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Spectral analysis of hot subluminous stars

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Abstract.

Optical spectra of 40 sdOB stars drawn from the Palomar Green and the Hamburg-Schmidt surveys are presented (including three EC 14026 stars). Eight of which are spectroscopic binaries. The remainder of the sample is analysed for their atmospheric parameters ($T_{\rm eff}$, $\log g$ and He/H) using both metal line blanketed LTE models and metal free H-He line blanketed NLTE models. Systematic differences between parameters derived from the two model grids are small.

All but ten stars of our analysed sample are found to lie in the temperature range 30 000K to 40 000K. Nine stars appear to be considerably hotter than 40 000K. However, for four of them the temperature indicated by the He II/ He I line ratio is inconsistent with that deduced from the Balmer lines creating a new "Balmer line problem" similar to that found in very hot DAO white dwarfs.

The results for the EC 14026 stars, PG 1047+003, PG 1336-018 and PG 1605+072, are consistent with those from other groups.

1. Introduction

The sdB and sdOB stars form a homogeneous sequence populating an extension of the Horizontal Branch B (HBB) stars in the ($T_{\rm eff}$- $\log g$) – diagram towards higher temperatures. $T_{\rm eff}$ range from 25 000 K up to 30 000 K for sdBs, the sdOBs reach up to 40 000 K. Gravities vary between $\log g = 4.5$ and $\log g = 6.0$. The chemical abundance pattern (He deficiency, the ^{3}He/^{4}He isotopic and sometimes large metal anomalies) is a clear indication for atmospheric diffusion processes (see Heber, 1998 for a review). Following ideas outlined by Heber (1986) the sdB/sdOB stars can be identified with models for extreme Horizontal Branch (EHB) stars, which differ markedly from those for normal HB stars. An EHB star bears great resemblance to a helium main-sequence star of half a solar mass and its further evolution should proceed similarly, i. e. directly to the white dwarf graveyard.

Recently, several sdB stars have been found to be pulsating (see the review of O'Donoghue at this workshop), defining a new instability strip in the HRD.

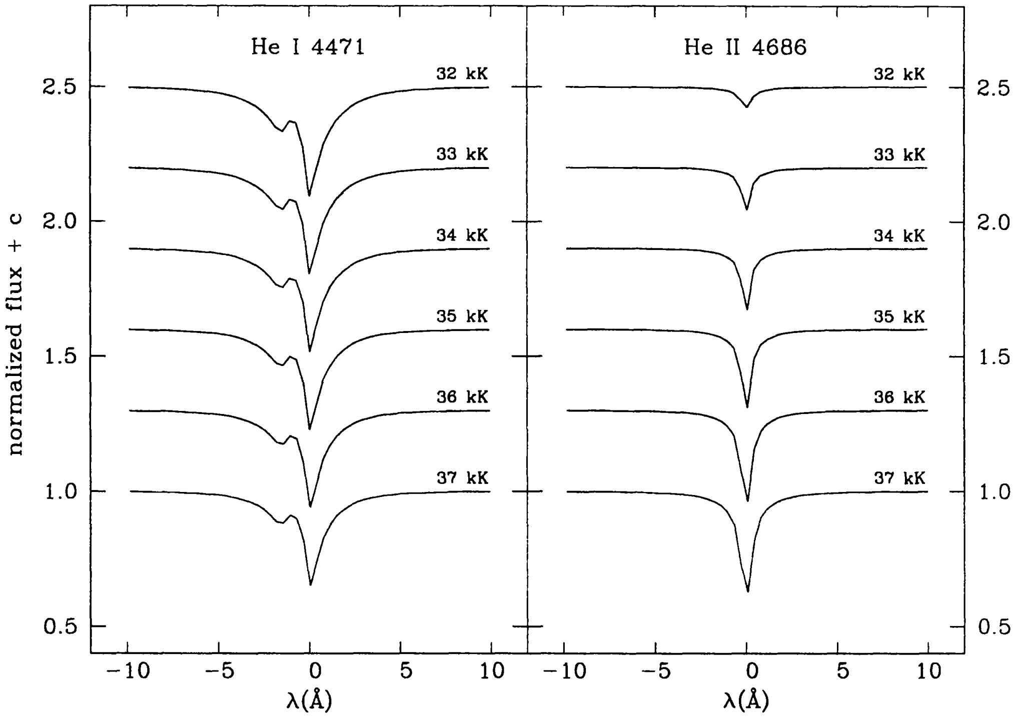

Figure 1. Theoretical He I 4471Å (left panel) and He II 4686Å (right panel) profiles as a function of $T_{\rm eff}$. log g=5.5 and He/H=0.03 are adopted.

The study of these pulsators offers the exciting possibility of exploiting the full power of asteroseismology to investigate the sdB phase of stellar evolution (cf. the review of Kawaler at this conference). The existence of pulsating sdB stars was predicted theoretically by Charpinet et al. (1996), who uncovered an efficient driving mechanism due to an opacity bump associated with iron ionization in such models. However, in order to drive the pulsations, iron needed to be enhanced in the appropriate subphotospheric depths which could possibly result from diffusion processes. In a subsequent study, Charpinet et al. (1997) calculated iron abundances from the equilibrium between gravitational settling and radiative levitation and found that, indeed, iron is enriched in the driving regions.

However, empirical determinations of sdB atmospheric parameters disagree. Using Strömgren photometry plus line profiles, Moehler et al. (1990) derived considerably lower $T_{\rm eff}$ and log g than Saffer et al. (1994) who simultaneously derived the atmospheric parameters by fitting line profiles alone.

Here we propose another variant of the method of Saffer et al. (1994). In the spectra of sdOB stars, helium is represented by two stages of ionization (He I and He II). Since the ionization equilibrium of Helium is very temperature sensitive (see Fig. 1), we can derive $T_{\rm eff}$ from matching this ionization equilibrium. Including the Balmer lines we derive all three parameters simultaneously. The difference to the approach of Saffer et al. (1994) lies with the high weight we give to the helium lines, in particular He I 4471Å and He II 4686Å.

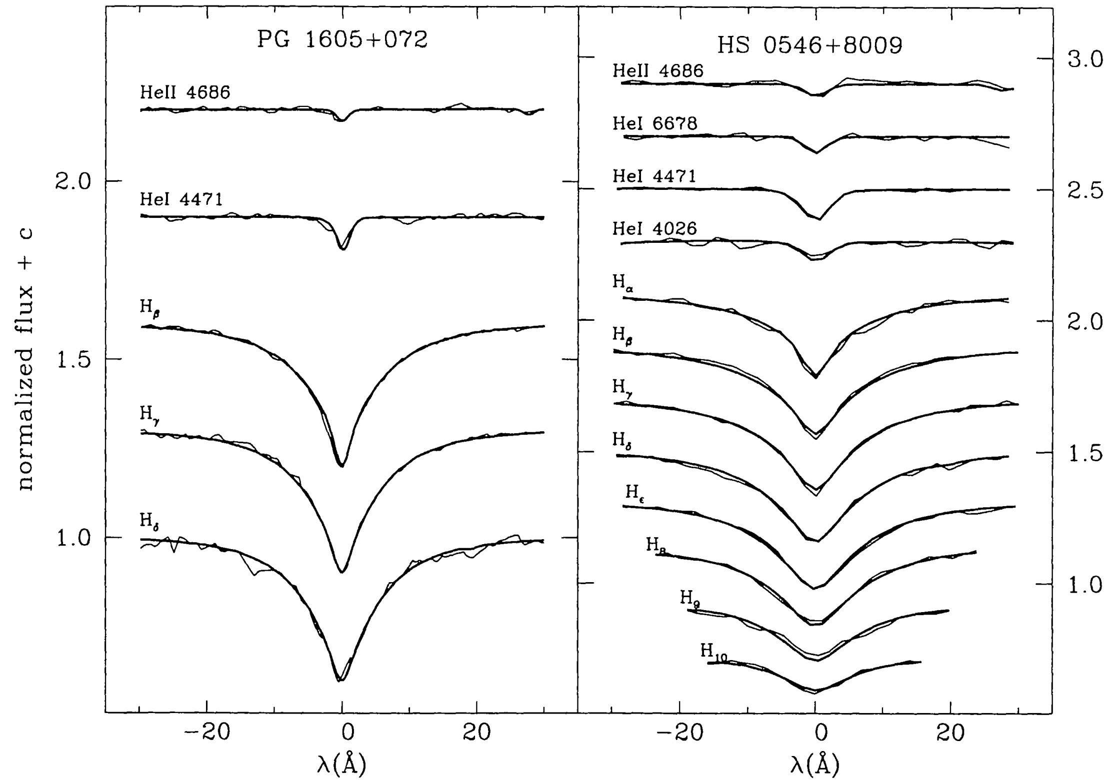

Figure 2. Profile fit for the pulsating sdB star PG 1605+072 (($T_{\rm eff}$=32 000 K, log g=5.1, log(He/H)=-2.6, left panel) and HS 0546+8009 ($T_{\rm eff}$=33 900 K, log g=5.75, log(He/H)=-2.0, right panel).

2. Observations

We have obtained spectra of 40 sdOB stars, i.e. of sdB stars with a trace of an O star (He II 4686Å) in their spectra, during various observing runs. Therefore the observational material is inhomogeneous. The spectral resolution ranges from 1.9Å (4050 ... 4930Å wavelength coverage) to 7.0Å (3370 ... 9350Å). 23 stars come from our follow-up observations of the Palomar Green survey, while 17 are from HS survey (Hagen et al. 1995). Eight stars of the sample turned out to be spectroscopic binaries and are not analysed further.

3. Model atmospheres and synthetic spectra

Two sets of model atmospheres were used. First, a grid of metal line blanketed LTE model atmospheres assuming solar metal abundances calculated with an update version of the code used by Heber (1986). The line blanketing is incorporated by means of Kurucz' ATLAS6 Opacity Distribution Functions.

Second, a grid of H-He line blanketed, metal free NLTE model atmospheres (Napiwotzki, 1997), calculated with the ALI codes of Werner, Dreizler & Rauch (see Werner & Dreizler, 1998 for details).

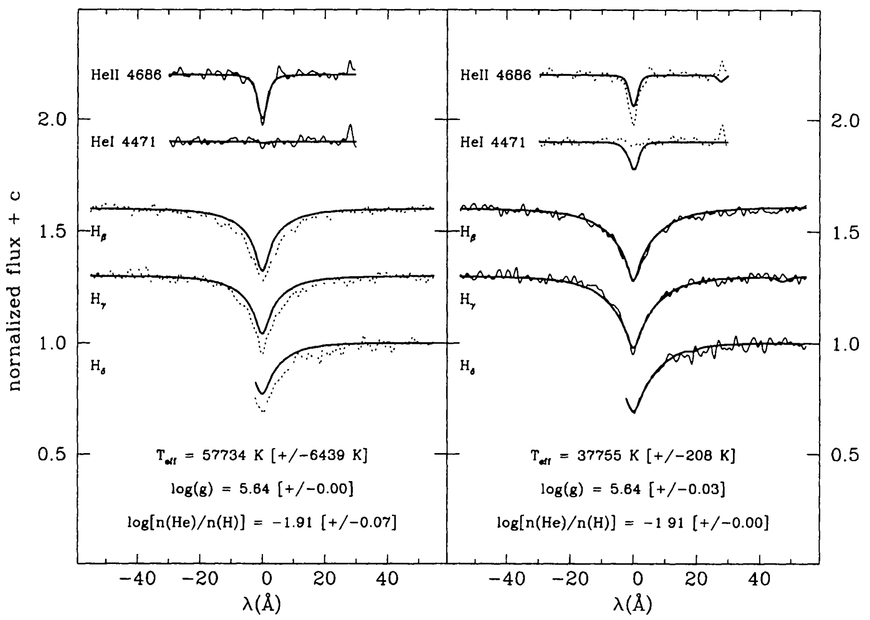

Figure 3. Line profile fit for PG 1543+629. Left panel: Fitting of He II 4686Å and He I 4471Å. Note the Balmer line discrepancy. Right panel: Fit of the Balmer lines. Note the helium line discrepancy.

4. Results

The effective temperatures from NLTE models are hotter by $\Delta T_{\rm eff}$=500 K ... 1000 K than from LTE models. At the low temperature end this difference is due to the neglect of metal line blanketing in the NLTE models, whereas at the hot end some deviation from LTE occur.

The gravities derived from NLTE models are slightly lower by $\Delta \log g \approx 0.05$ dex than from LTE models. We find no systematic dependence of $\log g$ on the number of Balmer lines used in the fit.

For eight stars atmospheric parameters have been determined in the literature. Table 1 indicates that our results are inconsistent with those derived by Theissen et al. (1993) but agree within the mutual error ranges with all other investigations except for PG 2317+046 which will be discussed below.

As expected from the spectral classification most of the stars (22 stars) lie in the range from $T_{\rm eff}\approx$30 000 K to $\approx$40 000 K (see Fig. 4). However, nine stars are considerably hotter with $T_{\rm eff}$ ranging from 42 000 K to more than 60 000 K. (see Fig.4)

While for most stars consistent fits for both helium and Balmer lines could be achieved (see Fig. 2), this was not possible in the cases of four apparently hot subdwarfs. The absence of He I 4471Å and the strength of He II 4686Å indicate a *high* $T_{\rm eff}$ whereas the Balmer lines require a *low* $T_{\rm eff}$. Actually, the non-detection of He I 4471Å sets a lower limit to $T_{\rm eff}$ only. This discrepancy is reminiscent of the "Balmer line problem" in very hot DAO white dwarfs (Napiwotzki & Rauch, 1994). In the hottest DAO stars no consistent fit of the Balmer lines was possible (Napiwotzki, 1992), the higher the Balmer line the higher the deduced $T_{\rm eff}$. Werner (1996) has suggested that proper treatment of the metal line blanketing in NLTE can resolve the "Balmer line problem" in DAO white dwarfs. Whether metal line blanketing can also resolve the discrepancy between "Helium ionization"- and "Balmer line" temperatures for sdOB stars needs to be explored by detailed modelling. UV spectra are required to measure the metal abundances. Also, binarism should be considered and radial velocity variations should be searched for.

Table 1. Comparison of our results to literature. For PG2317+046 alternative $T_{\rm eff}$ from the helium ionization equilibrium (marked He) and from the Balmer line fit (B) are given. S94=Saffer et al. (1994); T93=Theissen et al. (1993); Bi97=Billeres et al. 1997, ApJ 487, L81; Ki98=Kilkenny et al. 1998, MNRAS 296, 329; Ko98=Koen et al. 1998, MNRAS 296, 317; O98=O'Donoghue et al. 1998, MNRAS 296, 306.

star	$T_{\rm eff}$/K log g log(n_{He}/n_H)	S94	T93
PG 1343-102	28200 ± 700	28900 ± 1000	
	5.35 ± 0.10	5.65 ± 0.15	
	-3.3 ± 0.2	-3.0 ± 0.1	
Feige 36	29000 ± 700	29600 ± 1000	
	5.80 ± 0.10	5.82 ± 0.15	
	-2.0 ± 0.2	-1.9 ± 0.1	
PG 2059+013	33500 ± 800	32400 ± 1000	26300± 1200
	5.85 ± 0.10	5.80 ± 0.15	5.05 ± 0.20
	-1.3 ± 0.2	-1.7 ± 0.1	-1.5 ± 0.2
PG 2128+096	39500 ± 1000	39400 ± 1000	31700 ± 1700
	5.80 ± 0.10	5.87 ± 0.15	5.4 ± 0.20
	-0.8 ± 0.2	-0.8 ± 0.1	-1.7 ± 0.2
PG 2317+046	≈ 48000 He		
	≈ 39500 B	39400 ± 1000	
	5.40 ± 0.10	5.87 ± 0.15	
	-2.6 ± 0.2	≈-2.7	
	pulsators		
PG 1336-018	31500 ± 800	33000 ± 1000	
	5.60 ± 0.10	5.7 ± 0.10	
	-3.0 ± 0.2		
PG 1605+072	32000 ± 700	32100 ± 1000	
	5.10 ± 0.10	5.25 ± 0.10	
	-2.6 ± 0.2		
PG 1047+003	34200 ± 700	35000 ± 1000	
	5.60 ± 0.10	5.9 ± 0.1	≈ 34370
	-2.0 ± 0.2		≈ 5.7

In Figure 4 we compare the atmospheric parameters to evolutionary calculations (Dorman et al. 1993) for extreme Horizontal Branch (EHB) stars. Most stars have gravities somewhat lower than the Zero Age Extreme Horizontal Branch (ZAEHB) and lie close to or even above the Terminal Age Extreme Horizontal branch (TAEHB). The hot stars ($T_{\rm eff}$>40 000 K) are clearly evolved from

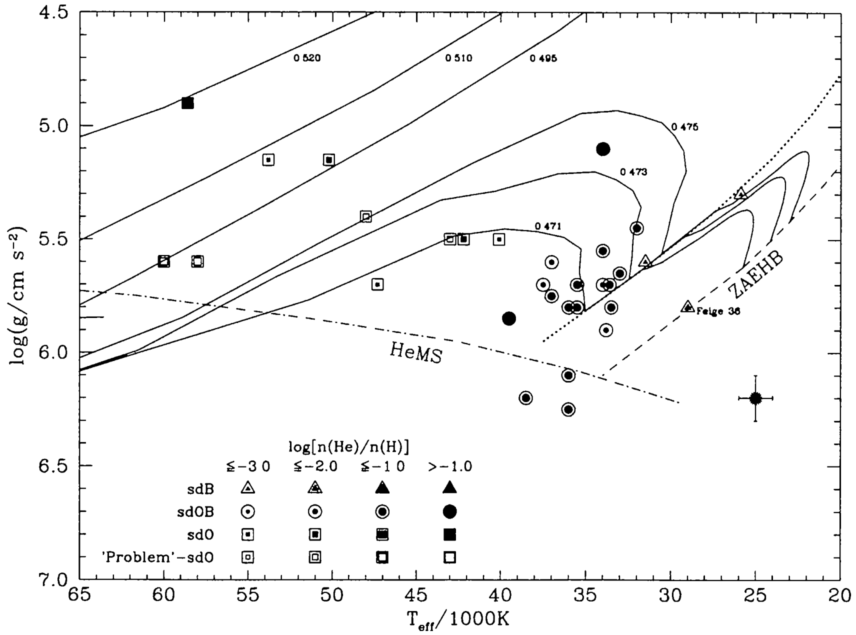

Figure 4. Comparison of $T_{\rm eff}$ and log g of the programme stars to evolutionary calculations (Dorman et al. 1993) labelled by their mass (solar units), see text. The dotted line is the TAEHB.

the EHB. The most luminous star (PG 1545+035, $T_{\rm eff}$=58 600 K, log g=4.9) could also be a descendant of the asymptotic giant branch.

Since EHB evolution proceeds more or less horizontally in the ($T_{\rm eff}$, log g) diagram, this could be explained by an evolutionary effect if there is a large reservoir of sdB stars ($T_{\rm eff}$<30 000 K) from which many sdOBs could have evolved. A statistically complete sample of (sdB and sdOB) stars is required to address this issue.

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Discussion

Detlev Koester: Can you comment on the metal abundance analysis?

Uli Heber: Metal abundance analyses for some sdOB stars have been carried out already in the 70's by Baschek and collaborators. Lots of iron lines have been detected in the UV, the corresponding iron abundances are close to solar, similar to the sdB star Feige 36 presented in the poster by Edelmann et al. at this meeting. One the other hand some elements are extremely depleted, like silicon and carbon (in Feige 110 Si is depleted by more the 10^{-5}). I think it is impossible to predict the metal abundances from low-resolution optical spectra. One cannot speak of metallicities because some elements will be depleted strongly, others will be levitated. This is more important for sdB stars than it is for white dwarfs because the gravities are smaller and the radiative levitation has a better chance to overcome gravitation.

Detlev Koester: Have you investigated how much the abundance results depend on NLTE-effects?

Uli Heber: I think that Napiwotzki (1997, A&A 322, 256) has already explored it. Below 35 000 K the NLTE effects are negligible, except for the H-alpha line core, which we did not include in our analysis. Hence the differences stem from metal line blanketing. At temperatures as hot as 40 000 K, there is a little increase in the non-LTE effects, which also depend on gravity. At lower gravity, they become somewhat more important. But my intention was just to demonstrate the size of differences when using different models.

Darragh O'Donoghue: How do you think we should proceed in order to remove the log g differences amongst the various groups? These differences are, of course, disastrous for asteroseismology.

Uli Heber: Since all of us use very similar fitting procedures and model atmospheres, we can explore that only by doing repeat observations of the spectra with different instrumental set-ups to find out what the influence of data reduction is. A careful comparison of the results from different groups should be done in a similar way as Napiwotzki, Green and Saffer (this meeting) did for DA white dwarfs. I believe that due to systematic errors we will be very hard or even impossible to derive spectroscopic gravities to an accuracy of only a few hundreds of a dex for individual stars.

Rex Saffer: Comment: My comparison of the number of Balmer lines used for fitting was with Sabine Moehler's use of Strømgren colors and UV energy distributions to fix T_{eff} and one or two Balmer lines to give log g, while here you use exclusively Balmer He-lines. And the problem of systematic subdwarf log g differences is still very much with us, as Francois Wesemael has shown in the Blanes workshop.

Pierre Maxted: How did you detect binarity in your 8 binaries?

Uli Heber: Through spectral features of late-type stars e.g. the presence of the G-band.

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