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Search for trace amounts of hydrogen in hot DO white dwarfs*

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Abstract. The question as to the hydrogen content in the atmospheres of helium-rich white dwarfs is of considerable importance to explain the long-standing problem of the chemical surface abundance evolution of white dwarfs along their cooling sequence. It is hoped that the H abundance gives a hint to the origin of the bifurcation of the white dwarf cooling sequence into a H-rich (DA) and a He-rich (non-DA) branch and the possible relationship between these.

We present high resolution spectra from two hot He-rich white dwarfs (RE 0503−289 and PG 1034+001) and the prototype of the PG 1159 spectral class (PG 1159−035). The spectra cover the core of the He II 6560Å line and were taken in order to detect possible weak Hα emission components. The search was entirely negative and imposes an upper limit ($\approx$ 5% by number) for the hydrogen abundance which is tighter than determined from previous medium resolution spectroscopy. We consider implications of this result on the evolutionary scenario.

Key words: stars: individual: PG 1034+001– stars: individual: RE 0503−289– stars: individual: PG 1159−035– stars: abundances – stars: evolution – white dwarfs

1. Introduction

From recent analyses of hydrogen-deficient post-AGB stars an evolutionary link between the Wolf-Rayet central stars of planetary nebulae ([WC] CSPN) and PG 1159 stars seems to be firmly established (see review by Dreizler et al. 1995). This is based on the detection of very similar abundance patterns in both types of stars (He, C, O-rich) as well as on our knowledge about at least two transition objects (A 30, A 78) and a single object which changed its spectral type and group membership from one into the other (Lo 4). The PG 1159 phase is the hottest during post-AGB evolution and resembles the beginning of the white dwarf cooling sequence. Later the stars contract and with the onset of gravitational settling carbon and oxygen are removed from the atmosphere leaving an essentially pure helium envelope. Thus the hot helium-rich white dwarfs (spectral type DO) are probably descendants from the PG 1159 stars. The subsequent evolution might be considered as that of a cooling white dwarf without drastic changes in the chemical composition of the atmosphere. However, the detection of the DB-gap (the non-existence of He-rich white dwarfs in the $T_{\rm eff}$ range 28 000–45 000 K, Liebert 1986) suggests that perhaps all non-DAs have retained some hydrogen mixed within the He-envelope which floats atop the atmosphere during evolution through this gap.

Hence, the knowledge of the hydrogen content in all objects representing preceding phases of post-AGB evolution is of utmost importance. The question arises if the H-deficient and H-rich post-AGB stars during the early post-AGB phase and all along the WD cooling sequence form two distinct channels or if there are further clues (aside from the DB gap) for a closer relation between both. Indeed, the detection of hydrogen in a [WC] central star (20% [number fraction] in V 348 Sgr, Leuenhagen & Hamann 1994) and the discovery of hybrid stars (Napiwotzki & Schönberner 1991, Dreizler et al. in prep.) with relatively high amounts of He,C, O *and* H (H=60–80%, Dreizler et al. 1995) calls for an intense search for hydrogen in PG 1159 stars and hot DO white dwarfs. For two cool DOs the detection of hydrogen was claimed: HZ 21, H=14%, (Koester et al. 1979, Wesemael et al. 1985) and HD 149499 B, H=18% (Napiwotzki et al. 1995).

The principal difficulty with the search for hydrogen in PG 1159 stars and hot DO white dwarfs arises from the fact that with increasing temperature the hydrogen ionization becomes extreme and the lines become rather weak making their detection within the dominant He II lines very difficult. In the case of PG 1159−035 for example a H/He ratio of unity could not be excluded (Werner et al. 1991, "WHH"), because the He II absorption profile is hardly affected by a possible H absorption contribution. Inspection of synthetic line profiles indicated an alternative possibility to detect hydrogen down to a more sensitive limit. The models predict a narrow Hα emission feature when the abundance fraction exceeds about 1%. However, high-

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* Based on observations obtained at the European Southern Observatory, La Silla, Chile

resolution high-S/N spectra are required to detect this weak feature and to separate it from the nearby (2.7Å redward) He II line core.

We decided to observe three representative targets along the hot DO sequence. The primary target out of the PG 1159 class is the prototype itself ($T_{\rm eff}$=140 000 K). It is the brightest (V=14.8) PG 1159 star which is not associated with a PN. All brighter ones are associated with a PN and were rejected because of nebular contamination of the Hα line. The second object is PG 1034+001 (V=13.2), one of the brightest DO white dwarfs, and the second hottest known ($T_{\rm eff}$=100 000 K). The third star is RE 0503−289 (V=13.9) which may be regarded as a borderline white dwarf between the hot and cool DOs ($T_{\rm eff}\approx$65 000 K). Cool DOs were excluded from this project because less time consuming medium resolution spectroscopy could already be successful. Effective temperature and surface gravity of all three target stars were previously determined. In the following section we describe our observation and data reduction techniques. Then we turn to details concerning our model atmosphere calculations before reporting the results of our analysis.

2. Observations

Observations were carried out with the 3.6m telescope at the European Southern Observatory at La Silla, Chile, in February 1995. We used the Cassegrain Echelle Spectrograph (CASPEC) in the longslit mode. In this mode the cross-disperser is replaced by a flat mirror and a spectral region is isolated by means of a narrow band interference filter. This has the important advantage that a proper sky background subtraction is possible because the slit length is 144" compared to a maximum possible value of 11" when the Echelle mode is used. This point was regarded as essential because only a reliable sky subtraction guarantees the detection of possible weak photospheric emissions. We employed the standard Hα filter (#5, bandwidth 25Å) which resulted in useful spectra in the range 6560±20Å, and the detector was a CCD (ESO #32). The spectral resolution amounts to 0.4Å. At least two spectra were taken of each star and co-added after reduction. We aimed at a high signal-to-noise ratio and since the target stars are relatively faint and the resolution is high, long exposure times were required. The total exposure times amount to: 2.7 hours (RE 0503−289), 4 hours (PG 1034+001), and 6 hours (PG 1159−035).

Using the IRAF[1] program package, data reduction was done with dome flat-field images and Th-Ar comparison spectra taken immediately before or after each science exposure. Due to the very small wavelength coverage this procedure already results in almost rectified spectra. This was verified by the observation of a DQ6 white dwarf (LTT 4364 = WD 1142-645, V=11.5) which has a continuous spectrum. Final normalization of the spectra was performed by degrading their resolution and scaling them to medium resolution spectra which we have obtained and published earlier (WHH, Werner et al. 1995a "WDW", Barstow et al. 1994). This was very helpful because our narrow wavelength interval does not cover the stellar continuum but it is located well in the He II 6560Å line core. The resulting spectra are shown in Fig. 1. The radial velocities of the stars are known and we shifted the spectra to the rest wavelength. Radial velocities are based on measurements of high resolution ultraviolet spectra. For RE 0503−289 it was estimated to +50 km s^{-1} from the O V 1371Å line in a IUE (International Ultraviolet Explorer) spectrum shown by Barstow & Sion (1994). A value of +35 km s^{-1} for PG 1159−035 was determined by Liebert et al. (1989) from IUE data. Finally, the radial velocity of PG 1034+001 was estimated from Hubble Space Telescope (HST) spectra to +35 km s^{-1} (WDW).

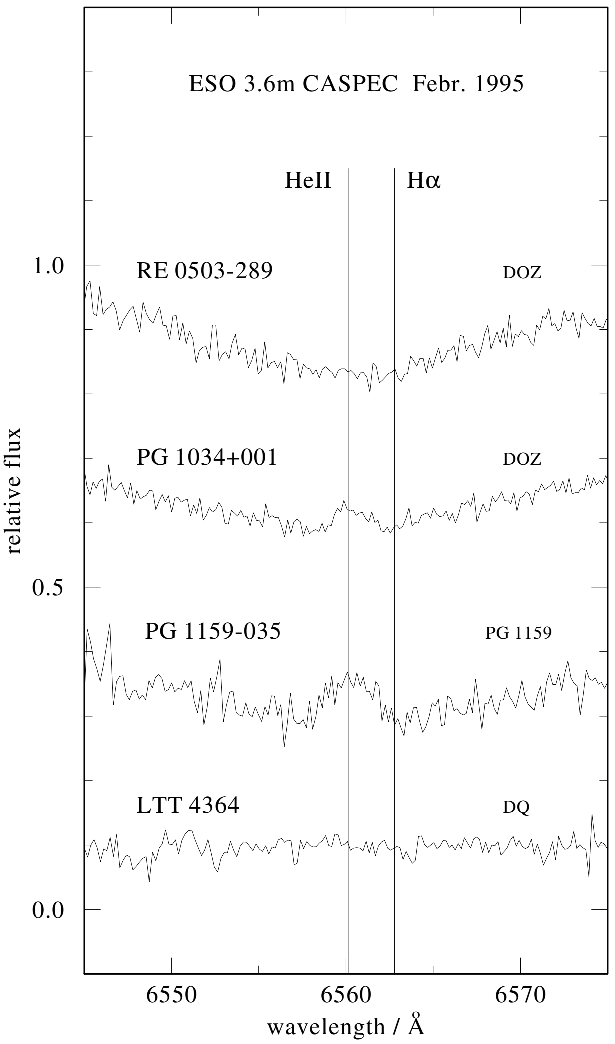

Fig. 1. ESO CASPEC spectra of the three program stars together with the spectrum from a DQ white dwarf (bottom). The spectra are shifted to the rest wavelength. Vertical bars denote the laboratory wavelength of He II 6560Å and Hα

1 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation

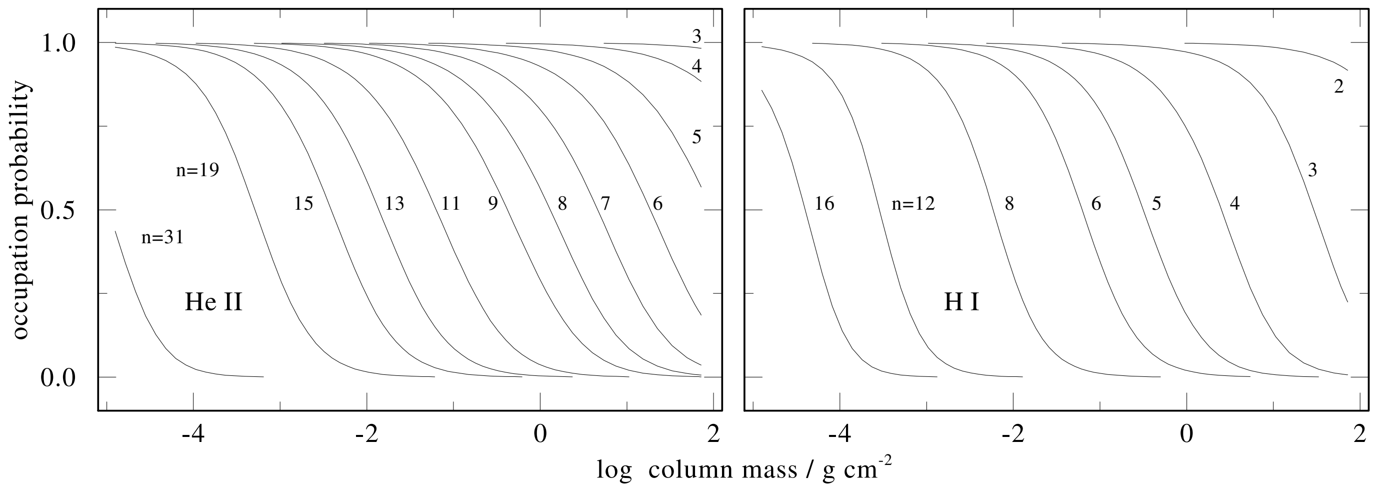

Fig. 2. Occupation probabilities of atomic He II levels (left) and H I levels (right) as a function of depth in the DO model atmosphere with $T_{\rm eff}$=100 000 K, log g =7.5, and H/He=0.1%.

As expected, the spectra of PG 1159−035 and PG 1034+001 exhibit central emission reversals in the He II line core in contrast to RE 0503−289 which has a pure absorption line. There is definitely no indication of emission reversals due to the Hα line. From the non-detection of hydrogen we will determine upper abundance limits. But before that, let us go into some details of our model atmosphere calculations.

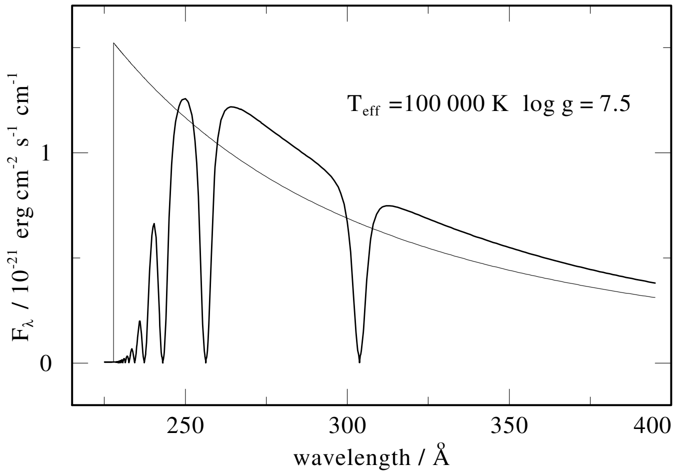

Fig. 3. Flux distribution of a DO model atmosphere computed with and without Stark broadened He II resonance lines.

3. Model atmospheres for DO stars

3.1. Hummer-Mihalas occupation probabilities

NLTE model atmospheres and line formation calculations were performed in order to fit the observed line profiles and to determine upper limits for the hydrogen abundance. The model atmospheres are chemically homogeneous, static, plane-parallel, and in radiative equilibrium (Werner & Dreizler 1995). Details on the models for PG 1159 stars and DOs can be found elsewhere (WHH, WDW). These models are now improved by incorporating the Hummer-Mihalas (1988) occupation probability formalism, which was generalized to NLTE conditions by Hubeny et al. (1994). Up to now our NLTE model atmospheres for DO stars were computed neglecting Stark broadening of He II lines. Clearly, it is desirable to account for the very broad He II lines already in the model calculations.

In the case of O stars Hubeny et al. (1994) discuss the effects of hydrogen line broadening and line merging on the model structure and line profiles. Since the Lyman edge is at the maximum of the stellar flux distribution, effects are not negligible. In parallel we expect that in the case of DOs flux blocking by the He II resonance lines in the dominant He II Balmer continuum has effects on the model structure. The concept how to incorporate the occupation probabilities into the atomic rate equations and the opacity calculations was essentially taken over from Hubeny et al. (1994). In contrast we do not use a special numerical treatment of the line-merging opacity. This is not necessary in our case, because due to the very high pressures the dissolution of higher levels is quite drastic. A full treatment of a 32-level He II model is performed and no assumption about additional opacities from higher levels is necessary. Figure 2 (left panel) shows that, e.g., the n=31 level is already completely dissolved (i.e. occupation probability =0) at log m=–3, which is above the line and continuum forming regions in the photosphere. This means that higher levels are essentially non-existing due to the high perturber density. The case for trace hydrogen in a DO atmosphere is similar. The right panel of Fig. 2 shows that our 16-level hydrogen model atom is completely sufficient because the highest levels are dissolved already in the upper parts of the atmosphere.

Figure 3 shows the flux distribution of a hot DO model. In one case it is blanketed by Stark broadened He II lines and in the other case Doppler broadened profiles were used for opacity

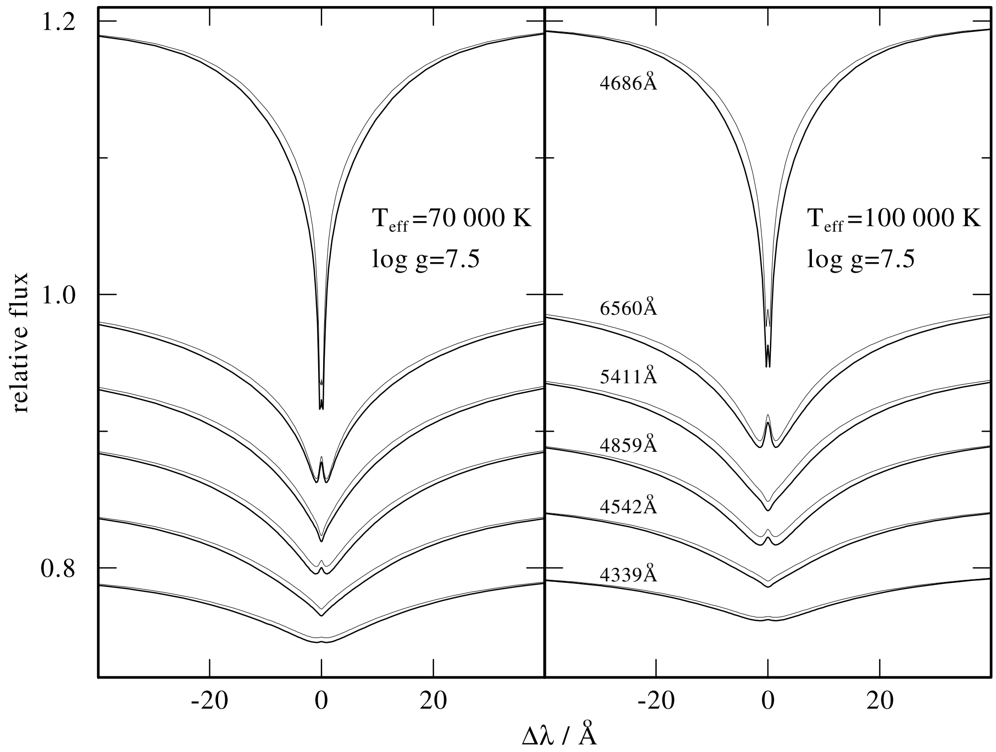

Fig. 4. Comparison of line profiles from DO models with and without Stark broadening plus occupation probability formalism for He II. The improved profiles (thick lines) are deeper. Obviously the alternating occurrence of emission cores in the Pickering series is not a NLTE effect but simply due to the fact that every other line lacks a central Stark component

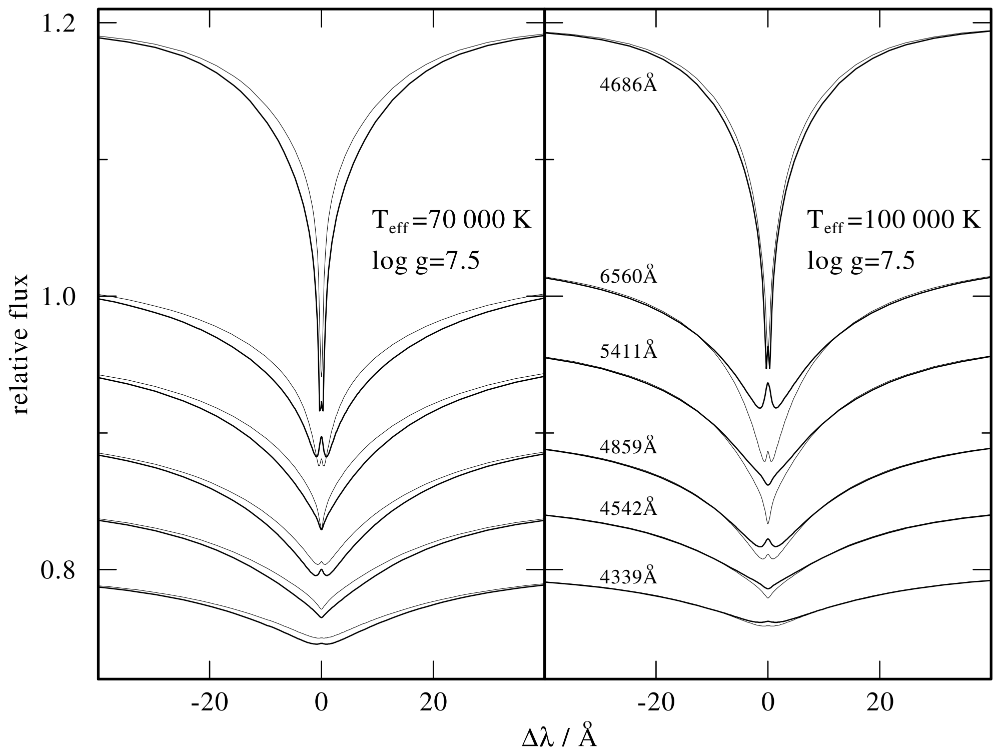

Fig. 5. Comparison of He II line profiles from LTE models (thin) and NLTE models (thick) for DO white dwarfs

and rate equation calculations. In the line merging region near the 228Å edge the flux is blocked and redistributed to longer wavelengths as a consequence of backwarming in the atmosphere. The enhancement of the continuum flux extends to the optical region and hence has consequences for the line profiles there.

The effect on the optical He II line profiles is displayed in Fig. 4 for two models with different effective temperatures. Generally, the line profiles become slightly deeper. The difference is not drastic, but significant for the interpretation of good observational data. In particular, the 4686Å profile in PG 1034+001, which was too narrow in the synthetic spectrum, can now be fitted satisfactorily (Werner et al. 1995b).

3.2. LTE – NLTE comparison: He II line profiles

Since NLTE model calculations are relatively costly, the question arises if they are necessary at all. In the case of the PG 1159 stars the answer is clear, because NLTE effects are responsible for many emission lines. For DO stars one could suspect that NLTE effects are confined to the innermost line cores, only. To answer this question we took two models with $T_{\rm eff}$=70 000 K and 100 000 K ($\log g$ =7.5) and artificially amplified the electron collisional rates to enforce LTE conditions. This procedure, instead of using results of an independent LTE code, guarantees that the LTE/NLTE comparison is not spoiled by different input physics or any numerical details. Figure 5 compares the He II line profiles from the LTE and NLTE models. At $T_{\rm eff}$=100 000 K (right panel) the 4686Å line is almost unaffected. But the cores of the Pickering lines (±10Å) are markedly shallower in the NLTE case, whereas the wings are unaffected. It is interesting to see that the occurrence of the central emission in every other Pickering line is not a NLTE effect but just a consequence of the fact that these lines have no unshifted central Stark component. Qualitatively this also holds for the cooler model ($T_{\rm eff}$=70 000 K, left panel). Now NLTE effects seize the line wings, too, and 4686Å is affected stronger. The reason for this is the following. In the cooler model the He II/He III ionization balance shifts in favor of He II. As a consequence, the line wings now form at higher regions in the atmosphere where densities are lower and NLTE effects on occupation numbers are stronger. But still, the He III ion prevails with at least 99% throughout the atmosphere. NLTE effects in even cooler models are not relevant to the present analysis and will be described in a forthcoming paper (Dreizler et al. in prep.) which deals with analyses of cooler DO white dwarfs.

4. Results

4.1. RE 0503−289

The top panel of Fig. 6 displays fits to the spectrum of RE 0503−289 with synthetic line profiles from models with different hydrogen content (the values are given in the figure and denote the number fraction). The higher the H abundance the stronger is the Hα emission peak. We adopt an upper limit of 5%. We kept fixed the other atmospheric parameters

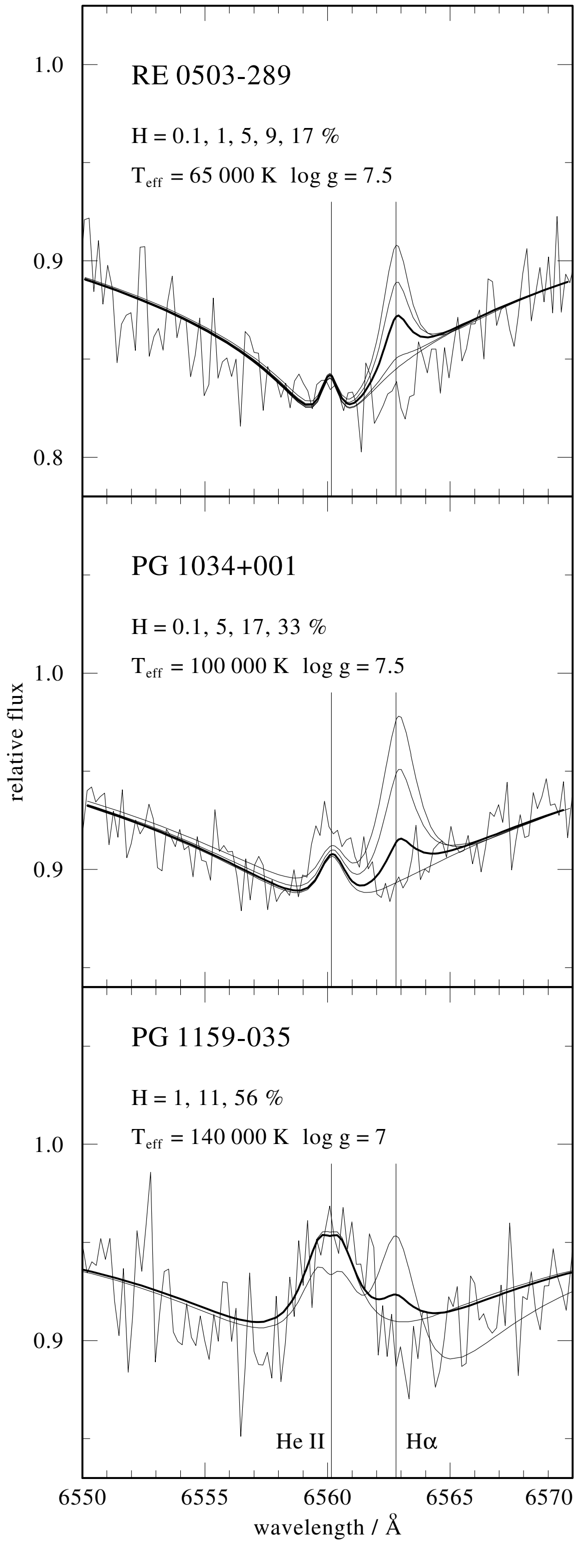

Fig. 6. Determination of upper limits of the hydrogen abundance in our three programme stars. The synthetic spectra differ by their H abundance fraction as given in each panel. A higher H fraction results in a stronger emission feature. The thick synthetic profile in each panel is representing the adopted upper limit for the H abundance. We determine H < 5%, 5%, 10% for RE 0503−289, PG 1034+001, PG 1159−035, respectively

to $T_{\rm eff}$=65 000 K and $\log g$ =7.5. Note that this temperature is near the lower limit of the error range in our original discovery paper (Barstow et al. 1994). This means that we estimate a conservative upper limit, because with increasing $T_{\rm eff}$ the Hα peak height increases, too.

4.2. PG 1034+001

The middle panel of Fig. 6 shows the fit procedure for PG 1034+001. Here we adopt 5% as an upper H abundance limit, too. Again, this is a cautious limit because there are hints (from ROSAT data) that $T_{\rm eff}$ is slightly higher than the fixed value we used here ($T_{\rm eff}$=100 000 K, $\log g$ =7.5). Details of the analysis of PG 1034+001 can be looked up in WDW. This 5% limit is only a factor of 2 lower than what we have estimated before from the non-detection of a Hβ absorption component within the He II 4859Å line (WDW). But we regard the limit given here to be based on more secure grounds.

4.3. PG 1159−035

In the bottom panel of Fig. 6 we fit the PG 1159−035 spectrum. It can be seen that due to the higher $T_{\rm eff}$ in comparison to the two DOs the detection of hydrogen becomes more and more difficult. In this case we adopt H=10%. Note that the parameters of PG 1159−035 are particularly well determined on hand of optical and UV (HST) spectra (WHH and Werner & Heber 1993). Other model parameters are, accordingly, $T_{\rm eff}$=140 000 K, $\log g$ =7, He/C/O=47/24/6 (number ratios). The upper limit derived here (corresponding to a number ratio H/He=0.2, or a mass fraction of 2%) represents a reduction of a factor of five as compared to earlier results, where we could not exclude H/He=1 (WHH). In addition the former value was based on a rather delicate analysis of the extremely shallow He II 4859Å line.

In summary, the best agreement of observed and computed line profiles is achieved assuming that hydrogen is completely absent. However, due to the very high temperatures detectable hydrogen line cores develop only if the H abundance exceeds about 1–10%.

5. Conclusion

Our search for trace hydrogen in three hot helium-rich white dwarfs ($T_{\rm eff} \geq$65 000 K) was unsuccessful. We derived upper abundance limits of the order of 5%. Although these limits are lower than from previous analyses, they are still not very tight when compared to analyses of the cooler DB white dwarfs ($T_{\rm eff} \approx$ 13 000–28 000 K). For some of them trace H was found in the order of H/He=10^{-4} (Shipman et al. 1987) and 10^{-6} (Weidemann & Koester 1991), and for some others the upper limit could be forced down even to 10^{-7} (Shipman et al. 1991). As mentioned above, the much higher $T_{\rm eff}$ of the DOs prevents such strict results here. The best that can be expected for the future is perhaps a limit of 10^{-3} from the Hα cores if spectra from very large telescopes with even better S/N will be available.

What can we learn from the present results? It seems that the hot DOs studied here cannot be simply descendants from the hybrid stars which have H around 70%, provided they will not suffer a drastic change in their surface abundance composition in favor of helium during subsequent evolution. Unless other processes are invoked (mixing and dilution of H, nuclear burning), this seems unlikely because radiation pressure cannot increase the helium abundance to this extent (Vennes et al. 1988). Does that mean that there exist other evolutionary sequences besides simply the two H-rich and H-deficient channels, namely those for hybrid objects, being represented by V 348 Sgr, hot hybrid pre-white dwarfs and cool DOs like HD 149499 B ? And what could be the range of H/He within this sequence? Even continuous ratios of H/He between both extremes are conceivable. To answer these questions we need to look for hydrogen in other [WC] central stars and PG 1159 stars which might be hidden even in large amounts. The same holds for the other few known hot DO stars and in particular the cooler DOs down to the DB gap, for which the detection of hydrogen becomes easier with decreasing temperature.

On the other hand the negative result of our search for hydrogen means that the existence of the DB gap remains a mystery. Since all DO white dwarfs and PG 1159 stars ultimately become DA white dwarfs, the question remains unanswered if the hydrogen atmosphere will originate from accreted interstellar material or formed by hydrogen which was previously mixed within the helium-rich envelope.

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