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How accurately do we know the parameters of hot DA white dwarfs?

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Abstract. We present new determinations of effective temperature, surface gravity, and masses for a sample of hot DA white dwarfs selected from the EUVE and ROSAT Wide Field Camera bright source lists in the course of a near-IR survey for low mass companions. Our analysis, based on hydrogen NLTE model atmospheres, provides a map of LTE correction vectors, which allow a thorough comparison with previous LTE studies. We find previous analyses underestimate both the systematic errors and the observational scatter in the determination of white dwarf parameters via fits to model atmospheres. We find a peak mass of our white dwarf sample of $0.59M_{\odot}$, in basic agreement with the results of previous investigations. However, we do not confirm a trend of peak mass with temperature reported in two previous analyses.

1. Introduction

Precise knowledge of the white dwarf mass distribution puts constraints on the theory of stellar evolution, especially the poorly understood mass loss processes during the final stages of stellar evolution. About twenty years ago Koester, Schulz & Weidemann (1979; KSW) established that the masses of white dwarfs cluster in a narrow range around $0.6M_{\odot}$. The analysis of KSW, along with other follow-up investigations in the early eighties, used photometric data. Higher precision became achievable at the beginning of the nineties, when it became possible to obtain high-quality spectra of large numbers of white dwarfs and determine the stellar parameters from a fit to the detailed profiles of the Balmer lines. The first comprehensive sample of white dwarfs analyzed by this method was presented by Bergeron, Saffer & Liebert (1992; hereafter BSL).

In 1997 three groups (Marsh et al. 1997, M97; Vennes et al. 1997, V97; Finley, Koester & Basri 1997, FKB) published results on the mass distribution of Extreme Ultraviolet (EUV) selected white dwarfs. Due to the selection criterion, these samples contain the hottest white dwarfs ($T_{\rm eff} > 25\,000$ K), as cooler white dwarfs do not emit significant EUV radiation. The derived mass distributions in the EUV-selected samples are similar to that of BSL. V97 and FKB found a trend of the peak mass with temperature. The V97 mass distribution peaks at $0.598 M_\odot$, while the BSL distribution of cooler white dwarfs peaks at $0.568 M_\odot$, with masses computed using Wood's (1995) mass-radius relation with "thick" layers ($M_{\rm H} = 10^{-4} M_{\rm WD}$, $M_{\rm He} = 10^{-2} M_{\rm WD}$). This discrepancy diminishes slightly, if the "very thin layer" ($M_{\rm He} = 10^{-4} M_{\rm WD}$, no hydrogen layer) mass-radius relations are used. V97 interpreted this as evidence for a very thin hydrogen layer of the DA white dwarfs. However, the effects are small so this result depends strongly on the accuracy of the derived stellar parameters. The obvious question one has to ask is, whether the achievable accuracy of spectral analysis is good enough to draw such conclusions. We will use the results of our recent NLTE analysis of EUV selected white dwarfs (Napiwotzki, Green, Saffer 1998; NGS) to focus on this topic.

2. Observational and methodological error sources

FKB estimated the internal accuracy of different analysis methods from Monte Carlo simulations. The precision reachable by Balmer line fitting is very compelling: $\Delta T_{\rm eff}/T_{\rm eff} < 0.01$ for $T_{\rm eff} < 60\,000$ K. However, for spectra with very high signal-to-noise ratios (S/N), errors introduced by details of the observation and reduction techniques (e.g., extraction, flat fielding, flux and wavelength calibration) might be more important, but are very difficult to determine. Additionally, one has to take into account differences in the model atmosphere calculations and fitting procedure.

Systematic errors may be introduced by simplifications used in the model atmospheres calculations. The analyses of FKB, F97, and V97 applied pure hydrogen models computed in local thermal equilibrium (LTE). We relax the LTE assumption and solve the detailed statistical equilibrium instead. Atmospheres are computed with the NLTE code developed by Werner (1986). Although deviations from LTE are small for most DA white dwarfs they become significant for the hottest stars in our sample (cf. Napiwotzki 1997). Since we intend to compare our results with LTE results, we have produced a map with LTE correction vectors. For this purpose we calculated a set of LTE model atmospheres using the technique described in Napiwotzki (1997). The resulting offsets are displayed in Fig. 1. We checked our models by a comparison of our LTE spectra with some DA model spectra kindly provided by D. Koester. The result was quite satisfactory: the temperature differences were always below 1.5% and the gravity differences never exceeded 0.03 dex.

Metals were ignored in our calculations, but they can modify the hydrogen line profiles by their effect on the atmospheric structure. Lanz et al. (1996) found these effects to be small in their analysis of the hot DA G 191 B2B. A recent study by Barstow et al. (1998) derived larger metal line blanketing effects of the order of the NLTE effects. Since the LTE analyses of M97, V97, and FKB are based on pure hydrogen models, our results should be consistent with theirs in any case.

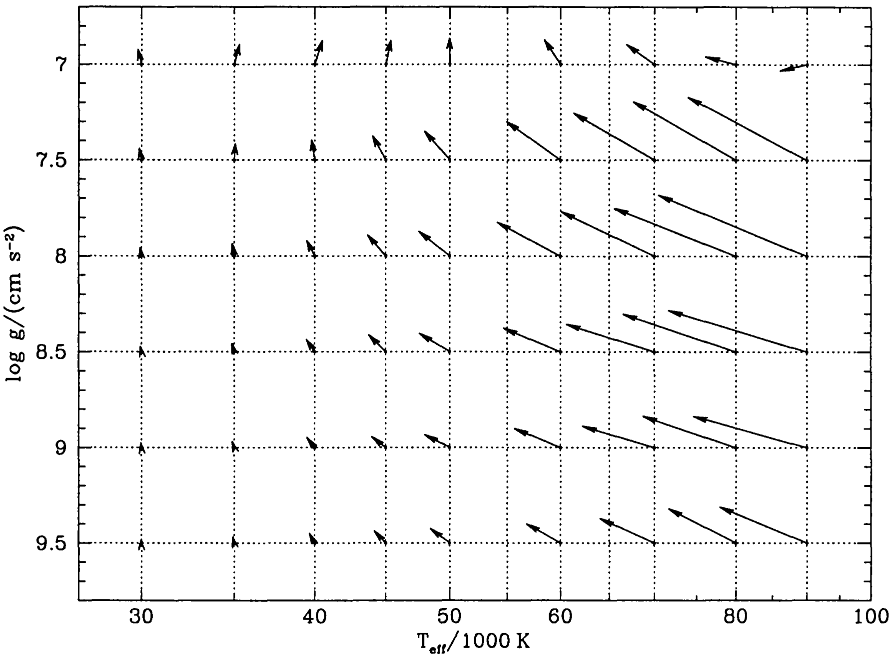

Figure 1. LTE offsets. The differences are magnified three times. The vectors give the correction, which must be applied to transform LTE results to the NLTE scale.

Once the temperature and gravity of the white dwarfs are known, the mass can be determined from theoretical mass-radius relations. The choice of the model sequences influences the derived masses. Since a detailed discussion is given in the article of Driebe et al. (1999, in these proceedings) we will only mention some important topics here.

The mass-radius relation depends on the thickness of the hydrogen and helium layer masses. Usually a constant mass fraction (either "thick" or "thin") is adopted. However, Blöcker et al. (1997) have shown that the envelope masses of evolutionary models depend on the stellar mass. The chemical mixture of the degenerate core is a function of mass, too. White dwarf with masses higher than $0.46 M_\odot$ have a carbon-oxygen core, but lower mass white dwarfs possess a helium core. Furthermore the structure, and therefore the mass-radius relation, of hot white dwarfs depends on the evolutionary history. Therefore it is important to use model sequences, which follow the evolution self-consistently from the main sequence through the red giant stages to the white dwarf cooling sequence.

We use the recent evolutionary models of C/O and He white dwarfs calculated by Blöcker et al. (1995) and Driebe et al. (1998), respectively. We supplement this set with the 1.0, 1.1, and $1.2 M_\odot$ carbon core sequences of Wood (1995) with "thin" layers.

3. Sample and analysis

The current study, conceived as a complement to optical studies, began as a near-IR photometric survey for low mass companions to hot white dwarfs (WDs). By investigating only EUV-detected WDs, we obtain a very reasonably-sized but

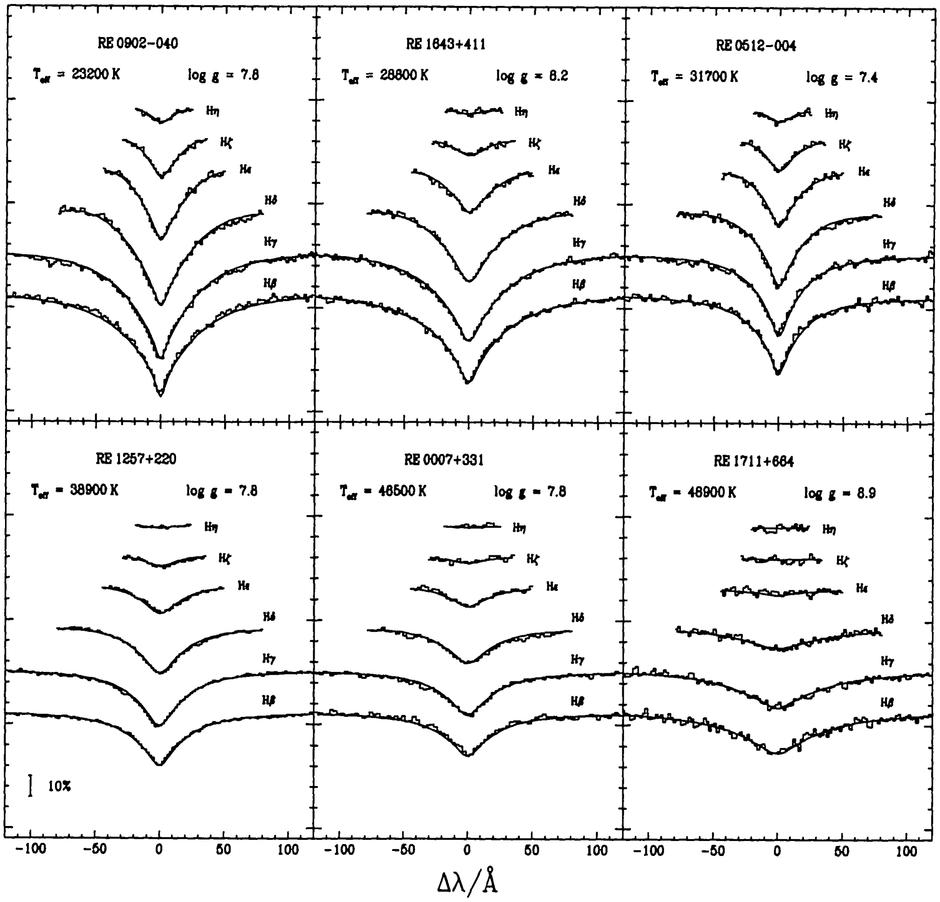

Figure 2. Balmer line fits for a representative set of white dwarfs.

complete sample of 45 young WDs. Results from the IR survey will be presented in an upcoming paper.

Spectra were obtained at Steward Observatory's Kitt Peak Station using the 2.3-m reflector equipped with the Boller & Chivens Cassegrain spectrograph and with the MMT on Mt Hopkins equipped with the Blue Channel spectrograph. The minimum spectral coverage was from about 3500 to 5600 Å with spectral resolution ranging from 4 Å to 8 Å. Exposures at both telescopes ranged from one to thirty minutes for program stars yielding an average signal-to-noise ratio for the sample of 90.

Atmospheric parameters of our DA white dwarfs are obtained by simultaneously fitting line profiles of the observed Balmer lines with the NLTE model spectra described above. We use the least-square algorithm described in BSL and NGS. Illustrative examples are shown in Fig. 2. Detailed results are available in NGS. The position of the analyzed white dwarfs in the temperature/gravity plane is shown in Fig. 3 along with the tracks used for the mass determination.

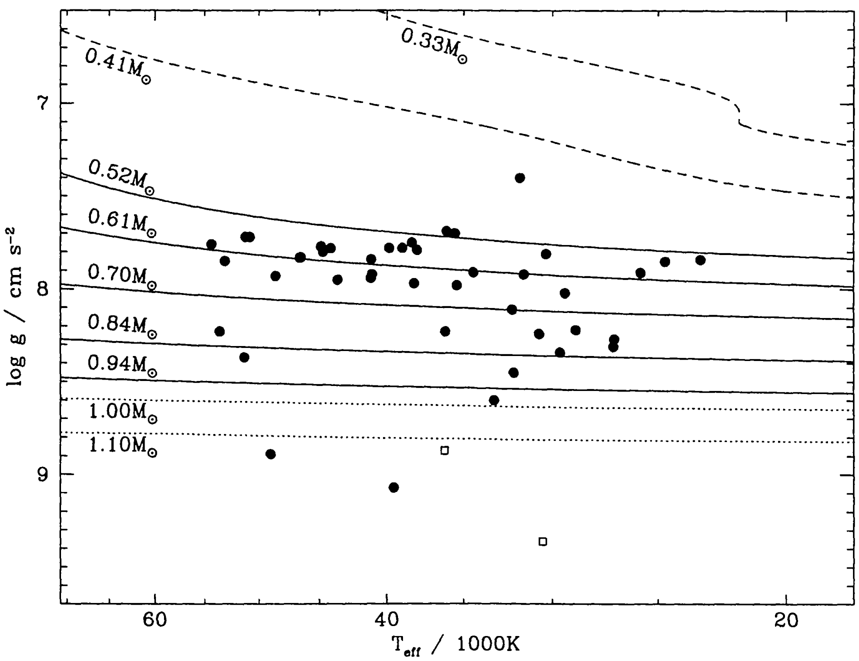

Figure 3. Effective temperature and gravity of our white dwarf sample compared with evolutionary tracks. Solid lines: Blöcker (1995); dashed lines Driebe et al. (1998); dotted lines: Wood (1995). Two magnetic white dwarfs are marked by open symbols.

4. Results and conclusions

We have now combined our results of a homogeneous analysis of a sample of 45 hot, EUV selected white dwarfs with the three other large samples analyzed with similar methods (M97, V97, and FKB). Since considerable overlap exists between all four samples, this allows a direct check for systematic errors and the individual scatter on a star by star basis for white dwarfs hotter than 25 000 K. Since in contrast to previous works our analysis is based on NLTE model atmospheres, we applied the LTE correction vectors given in Fig. 1 to correct for the LTE assumption.

First, we noticed considerable scatter, which is larger than expected from the internal error estimates. The smallest scatter is found for the "cool" group ($T_{\rm eff} < 30\,000$ K) with $\sigma(T_{\rm eff}) = 2.3\%$ and $\sigma(\log g) = 0.07$ dex. It increases to $\sigma(T_{\rm eff}) = 3.3\%$ and $\sigma(\log g) = 0.13$ dex for the hottest bin. This trend is in accordance with our expectations, because the Balmer lines become shallower and less temperature and gravity sensitive with increasing temperature. However, the values are larger by a factor of three or more than the internal parameter errors for a well exposed spectrum. Therefore, we conclude that the accuracy is not limited by the noise for good spectra, and we suggest that other effects, such as details of the extraction or fluxing and normalization procedures, contribute more.

We noticed statistically significant systematic offsets, which are temperature dependent and reach values up to ≈5% in $T_{\rm eff}$ and ≈0.1 dex in $\log g$. If one ignores the hot end, the agreement between the FKB and our temperature scale is good. Differences are below 1%, smaller than the maximum model differences to the Koester models (cf. Sect. 4), which were used by FKB. The same atmospheres are used in M97, and it is therefore surprising that significant differences with M97 are present. These trends are most likely caused by different reduction and analysis techniques. Offsets of the same order are found in our comparison with V97. In this case a different LTE model atmosphere code is used. This might explain at least partly the shifts in $T_{\rm eff}$ and $\log g$ in this case. However, we emphasize that all four analyses are based on state-of-the-art model atmospheres and χ^2 fitting techniques. Thus it seems that *these are the systematic shifts characteristic of modern analyses of hot white dwarfs.*

We computed individual white dwarf masses from the Blöcker/Driebe mass-radius relations described in Sect. 2. We decided to follow the recipe of FKB and fitted the mass peak with a Gaussian. With this method we derived a peak mass of our sample of $0.589 M_\odot$. We reanalysed the FKB, M97, and V97 samples with our mass-radius relations. We applied the LTE corrections and excluded the white dwarfs with temperatures in excess of 70 000 K. The peak masses are $0.555 M_\odot$ (FKB), $0.535 M_\odot$ (M97), and 0.582 (V97). These differences reflect the systematic differences of $T_{\rm eff}$ and $\log g$ determination discussed above.

We also redetermined the masses of the "cool" BSL white dwarfs and derived a peak mass of $0.559 M_\odot$. That's $0.03 M_\odot$ lower than our peak mass. However, this deviation may stem from systematic differences like those found for the four investigated samples. Even a relatively small systematic $\log g$ difference of 0.05 dex corresponds to a $0.02 M_\odot$ offset. Even a temperature dependence of the sample peak mass might be mimicked by systemtatic errors varying with temperature. The scatter σ of *individual* gravity determinations corresponds to $\sigma(M) \approx 0.04 M_\odot$ nearly independent of $T_{\rm eff}$.

FKB divided their sample into a cool ($T_{\rm eff} < 35\,000$ K) and a hot ($35\,000$ K $< T_{\rm eff} < 75\,000$ K) subsample and derived a $0.029 M_\odot$ higher peak mass for the hot sample. The difference is brought down to $0.010 M_\odot$ if we apply our LTE corrections and reanalyse the sample with the Blöcker/Driebe mass-radius relations. One can imagine that a difference of this order (if significant at all) can easily be produced by our neglect of metallicity effects (cf. Lanz et al. 1996; Barstow et al. 1998). Therefore, given the combination of sample selection and systematic effects in analyses to date, our results do not confirm the presence of intrinsic, systematic mass differences between hot and "cool" white dwarfs.

Discussion

M.Sean O'Brien: You mentioned for the high temperature low gravity models have the same temperatures even when the spectra are remarcably different. Any comment on why the temperatures turn out to be the same even the spectra are different?

Ralf Napiwotski: I don't have an idea why temperatures are in so very close agreement. They are much different in NLTE.

Jay Holberg: To what do you attribute the smaller systematic differences between your results and the other three EUV selected samples?

Ralf Napiwotski: A possible reason might be an important correction by the "NLTE correction vectors".

Uli Heber: A response to Jay Holberg - Perhaps non-LTE effects are responsible for the divergence of your high-temperature results from the others.

Steve Kawaler: In comparing T_{eff}, $\log g$ with evolutionary tracks to obtain masses, could you comment on the fact that most evolutionary sequences have envelopes of solar composition rather than pure Hydrogen?

Ralf Napiwotski: I don't think much, because the difusion is efficient only in most upper layers of the white dwarf, the highest layers of the white dwarf if it don't produce increasing radius of the star.

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