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LTE or NLTE for the analysis of hot white dwarf and subdwarf B stars?

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Abstract. We evaluate the influence of NLTE effects on hydrogen and helium lines of high gravity stars. This investigation covers the classes of hydrogen-rich DA and DAO white dwarfs and helium-rich DO white dwarfs. Furthermore, model atmospheres of hydrogen-rich subdwarf B (sdB) stars are investigated. Implications for model atmosphere analyses of such stars are discussed.

Pure hydrogen atmospheres of DA white dwarfs are well represented by LTE calculations for effective temperatures up to 80000 K. As soon as traces of helium are present, however, drastically larger NLTE effects on the Balmer lines occur, which persist down to effective temperatures as low as 40000 K. However, a simple recipe that yields reliable results, is to neglect the traces of helium in the LTE models for the analysis of DA white dwarfs. Since DAO stars, especially the hotter ones, tend to have lower gravities than the DA white dwarfs, NLTE effects can be very pronounced in DAO stars. Even at higher gravity moderate NLTE deviations are always present for the helium lines and should be taken into account for an accurate analysis of DAO stars.

Similar effects are present in the model atmospheres of sdB stars. However, due to the even lower gravities and, hence, lower densities in their photospheres, NLTE should be taken into account down to effective temperatures of about 30000 K, i.e. for the sdOB stars. Since there exist discrepancies between the results of different groups performing LTE analyses of sdB stars, we also discuss the impact of metal line blanketing.

The class of hot, helium-rich white dwarfs (DO) always displays moderate to strong deviations from LTE. Very strong effects are found in the 60000 K region. This implies that even for the so-called cool DO white dwarfs ($T_{\rm eff} \lesssim 60000$ K) the use of NLTE model atmospheres is highly recommended.

Some calculations were performed to test whether NLTE line formation calculations of hydrogen and helium on LTE atmospheres can yield reliable results. While this method considerably improved sdB and DAO models this was not the case for either DA model with trace helium or a DO model. This demonstrates that a careful check for the validity of line formation calculations has to be performed for each application.

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1. Introduction

The analysis of white dwarf and subdwarf B (sdB) star atmospheres is traditionally the domain of LTE techniques. Usually, deviations from LTE are kept small by the high densities of the atmospheres. NLTE calculations, and comparisons with LTE models in the white dwarf and subdwarf O star regions were performed by Kudritzki (1976), Wesemael et al. (1980), and Wesemael (1981). Kudritzki (1976) tried to define a LTE domain in which the stellar photospheres should be well represented by LTE models. According to his Fig. 3 LTE is valid for white dwarfs with $T_{\rm eff} \lesssim 50000$ K (but see below). Today LTE calculations are used for the analysis of even the hottest white dwarfs.

In this paper a detailed discussion of the influence of NLTE on white dwarf atmospheres is given. It is about time to revisit this question for several reasons. First of all, the spectroscopic material available today for many white dwarfs has now reached a quality which was Utopian some twenty years ago. For instance, Kudritzki's criterion for the importance of NLTE was a deviation of 15% in the equivalent width of Hγ. This was certainly a realistic error estimate for typical photographic spectra, but today we can do much better! Moreover, Kudritzki (1976) restricted the discussion to atmospheres with $n_{\rm He}/n_{\rm H}$ = 0.1 and 1.0, but some effects are present only for the generally very low helium abundances in the nearly pure hydrogen atmospheres of DA white dwarfs (see Sect. 4.1).

The performance of NLTE model atmosphere calculations have increased dramatically, too. The calculations of Kudritzki (1976), Wesemael et al. (1980), and Wesemael (1981) are all based on the pioneering complete linearization (CL) method developed by Auer & Mihalas (1969). This method limits the calculations to only a few NLTE levels ($\approx$15) and line transitions due to its numerical properties. New methods have been developed in the meantime, which are much more powerful tools for the calculation of NLTE atmospheres. Important are the so-called accelerated lambda iteration (ALI) method (Cannon 1973; Hamann 1985; Werner & Husfeld 1985) and the hybrid CL/ALI approach (Hubeny & Lanz 1995). Both methods now allow the consistent treatment of more than a hundred atomic levels and many hundreds of lines. Even the inclusion of highly complex atoms like iron with millions of lines is now possible through a statistical approach (Anderson 1989; Dreizler & Werner 1993; Hubeny & Lanz 1995). NLTE atmospheres have now reached a level of sophistication which is comparable to that of present day LTE atmospheres. However, the computational effort is still much larger than for LTE calculations. Lanz & Hubeny (1995) compared some selected metal line blanketed NLTE atmospheres of white dwarfs with simple hydrogen LTE models without any line blanketing. Koester & Herrero (1988) showed that line blanketing effects dominate over NLTE effects for white dwarfs at least at $T_{\rm eff}$ = 25000 K.

During the last years hot white dwarfs have become a field of intense research. LTE model atmospheres are widely used for the analysis of hot white dwarfs (spectral types DA, DAO, and DO) by, e.g., Wesemael et al. (1985), Kidder (1991), Bergeron et al. (1994), and Finley et al. (1996) as well as for sdB stars by Heber (1986) and Saffer et al. (1994). NLTE analyses have been performed for hydrogen-rich white dwarf central stars of old planetary nebulae by Napiwotzki (1993a, 1993b, 1995a), and for hot helium-rich DO white dwarfs by Werner et al. (1994, 1995) and Dreizler & Werner (1996).

The aim of this article is a comparison of hydrogen and helium composed NLTE and LTE models to detect the influence of NLTE effects on important spectroscopic features. The effects of deviations from LTE on the EUV flux of hot DA white dwarfs were already discussed in Napiwotzki et al. (1993). In Sect. 2 our model calculations and the construction of consistent NLTE and LTE models are described. After some general considerations in Sect. 3 the hydrogen-rich white dwarfs are discussed in Sect. 4. Special emphasis is laid on the LTE results of Bergeron et al. (1994) that Balmer lines of DA stars are strongly influenced by small, undetectable traces of helium in the atmosphere. We will discuss this effect and demonstrate that it is caused by the assumption of LTE and disappears in NLTE calculations. The investigation is extended to the Balmer and helium lines of DAO stars. In Sect. 5 we will show that deviations from LTE are important for (nearly) all helium-rich DO stars. The effects of NLTE and metal line blanketing on the spectral lines of the subdwarf B stars is discussed in Sect. 6. Finally, the use of NLTE line formation calculations on LTE atmospheres is checked in Sect. 7. A short summary of our results is given in Sect. 8.

2. Model calculations

Hydrogen and helium composed models are calculated with the NLTE code developed by Werner (1986), which is based on the ALI method mentioned above. Plane parallel geometry as well as hydrostatic and radiative equilibrium are assumed. For a detailed description and recent updates see Werner & Dreizler (1996).

The aim of this article is a comparison of NLTE and LTE models to detect the influence of NLTE effects on important spectroscopic features. Comparisons of results of the NLTE program with LTE models is usually hampered by different physical input data and numerical algorithms used in both programs. To overcome this problem LTE models are calculated with the NLTE code by drastically enhancing the collisional rates ($\times 10^{20}$) between the atomic levels. An a posteriori check guarantees that the Saha and Boltzmann equations are fulfilled in every atmospheric layer. *The result are LTE models which are completely consistent with the corresponding NLTE atmospheres. Any difference is due to deviations from LTE!*

In our calculations the the influence of heavy elements is neglected. Metal line blanketed NLTE model calculations published during the last years generally showed only minor influence on hydrogen and helium lines; see, e.g., the computations of Werner & Dreizler (1993) for atmospheres of hot central stars, and Haas et al. (1996) for hot sdO stars, which includes line blanketing by C, N, O, and Fe. However, Werner (1996a) has demonstrated recently that the inclusion of Stark broadening for C, N, and O lines can have a strong influence on the atmospheric structure of very hot hydrogen-rich stars. It is likely that the effect on the emergent spectrum is pronounced enough to solve the Balmer line problem reported in Napiwotzki (1992) and Napiwotzki & Rauch (1994). Previous calculations generally took into account only Doppler broadening and thus failed to reproduce this effect.

However, the computional effort for including metal line blanketing in a proper way is large and the exploration of a reasonable large parameter space, as necessary for our investigation, would need an unrealistic amount of computer time. Thus we decided to restrict ourselves to model atmospheres without metals, which nevertheless should be sufficient to check the importance of NLTE effects.

Detailed hydrogen and helium model atoms are used for the model calculations (cf. Napiwotzki & Rauch 1994). In view of the high densities in white dwarf atmospheres which yield very broad lines, we consider the Stark broadening of the first two series of hydrogen and the first four series of ionized helium. For further sources of atomic data cf. Dreizler et al. (1990). Let us only note that the collisional ionization of H I and He II is calculated according to Mihalas (1967) and Mihalas & Stone (1968). However, the authors gave fit polynoms of the atom and level dependent function $\Gamma_n(T)$ based on the data of Kieffer & Dunn (1965) and Percival (1966), which are only valid for $T < 100000$ K and yield in some cases negative rates for higher temperatures. Therefore we calculated new fits, which are now valid up to $3 \cdot 10^6$ K (Napiwotzki 1993a).

The collisional rates (bound-bound and bound-free) are the major drawback of today's NLTE calculations because they are much less accurately known than the radiative data. More recent calculations for hydrogen cross sections were published by Giovanardi et al. (1987) and Giovanardi & Palla (1989). However, Chang et al. (1991) have shown that these data contain major inconsistencies. Thus they are not used for our calculations. Changes of the collisional rates within reasonable limits may moderately modify some NLTE results. However, it will hardly change the regions in which NLTE is important.

3. General considerations

Modern analyses utilize line profile fitting for the parameter determination, which is more accurate than the classical approach based on equivalent width measurements. However, the equivalent width W_λ is still a useful tool, and used in this article to illustrate the deviations between LTE and NLTE line profiles. For more insight we will also show selected line profiles.

Which deviations of line profiles from LTE are significant and should be considered in model atmosphere analyses? A general answer to this question is difficult, if not impossible. As a guideline we use the results of analyses of hot hydrogen-rich DA white dwarfs by Kidder (1991), Bergeron et al. (1994), and Finley et al. (1996), which were carried out with similar LTE model atmosphere programs. From an intercomparison of their results for the objects in common, we estimate that the parameters of a typical hot DA ($T_{\rm eff} \approx 50000$ K) with good observational material can be determined to within $\Delta T_{\rm eff} \approx 2000$ K and $\Delta \log g \approx 0.2$ dex. Both error ranges correspond to relative changes in W_λ of $\approx$5%. To avoid systematic errors of the order of the fitting errors the accuracy of the model calculations should be better than this. We assume that deviations from LTE of the order of $2 \ldots 3\%$ in W_λ can easily be neglected for practical purposes.

If one adopts the smaller formal errors given in the quoted analyses articles, one has to consider smaller deviations. On the other hand even larger deviations are unimportant for lower quality spectroscopic material. Therefore we will give overviews of the NLTE effects by plotting the relative differences

$$\Delta W_\lambda = \frac{W_\lambda^{\rm LTE} - W_\lambda^{\rm NLTE}}{W_\lambda^{\rm NLTE}}$$

(in percent) between W_λ calculated from LTE and NLTE for typical parameter sets. This allows a check whether the deviations between both types of models are important for the particular purpose. The comparison is limited to lines with $W_\lambda > 50$ mÅ. Lines of such strength are easily observable for brighter white dwarfs and sdB stars.

4. Hydrogen-rich white dwarfs

4.1. Balmer lines of hot DA/DAO white dwarfs

Due to the lack of other temperature indicators the Balmer lines of hot hydrogen-rich DA and DAO white dwarfs are used for the simultaneous determination of $T_{\rm eff}$ *and* $\log g$. In a recent paper Bergeron et al. (1994) reported a strong influence of small traces of helium ($n_{\rm He}/n_{\rm H} = 10^{-4} \ldots 10^{-5}$) on the Balmer line profiles and thus on the temperature determination of hot DA white dwarfs. Since such small traces are invisible in optical spectra this would introduce an uncomfortably large ambiguity for the parameter determination of these stars. The reason for

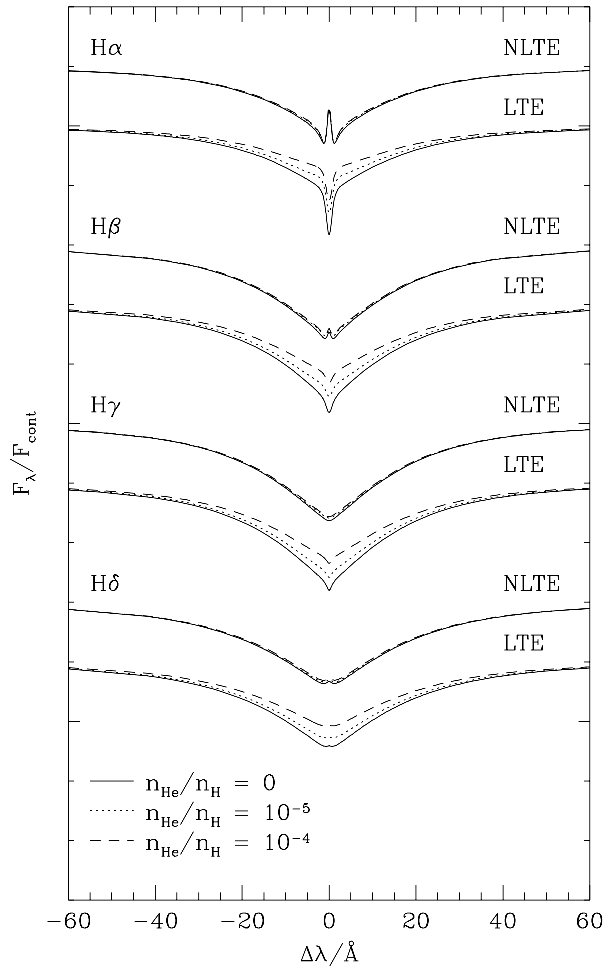

Fig. 1. Influence of different amounts of helium on the Balmer lines of LTE and NLTE model atmospheres with $T_{\rm eff}$ = 60000 K and $\log g$ = 7.5

this behavior is the strong He II absorption edge at 228 Å. Due to the lack of other opacity sources the EUV flux in the pure hydrogen atmosphere of a DA is very strong. In the presence of helium traces flux shortward of 228 Å is absorbed and heats the atmosphere. The resulting higher temperatures weaken the Balmer lines.

This effect is displayed in Fig. 1: the Balmer lines of LTE models ($T_{\rm eff}$ = 60000 K, $\log g$ = 7.50) with pure hydrogen and traces of helium ($n_{\rm He}/n_{\rm H} = 10^{-5}$ and 10^{-4}) are compared. A strong dependence of the Balmer lines on the helium content is visible, indeed. However, this sensitivity almost vanishes for the corresponding NLTE models and can be neglected for practical purposes.

The reason for this different behavior is the dramatic overionization of helium in NLTE. Due to the strong flux in the He II Lyman continuum most He II is ionized to He III. Fig. 2 displays the ionization structure of helium in NLTE and LTE atmospheres with $n_{\rm He}/n_{\rm H} = 10^{-5}$. In the Balmer line forming region He II is less abundant in the NLTE calculations by more than one order of magnitude compared to LTE. Thus it is ob-

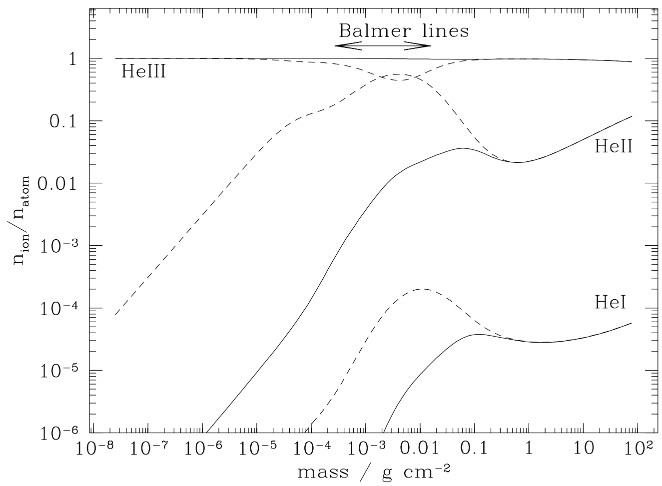

Fig. 2. Ionization structure of helium in the atmosphere of a DA star with $T_{\rm eff}$ = 60000 K, $\log g$ = 7.5, and $n_{\rm He}/n_{\rm H}$ = 10^{-5} for a NLTE model (solid lines) and a LTE model (dashed lines). The formation region of the Balmer lines is marked

vious that the temperature structure in the relevant region and thus the Balmer lines are much less affected by traces of helium than predicted by LTE calculations.

A general overview of the NLTE deviations of the hydrogen lines of DA/DAO white dwarfs and their temperature dependence is given in Fig. 3 for $\log g$ = 7.5, a typical gravity for hot white dwarfs. The relative deviation ΔW_λ is plotted for the Balmer lines Hα, Hγ, and Hδ and Lyman-α. Positive/negative values of ΔW_λ correspond to LTE profiles stronger/weaker than the NLTE profiles. It is well known that Hα is the Balmer line most sensitive to NLTE effects and thus this line is seldom used for LTE analyses. However, the two Balmer lines Hβ and Hδ are frequently used. Lyα is the only line of the Lyman series accessible by the IUE and HST space observatories and is of special importance for the analysis of white dwarfs in binary systems (e.g. Barstow et al. 1994). Calculations were carried out for pure hydrogen and $n_{\rm He}/n_{\rm H}$ ranging from 10^{-5} up to 10^{-2}. While helium traces of $n_{\rm He}/n_{\rm H}$ = 10^{-5} and 10^{-4} are undetectable in the optical and FUV range and the stars would therefore be classified DA, the models with $n_{\rm He}/n_{\rm H}$ = 10^{-3} and 10^{-2} correspond to DAO/DAB white dwarfs with visible He II or He I lines.

The results for $n_{\rm He}/n_{\rm H} = 0, 10^{-4}, 10^{-2}$ are displayed in Fig. 3. The NLTE deviations can be explained by two basic patterns. As can be seen for the pure hydrogen models individual departures of the hydrogen levels from LTE start to become significant at $T_{\rm eff} \gtrsim$ 60000 K and are very important for the hottest models with $T_{\rm eff} >$ 80000 K. As was discussed above the influence of helium on the temperature structure is overestimated in the LTE atmospheres due to overionization in NLTE. This effect becomes important at different $T_{\rm eff}$ ranges for different helium content. Generally, the structure is not significantly different below a certain temperature and after the maximum is reached more and more helium is ionized to He III. Therefore

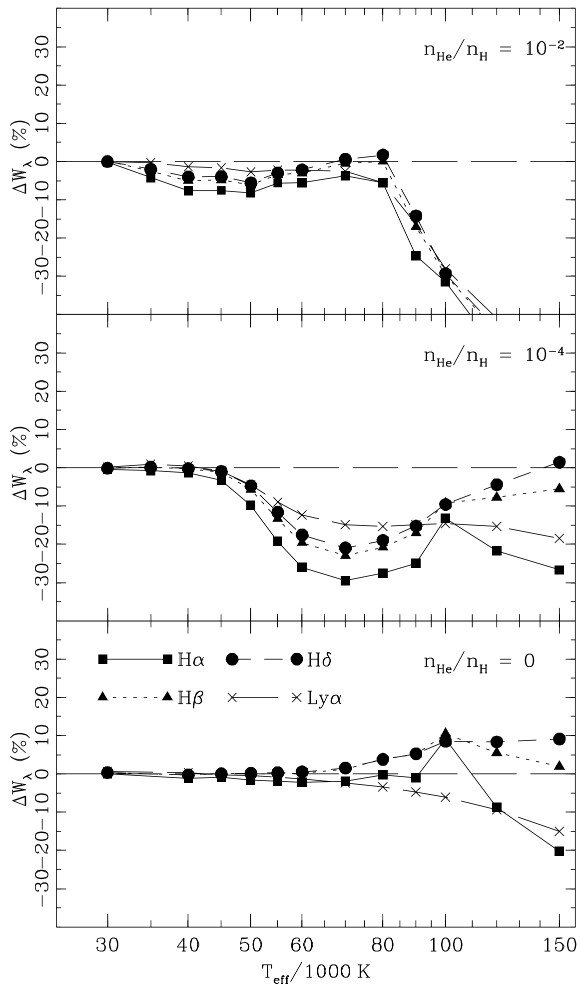

Fig. 3. NLTE effects on Balmer and the Lyman-α lines of DA/DAO white dwarfs with various helium contents as function of $T_{\rm eff}$ for $\log g$ = 7.5. The deviation of equivalent width W_λ in percent is plotted. The symbols are explained in the plot

finally even in the LTE atmospheres virtually no He II is left to heat the atmosphere in the line forming regions. This is reflected in the very similar deviations of the pure hydrogen and the $n_{\rm He}/n_{\rm H}$ = 10^{-4} models at the hottest temperatures.

The $T_{\rm eff}$ of maximum NLTE deviations and the amplitude increase with increasing helium abundance. Bergeron et al. (1994) reported that the influence of helium traces on the Balmer lines vanishes for $T_{\rm eff} \leq$ 40000 K. This corresponds to the lower temperature limits for NLTE effects on the Balmer lines. From Fig. 1 it can be concluded that the differences of hydrogen lines calculated from more realistic NLTE models with $n_{\rm He}/n_{\rm H} \lesssim 10^{-4}$ and pure hydrogen models don't exceed a few percent in the relevant $T_{\rm eff}$ range. Thus we recommend the following recipe: for LTE analyses of hot DA white dwarfs it is better not to include trace helium abundances in the model atmospheres. Otherwise the neglect of NLTE overionization of helium leads to unrealistic temperature stratifications.

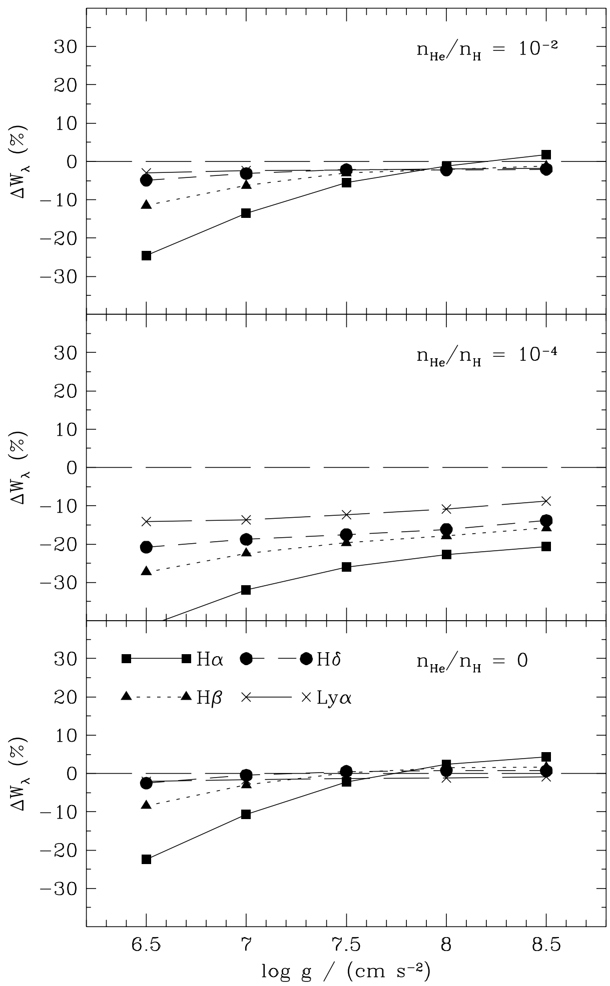

Fig. 4. NLTE effects on Balmer and the Lyman-α lines in dependence of $\log g$ for T_{eff} = 60000 K. The deviation of equivalent width W_λ in percent is plotted

Since the collisional coupling of the occupation numbers to the local temperature is more effective for higher densities and hence gravities, it is expected that NLTE deviations increase with decreasing gravity. The effect of varying g is shown in Fig. 4 for models with T_{eff} = 60000 K. The expected trend is indeed present: high gravity models of $\log g$ = 8.5 show only relatively small NLTE deviations, while the effects become quite strong for $\log g \leq 7.0$. However, note that the $\log g$ = 8.5 model with $n_{\text{He}}/n_{\text{H}} = 10^{-4}$ still shows 15% difference between LTE and NLTE! The remaining Hα deviation of the $n_{\text{He}}/n_{\text{H}} = 10^{-6}$, $\log g$ = 8.5 model is due to the NLTE emission core (see Fig. 1).

Since the surface gravity of DAO white dwarfs is generally lower than that of DA stars being typically in the range $6.5 \lesssim \log g \lesssim 7.5$ (Napiwotzki 1993a, 1993b, 1995a; Bergeron et al. 1994), we calculated a sequence of models with $\log g$ = 6.5 and a helium abundance $n_{\text{He}}/n_{\text{H}} = 10^{-2}$, typical for these stars. The deviations are quite strong even for relatively low temperatures. A comparison of line profiles is shown in Fig. 5. It is evident that the complete profiles of the Balmer lines are affected, though the differences in the cores are strongest. We conclude that the results of LTE analysis of hot DAO white dwarfs are therefore unreliable. Additionally, one should be aware of moderate NLTE effects also in cool DAO white dwarfs, still. However, we should add that even the NLTE model atmospheres presented here are not able to fit the observed spectra of the very hot DAO central stars consistently (Napiwotzki 1992; Napiwotzki & Rauch 1994). The inclusion of C, N, O with Stark broadened lines in the atmospheric calculations is necessary to achieve a satisfactory fit (Werner 1996a). However, while the agreement for the calculated Hδ profiles used by Napiwotzki (1995a) for the temperature determination, is reasonable for NLTE calculations with and without this treatment of metal lines, the LTE results deviate from both.

4.2. The helium lines of DAO/DAB white dwarfs

Since no other helium lines are strong enough in the optical range, the helium abundance of DAO white dwarfs is commonly determined from the He II 4686 Å line. Another strong line available in the FUV is He II 1640 Å. In cooler stars of this class He I lines may become detectable and provide a potentially accurate temperature indicator via the He I/He II ionization equilibrium. Still cooler hydrogen-rich white dwarfs display only the He I lines and are called DAB.

A NLTE/LTE comparison for DAO/DAB models with $\log g$ = 7.5 and $n_{\text{He}}/n_{\text{H}} = 10^{-2}$ is shown in Fig. 6. It is evident that the important He II line at 4686 Å is always smaller in NLTE than in LTE by about 10 . . . 15%. This causes the helium abundance to be overestimated by a LTE analysis of DAO white dwarfs. As expected, the differences become larger for smaller gravities. Changing the gravity from $\log g$ = 7.5 to 6.5 increases ΔW_λ by approximately a factor of two to three. This also holds for the other helium lines discussed in this section. The NLTE emission core of He II 4686 Å causes the large fluctuations of the equivalent width ratio for $T_{\text{eff}} > 100000$ K (cf. Figs. 5 and 6). The deviations for He II 1640 Å are smaller and can certainly be ignored for most stars with FUV spectra of IUE quality. The He I lines deviate moderately from LTE as well. The effect is stronger for the 5876 Å line, which remains detectable for higher temperatures than the 4471 Å line does.

5. DO white dwarfs

Hot helium-rich white dwarfs that show He II lines are classified DO. They are divided according to the presence or absence of He I lines into a cool DO and a hot DO region (Wesemael et al. 1985). The cool boundary of the DO sequence is defined by the so-called DB gap (28000 K $\lesssim T_{\text{eff}} \lesssim$ 45000 K) in which no helium-rich white dwarfs are known. For the cooler DO stars with detectable He I lines the ionization equilibrium of He I/He II provides a valuable temperature indicator. However, the He I lines are invisible in the hottest DO white dwarfs and T_{eff} and g must be derived from a fit of the He II lines alone, similar to the case of the DA white dwarfs.

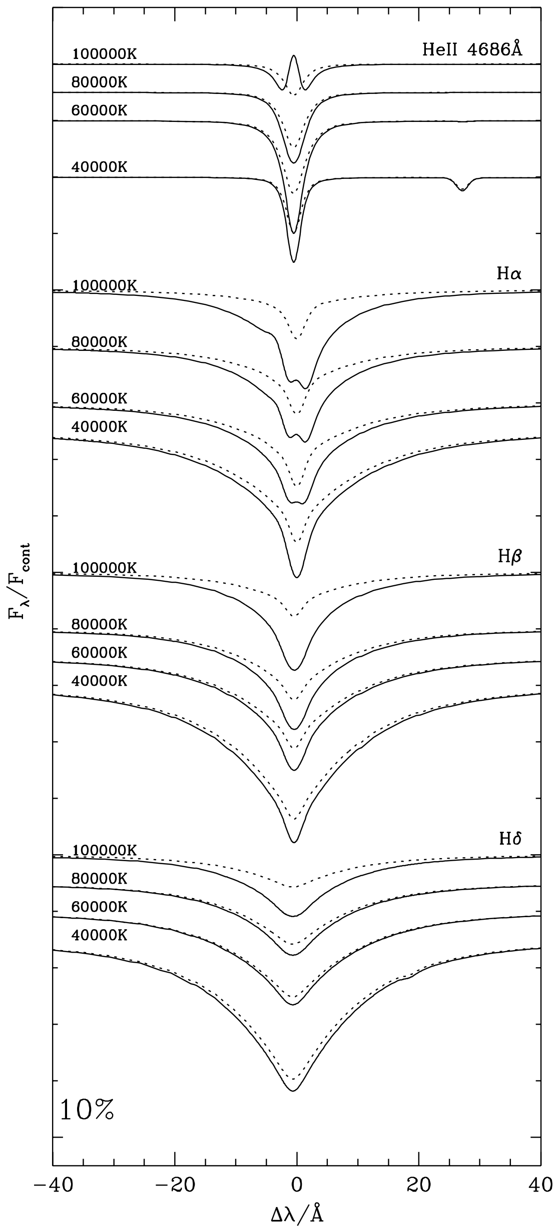

Fig. 5. Synthetic spectra for DAO stars with $\log g = 6.5$ and $n_{\rm He}/n_{\rm H} = 10^{-2}$. The profiles are convolved with a Gaussian of 2 Å FWHM. NLTE is drawn with solid lines, LTE with dashed lines

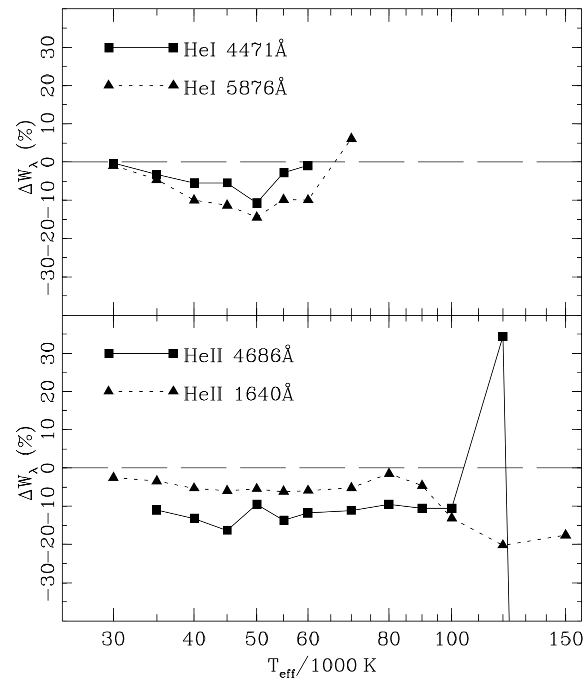

Fig. 6. NLTE effects on the helium lines of DAO models with $n_{\rm He}/n_{\rm H} = 10^{-2}$ and $\log g = 7.5$

An exploratory calculation by Napiwotzki (1995b) resulted in strong NLTE deviations for a model of a cool DO white dwarf (55000 K). Werner (1996b) presented a LTE/NLTE comparison of two DO models with $T_{\rm eff}$ = 70000 K and $T_{\rm eff}$ = 100000 K focussed on effects on the He II lines coinciding to Balmer lines. Here we calculated a representative grid of model atmospheres covering the range from $T_{\rm eff}$ = 50000 K up to 120000 K ($\log g$ = 7.5 and $n_{\rm He}/n_{\rm H}$ = 100), which is representative for the whole DO class. The result is displayed in Fig. 7. Line profiles of representative models are shown in Fig. 8 (see also Dreizler & Werner 1996). At first glance the temperature dependence of the NLTE deviations is astonishing: strong effects are present around $T_{\rm eff}$ = 60000 K. They become smaller for higher temperatures. The reason for this is the high sensitivity of the ionization equilibrium of helium at $T_{\rm eff} \approx 60000$ K. While at higher temperatures the ionization stage He III is highly dominant the equilibrium is just flipping from He III to He II in this cooler region. In addition the flux maximum for a 60000 K DO star is close to the He II 228 Å ionization edge causing an overionization of helium.

From Fig. 7 it can be seen that moderate to strong NLTE deviations are present for important lines of DO white dwarfs for virtually the complete temperature range covered by this class. Especially if one wants to use the full potential of the He I/He II equilibrium for the $T_{\rm eff}$ determination it is mandatory to use NLTE model atmospheres.

6. Subdwarf B stars

Subdwarf B (sdB) stars have somewhat lower gravities ($\log g$ = 5.0 . . . 6.0) than white dwarfs. Their temperatures are in the range $T_{\rm eff}$ = 20000 K. . . 40000 K. The photospheric helium of a typical sdB star is moderately depleted with respect to the solar value. Yet, a wide spread of abundances is observed. The hotter stars of this class ($T_{\rm eff} > 30000$ K), which display He II lines in addition to the Balmer and He I lines are often classified sdOB (see Heber 1992 for a review).

There exist two different strategies for the analysis of sdB stars in the literature. Saffer et al. (1994) determine $T_{\rm eff}$ and g by a simultaneous fit of the Balmer lines, similar to the method commonly adopted for the analysis of DA white dwarfs. Since

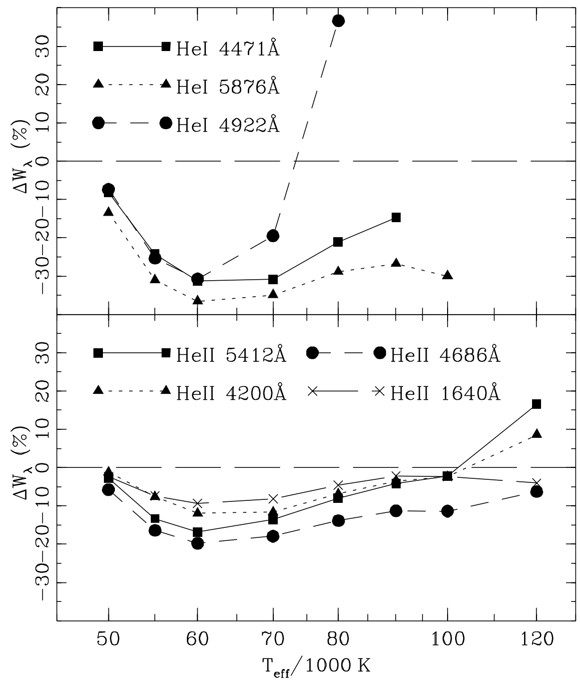

Fig. 7. NLTE effects on important He I and He II lines in the atmospheres of DO white dwarfs. The deviation of equivalent width W_λ in percent is plotted

Table 1. Parameters of the sdB model atmospheres

$T_{\rm eff}$/K	$\log g$	$n_{\rm He}/n_{\rm H}$
25000	5.00	10^{-2}
30000	5.50	10^{-2}
32000	5.60	10^{-2}
35000	5.75	10^{-2}
40000	6.00	10^{-2}

the sdB stars are cooler than the hot white dwarfs discussed in the previous sections, a temperature determination from the FUV or optical continuum is also possible. Gravity is then derived from one or more Balmer lines with $T_{\rm eff}$ fixed. This approach was used, e.g., by Heber (1986) with temperature determination from IUE UV spectrophotometry, and by Moehler et al. (1990) with temperatures derived from optical Strömgren photometry. Unfortunately, the results of the two different approaches are *not* in good agreement. An extensive discussion of this problem is given in Saffer et al. (1994) arguing that the most important reason for the discrepancy lies in the use of inappropriate color-temperature calibrations for the analysis of the photometric data. However, this issue is not yet settled.

Since the sdB gravities are lower than white dwarf gravities, one expects stronger NLTE effects in the atmospheres of sdB stars. We calculated a set of models along the sdB sequence (see e.g. Heber 1986 or Saffer et al. 1994) for this purpose. A typical helium abundance of $n_{\rm He}/n_{\rm H} = 10^{-2}$ was chosen. Model parameters are given in Table 1.

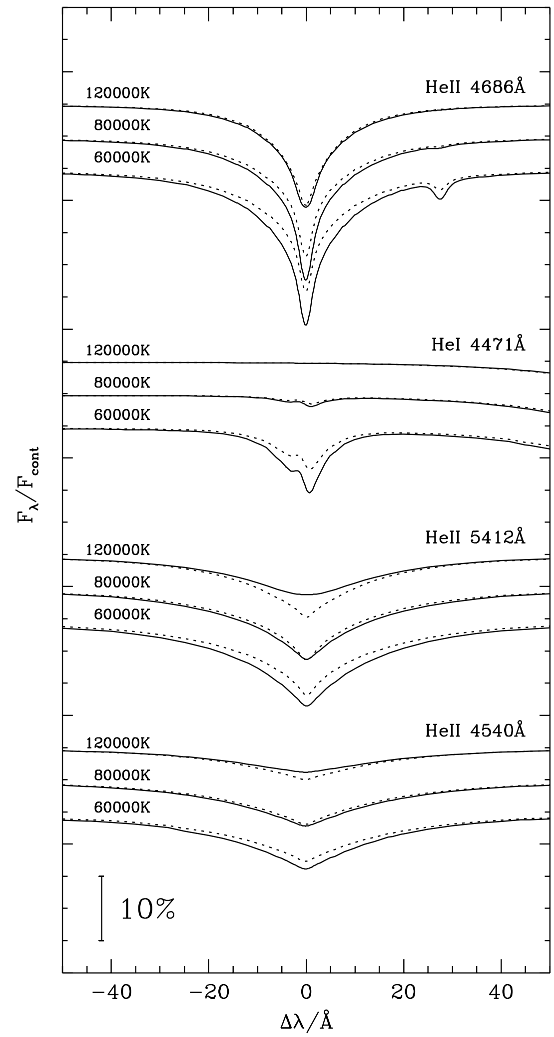

Fig. 8. Line profiles computed for DO model atmospheres at different temperatures ($n_{\rm He}/n_{\rm H}$ = 100, $\log g$ = 7.5). NLTE is drawn with solid lines, LTE with dashed lines. The profiles are convolved with a Gaussian of 2 Å FWHM

The results are shown in Fig. 9. For the Balmer lines and the He I 4471 Å line the LTE and NTLE calculations agree very well for $T_{\rm eff} \lesssim 30000$ K if we exclude the notorious He I 5876 Å and other red He I lines. Moderate differences are still present the cores of the Balmer lines at $T_{\rm eff}$ = 30000 K, but only a small influence on the analysis is expected. However, the NLTE deviations rapidly increase above 30000 K. The Balmer lines for the representative 35000 K model atmosphere are plotted in Fig. 10 together with a metal line blanketed LTE model (see discussion below). It is obvious that these effects modify the whole line profiles of the Balmer lines and not only the cores. Now, the He I 4471 Å line is deviating from LTE, too, and the He II 4686 Å line is virtually never in agreement with LTE models.

The implications of the NLTE deviations on the results are different for both analysis strategies discussed above. Since Saffer et al. (1994) derived both temperature and gravity from the line fits, it is obvious that both can be influenced. Since Hβ,

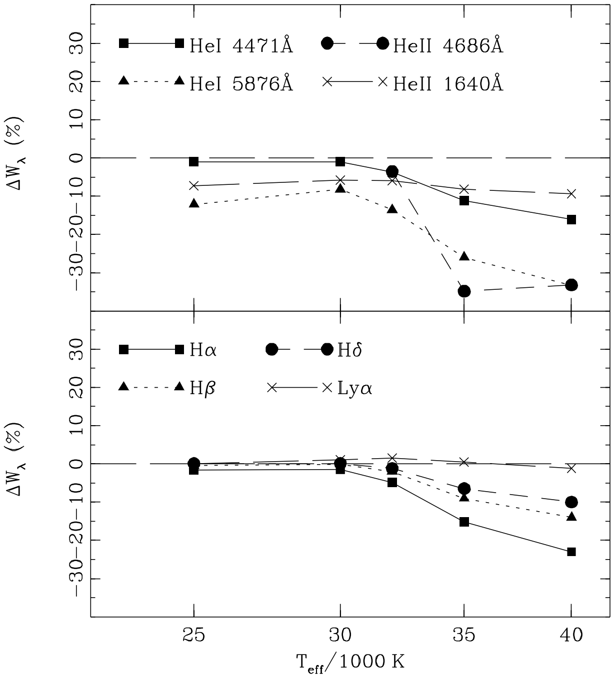

Fig. 9. NLTE effects on important hydrogen and helium lines of sdB stars. The deviation of equivalent width W_λ in percent is plotted. Note that both $T_{\rm eff}$ and g are varied simultaneously to match the observed sdB sequence

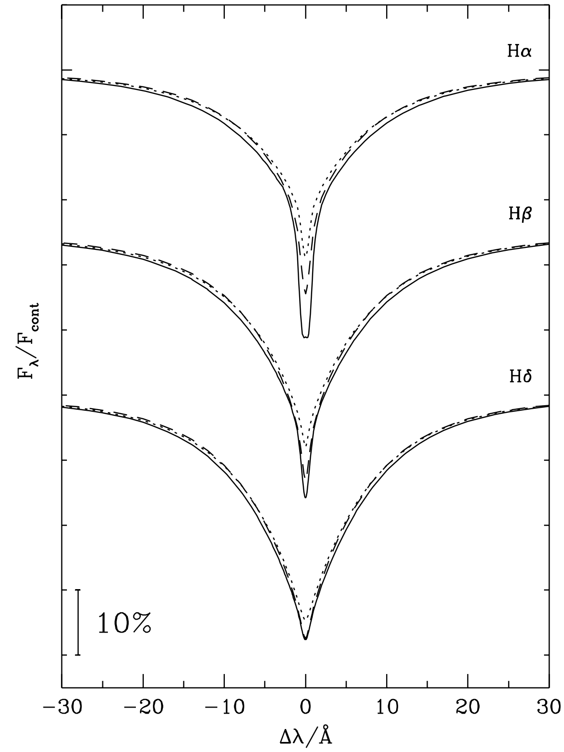

Fig. 10. Comparison of synthetic Balmer line profiles computed for NLTE (solid lines) LTE (dotted lines) hydrogen and helium composed model atmospheres with a LTE model atmosphere including metal line blanketing (dashed line). Model parameters are $T_{\rm eff}$ = 35000 K, $\log g$ = 5.75, $n_{\rm He}/n_{\rm H}$ = 0.01

which is predominantly temperature sensitive (Saffer et al.), shows the strongest NLTE deviations of the lines used by Saffer et al., the primary effect would be an underestimate of temperature. This would change the derived gravity, too. Heber (1986) and Moehler et al. (1990) used the Balmer lines only for the determination of gravity. Thus only the gravity determination is influenced by NLTE effects on the lines. NLTE deviations of the continuum are unimportant in the sdB regime (Wesemael et al. 1980). In their Fig. 8 Saffer et al. show the result of a comparison of photometric temperature determinations with the $T_{\rm eff}$ from their line fits. The general agreement is good, but for $T_{\rm eff} > 30000$ K a trend of higher $T_{\rm eff}$ from the photometric determinations is present. This is in line with our prediction of the impact of the NLTE effects on the analysis method applied by Saffer et al.

However, the overall disagreement of the results derived with the different analysis methods can certainly not be explained by the influence of NLTE. Thus we will shortly discuss the different LTE model calculations performed by the different groups. While, e.g., Heber (1986) and Moehler et al. (1990) applied fully metal line blanketed model atmospheres, Saffer et al. (1994) based their analysis on relatively simple LTE atmospheres considering only hydrogen and helium. The latter calculations are similar to the LTE models presented in this article. The impact of metal line blanketing on the Balmer lines is demonstrated in Fig. 10 and compared to the NLTE deviations. The metal line blanketed LTE atmosphere is calculated with the LTE program of Heber et al. (1984) using the opacity distribution functions of Kurucz (1979) with a solar mixture.

It is obvious that both metal line blanketing as well as NLTE cause pronounced effects on the line profiles. Since we are interested in the impact on fit results we performed a fitting of the Balmer line profiles (Hβ, Hγ, Hδ) of the hydrogen and helium composed model spectra with a grid of metal blanketed LTE model atmospheres. A simultaneous determination of $T_{\rm eff}$ and g was done according to the procedure described in Saffer et al. (1994). Our "fit" result of the H and He LTE model spectrum is $T_{\rm eff}$ = 36319 K and $\log g$ = 5.91 corresponding to a shift of $\Delta T_{\rm eff}$ = +1319 K and $\Delta \log g$ = +0.16 caused by the neglect of heavy elements. Analogous we found $\Delta T_{\rm eff} = -1661$ K and $\Delta \log g = -0.06$ for the NTLE/LTE differences. This proves that both effects are important for the chosen parameter set. While NLTE becomes less and less important for cooler temperatures the influence of metal line blanketing is not very temperature sensitive and thus remains important. A proper way to include both effects, NLTE and metal line blanketing, might be the NLTE line formation on a LTE atmosphere as discussed in the next section.

7. NLTE line formation calculations on LTE atmospheres

Since NLTE calculations can be very (computer) time consuming, one is interested in performing them as cheaply as possible. One way which is often applied for e.g. main sequence A and B stars is a NLTE line formation of a certain element on a LTE atmosphere with the temperature structure kept fixed. For this purpose one has to assume that the influence on the atmospheric structure of modified occupation numbers of this element can be neglected. It is obvious that this is not always guaranteed for hydrogen and helium. To check the validity of this assumption we performed a few NLTE line formation calculations on our LTE atmospheres.

We selected models representative for the stellar classes discussed in the previous sections. We derive different results for the different classes and parameter ranges. For the sdB stars NLTE line formation on LTE atmospheres seems to be a very successful approach. The remaining deviations of the sdB model ($T_{\rm eff}$ = 40000 K, $\log g$ = 6.0, $n_{\rm He}/n_{\rm H} = 10^{-2}$) from the self-consistent NLTE atmosphere amount to only ≈2%, except for the very temperature sensitive He I 4471 Å line with 4%. The hot DAO LTE models ($T_{\rm eff}$ = 100000 K, $\log g$ = 6.5 and 7.5, $n_{\rm He}/n_{\rm H} = 10^{-2}$) are considerably improved by NLTE line formation. The original deviations of ≈50% and ≈30% of the $\log g$ = 6.5 and 7.5 models, respectively, are reduced to 10 . . . 15% (Hα not considered). However, this is still uncomfortably large. The same amount of deviation remained for the DA model with trace helium ($T_{\rm eff}$ = 60000 K, $\log g$ = 7.5, $n_{\rm He}/n_{\rm H} = 10^{-4}$) after NLTE line formation, so there was no substantial improvement in this case. Virtually no improvement could be derived for the DO model ($T_{\rm eff}$ = 60000 K, $\log g$ = 7.5, $n_{\rm He}/n_{\rm H}$ = 100). The reason for the failure in the latter two cases is that the atmospheric structure is substantially modified due to NLTE effects. These few examples demonstrate that NLTE line formation calculations on LTE atmospheres can be a useful and time saving tool. However, it has to be verified whether the atmospheric structure is influenced by NLTE deviations. One indicator for a violation of this basic assumption of line formation calculations is flux conservation. If the emergent flux of the atmosphere is considerably changed after line formation has been performed, some feedback on the structure is to be expected.

8. Summary

We have investigated the influence of NLTE effects on the analysis of hot white dwarfs and subdwarf B stars. Present day NLTE atmospheres are of similar sophistication as up-to-date LTE atmospheres. Thus there exists no more a fundamental reason to prefer LTE atmospheres as in former times, when drastic simplifications were necessary to perform NLTE computations. Nevertheless, the numerical effort required to perform those calculations is still very large. For economical reasons one is therefore interested to use LTE model atmospheres whenever that is possible without a loss of accuracy. To establish when loss of accuracy is to be expected we have compared profiles from self-consistent NLTE and LTE models representative for hot white dwarfs and sdB stars.

Model atmospheres for hydrogen-rich white dwarfs were calculated for $\log g$ = 7.5, typical for hot white dwarfs with various traces of helium. The pure hydrogen models show moderate NLTE deviations only for $T_{\rm eff} \gtrsim$ 80000 K. NLTE and LTE models are in perfect agreement for temperatures up to 70000 K. This means that nearly all DA white dwarfs, except a few extraordinary hot ones, are accessible to LTE techniques. The situations becomes completely different, however, as soon as traces of helium are present in the atmosphere. As Bergeron et al. (1994) have shown, the Balmer lines are strongly modified in LTE atmospheres with $n_{\rm He}/n_{\rm H} = 10^{-5}$ or 10^{-4} and temperatures not much higher than 40000 K. We have shown that this is an artifact caused by the assumption of LTE. The influence of small traces of helium on the Balmer lines vanishes for NLTE atmospheres. If a LTE analysis of the hydrogen lines is to be performed we recommend to use pure hydrogen models, even if it is likely that trace elements are present in the atmosphere.

For DAO white dwarfs with $T_{\rm eff} \lesssim$ 60000 K there is reasonable agreement between LTE and NLTE Balmer line profiles. Nevertheless, one should always be aware of moderate NLTE deviations. They only vanish for $T_{\rm eff} <$ 40000 K, the regime of the DAB white dwarfs. Drastic effects are present for hot DAO white dwarfs ($T_{\rm eff} >$ 60000 K). The situation becomes even worse, because the hot DAO white dwarfs tend to have lower gravities, which amplifies deviations from LTE. Thus the use of NLTE atmospheres is mandatory for reliable results. Generally speaking the result for the helium lines is similar. Moderate NLTE effects are present for cooler DAO atmospheres. They become quite drastic for hot (lower gravity) DAO stars.

For the hot, helium-rich DO white dwarfs we found large differences for many important lines even at relatively low temperatures. This prevents accurate LTE analysis for virtually all DO white dwarfs. The use of NLTE calculations is strongly recommended.

Subdwarf B stars have lower gravities than white dwarfs. Thus the NLTE effects are more pronounced. LTE results are in good agreement with NLTE results for $T_{\rm eff} \lesssim$ 30000 K. However, for higher temperatures (the sdOB regime) the deviations become larger very quickly and should be considered for accurate analyses. Additionally, we have checked the effect of metal line blanketing on sdB atmospheres and shown that the influence is only slightly smaller than that of NLTE effects for the hot sdOB stars, but for the cooler "classical" sdB stars the influence of metals is certainly the dominant effect of both.

We further investigated whether LTE results could be improved by NLTE line formation calculations. For the sdB model this worked well. Also the hot DAO models were substantially improved, although notable deviations remained. No substantial improvement could be obtained for the DA model with trace helium nor the DO model atmosphere. The reason is a modification of the atmospheric structure by NLTE effects in the latter two cases. We conclude that NLTE line formation on LTE atmospheres can be an useful tool, but a careful verification of the basic assumption (no repercussion on the atmosphere) is necessary beforehand.

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