stark broadening is not important and is therefore included in a very approximate way by using a Voigt profile with appropriate width Γ_2 and Γ_4 (for linear or quadratic Stark effect the interaction energy is $\propto r^{-2}$ resp. $\propto r^{-4}$).

We have tested models with different log g and also changes of the damping parameters within plausible uncertainties, but none of the calculations could produce the observed steep Balmer decrement. This leaves as the most likely culprit for the unsatisfactory fit the treatment of non-ideal effects in the gas with the Hummer-Mihalas (HM) occupation probability mechanism (Hummer & Mihalas 1988; Mihalas et al. 1988; Däppen et al. 1988). In that theory the occupation probability or the probability that a state still exists as a bound state depends on interactions of the emitter with neutral and charged perturbers. In our case only the neutral perturbers are important which lead to increasingly lower probabilities for higher exited states of hydrogen and as a consequence to a weakening of the higher Balmer lines and finally to a smooth merging of the highest series members into the continuum, as can be very well observed in normal DA white dwarfs. Bergeron et al. (1991) noticed that with the original description of the neutral interactions in HM – which is based on a hard sphere model – they obtained a systematically low surface gravity for cool DAs and concluded that the interaction has to be smaller than assumed. They introduced a correction factor of 0.5 (compared to 1.0 in the original HM) for the interaction radius (their Eq. (15)). We have in our models in the past been following this suggestion with the small change that we use a correction factor of $f = 1/8 = 0.125$ to the total excluded volume $(r_n + r_{n'})^3$ (their Eq. (16)). Since the higher level dominates the volume this is very nearly equivalent to the Bergeron et al. (1991) assumption. One should bear this in mind, however, in the following discussion, where we use our notation for the correction.

The model fit in Fig. 3 uses our standard model grids with $f = 0.125$. Although weaker than the standard HM model the interaction still seems to be too strong, unless we want to consider surface gravities much lower than 7.5. We have experimented with further decreasing f and find that a value as low as $f = 0.005$ is needed to give a reasonable fit. Further decreasing f does not lead to significant improvements anymore. This factor corresponds roughly to a correction factor of 0.17 in the Bergeron notation.

The final fit using a model grid calculated with this assumption is shown in Fig. 5. While the Balmer decrement still does not agree completely with the observation, the improvement is very noticeable for Hδ and Hϵ, visible in the wings of the Ca II K line. The parameters for the best fitting model are then (log g = 8 assumed)

$$T_{\rm eff} = 11\,500 \pm 300\ {\rm K}$$

$$[{\rm H/He}] = -2.89 \pm 0.3, \qquad [{\rm Ca/He}] = -8.7 \pm 0.2$$

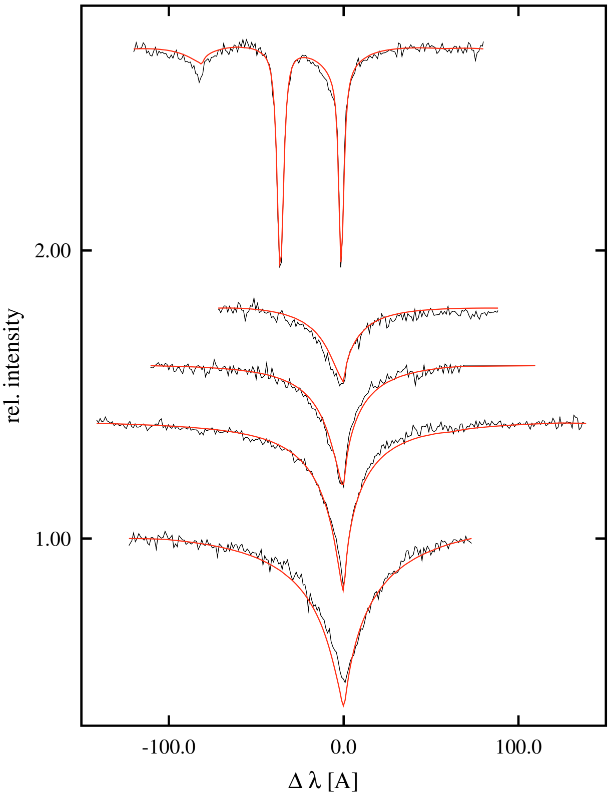

Fig. 5. Best fit with He-rich models including H and Ca, using a correction factor of 0.005 for the neutral interactions.

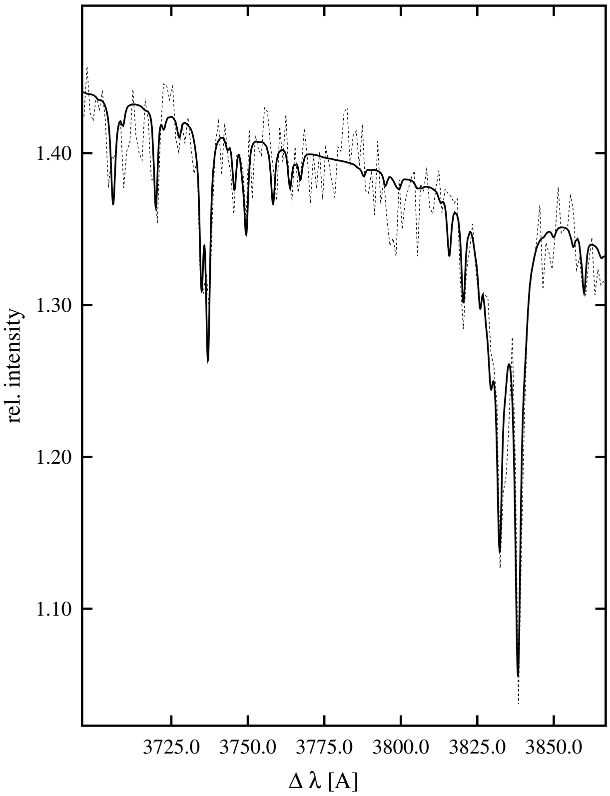

Fig. 6. Metal lines of Mg and Fe in the blue part of the spectrum (thin dotted line) compared to the model (thick line).

where we use the [ ] notation for logarithmic number ratios. The errors are our best estimate comparing the influence of abundance changes on the synthetic spectra. The formal errors from the χ^2 routine are as usually significantly smaller than this.

2.2. Other metals and final results

In the blue part of the spectrum, shortward of 4000 Å, a few stronger and a large number of weak lines are visible, which can be identified as belonging to Mg I and Fe I. These lines are quite often found also in DZ with helium-rich atmospheres. We were not able to identify Al, Si, and Ni, which also have lines in this region. In order to determine abundances we have calculated synthetic spectra for the range 3500 to 4000 Å, using the atmosphere stratification from the best fitting model with only He, H, and Ca included. The calculations included 9 Mg I and 480 Fe I lines; abundances were estimated from the strong lines Mg I 3832.304 and Mg I 3838.292 and several stronger blends of Fe lines, most importantly 3700–3750 Å. The abundances derived are [Mg/He] = −7.22 ± 0.2 and [Fe/He] = −7.70 ± 0.3. Figure 6 shows these regions for the observed spectrum and the model.

Since the Mg and Fe abundances are even higher than the Ca abundance we have calculated a fully consistent atmosphere model with all identified elements included in the equation of state. This did not change the model or the Balmer and He lines, thus confirming the validity of the atmospheric parameter determination. As a final test we have kept fixed all metal abundances and the effective temperature, with $\log g$ remaining the only unknown parameter. The best fit model was then found at $\log g = 7.94$. While this cannot be considered a real determination, it at least suggests that our assumption of $\log g = 8.0$ is consistent.

The photographic magnitude m_{ph} of HS 0146+1847 is 15.5 (Giclas et al. 1965). Our final model has an absolute magnitude $M_V = 12.05$, assuming $\log g = 8.0$, and $B - V = 0.01$. We can thus assume that $V \approx m_{\mathrm{ph}}$ and derive a distance $d \approx 50$ pc.

3. Discussion

We have demonstrated that contrary to the first impression from rather strong Balmer lines the main constituent of the atmosphere of HS 0146+1847 is helium. The broadening of the Balmer lines is thus dominated by van der Waals broadening by neutral helium atoms, leading to asymmetric line profiles. Direct implementation of the Hummer-Mihalas-Däppen occupation probability mechanism leads to much weaker higher Balmer lines than are observed. We are thus forced to decrease the strength of the neutral interactions even more than was found by Bergeron et al. (1991). This leads to satisfactory fits for HS 0146+1847.

We do not believe that this result should be applied to hydrogen-rich white dwarfs without further evidence and testing. There are still some problems with the determination of surface gravities and masses in cool DA white dwarfs; see e.g. Kleinman et al. (2004), who find an increase in $\log g$ at the cool end of the DA sequence. However, that upturn starts above

$T_{\rm eff} \approx 10\,000$ K, where the interactions with charged particles still dominate in hydrogen.

The only plausible explanation for metals in cool white dwarfs is accretion from the outside, since the timescales for gravitational settling are always short compared to evolutionary timescales. This scenario has a number of problems, which are related to the conditions of the ISM in the solar neighborhood (for a discussion of the problems and alternative models see Zuckerman et al. 2003). The problems have become very severe recently with the discovery of many hydrogen-rich objects with metals, where the timescale for diffusion is extremely short and the star has to be now practically at the place where accretion occurred.

This is not true for HS 0146+1847. The current distance places it (with very large uncertainty because of the unknown $\log g$) possibly within the local bubble with very low neutral hydrogen column densities. However, the diffusion timescales in this helium-rich atmosphere are much larger, of the order of 10^6 yr (Dupuis et al. 1993a), and the object could have traveled many pc since the last accretion episode.

The abundances relative to helium of the three metals are very comfortably within the range predicted by Dupuis et al. (1993b, their Figs. 1, 3, 4) for high and low accretion rates, and similar to those found in typical DZ and DBZ objects. What makes this object unique and important is the large hydrogen abundance. Looking at the abundance ratio of the heavy elements to hydrogen, we find [Ca/H] = −5.81 (−5.69), [Mg/H] = −4.33 (−4.47), and [Fe/H] = −4.81 (−4.55), where the numbers in parentheses are the solar ratios (Asplund et al. 2004). The ratios are very close to the solar values, slightly lower for Ca and Fe, and slightly higher for Mg. It is tempting to interpret the numbers for Ca and Fe with the fact that the diffusion timescale for Mg is more than a factor of 2 longer than for Ca and Fe (see Table 1 in Dupuis et al. 1993a), but this is probably over-interpreting the accuracy of the results. In any case hydrogen in this star is very likely accreted with solar abundances, in stark contrast to most other DZ and DBZ in this temperature range (Koester & Wolff 2000; Wolff et al. 2002). The only viable explanation which has been discussed for the missing hydrogen in these objects is the propeller mechanism (Wesemael & Truran 1982), which needs a magnetic field and non-zero rotation in the white dwarf to prevent hydrogen from accreting. Since this was obviously not the case for HS 0146+1847, further studies for rotation and magnetic fields along the lines of Friedrich et al. (2004) would be very interesting.

Acknowledgements. This work in Kiel was supported partly by grant KO 738/21-1 from the *Deutsche Forschungsgemeinschaft*. R.N. acknowledges support by a PPARC Advanced Fellowship.

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