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Physical parameters of helium-rich subdwarf B stars from spectral energy distributions★

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Abstract. We present effective temperatures and angular radii for eleven helium-rich subdwarf B stars. These are measured using spectral energy distributions from archival IUE spectra and existing optical and infrared photometry. The data have been analysed using a grid of high-gravity helium-rich LTE model atmospheres and a χ^2-minimization procedure. The parameters derived here allow for independent verification of the parameters derived from the analysis of optical spectra.

Key words. stars: chemically peculiar – stars: early-type – subdwarfs – stars: atmospheres – stars: fundamental parameters

1. Introduction

Helium-rich subdwarf B stars (He-sdB) stars are rare faint blue stars first identified as sdOD stars in the Palomar-Green (PG) survey of faint blue objects (Green et al. 1986). They are found both in our Galaxy (PG survey) as well as in globular clusters (Moehler et al. 1997, 2002). The optical spectra of He-sdB stars, by definition show strong HeI and in some cases HeII absorption lines. Some of them also show strong carbon lines.

The evolution of these stars has been under much debate. Initially it was suggested that they might be the products of merged white dwarfs (Iben & Tutukov 1986). More recently Brown et al. (2001) have suggested that these stars might be the product of late flash-mixing in single star evolution.

Analysis of optical spectra (Ahmad & Jeffery 2003 – Paper I) of a sample of fifteen He-sdB stars indicate that they have effective temperatures ($T_{\rm eff}$) in the range 30 000–40 000 K, surface gravities ($\log g$) in the range 5.0–6.0 (cgs) and helium abundances ($n_{\rm He}$) ranging from 0.10–0.99. Although He-sdB stars exhibit a range of helium abundance, most of them are extremely helium-rich, having $n_{\rm He} \geq 0.90$.

Misclassification of He-sdB stars is a known problem (Paper I). The PG catalogue classified cooler subdwarfs having "pure" HeI spectra with weak or absent hydrogen Balmer lines as sdOD stars implying that He-sdB stars should be extremely helium-rich. Other authors have identified sdB stars showing significantly more helium than "normal" to be He-sdB stars, e.g. JL 87 ($n_{\rm He} \sim 0.17$, Schulz et al. 1991) and LS IV–14°116 ($n_{\rm He} \sim 0.21$, Paper I). Such stars have also been analysed in this paper although they are not "typical" He-sdB stars.

This paper aims to measure the fundamental parameters – effective temperature ($T_{\rm eff}$), interstellar reddening (E_{B-V}) and angular diameter (θ) of a sample of He-sdB stars by studying their flux distribution using a grid of helium-rich model atmospheres and a χ^2-minimization procedure. Stars selected for this study include all He-sdB stars from the literature which have been observed with the International Ultraviolet Explorer (IUE) satellite. These observations were supplemented with optical photometric measurements from the literature and from the recently released 2MASS infrared measurements. The parameters derived by this method are independent from those obtained from the analysis of optical spectra (Paper I), thus providing an independent verification.

2. IUE observations

IUE observations for eleven He-sdB stars, shown in Fig. 1, have been collected from the IUE Final Archive at MAST as "IUE Newly Extracted Spectra" (INES, Nichols & Linsky 1996). The observations listed in Table 1 were made at low resolution (∼6 Å) with the Short Wavelength Prime (SWP: 1150–1980 Å) and the Long Wavelength Prime and Redundant (LWP and LWR: 1850–3350 Å) cameras. The short wavelength cameras on the IUE were more sensitive than the long wavelength cameras and hence the SW and LW observations were merged in the overlap region (1850–1980 Å) using weights of 100:1 with the Starlink package DIPSO (Howarth et al. 1998). For the analysis the IUE spectra were trimmed at the long and short wave limits to remove noisy data.

We found that two stars originally classified as He-sdB stars by Beers et al. (1992) and observed with the IUE are actually white dwarfs; BPS CS 29517–0049 is a DB white dwarf (Wegner & Nelan 1987) and BPS CS 22968–0019 is a DB4 white dwarf (Wesemael et al. 1993). These two stars were not analysed.

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★ Based on INES data from the IUE satellite.

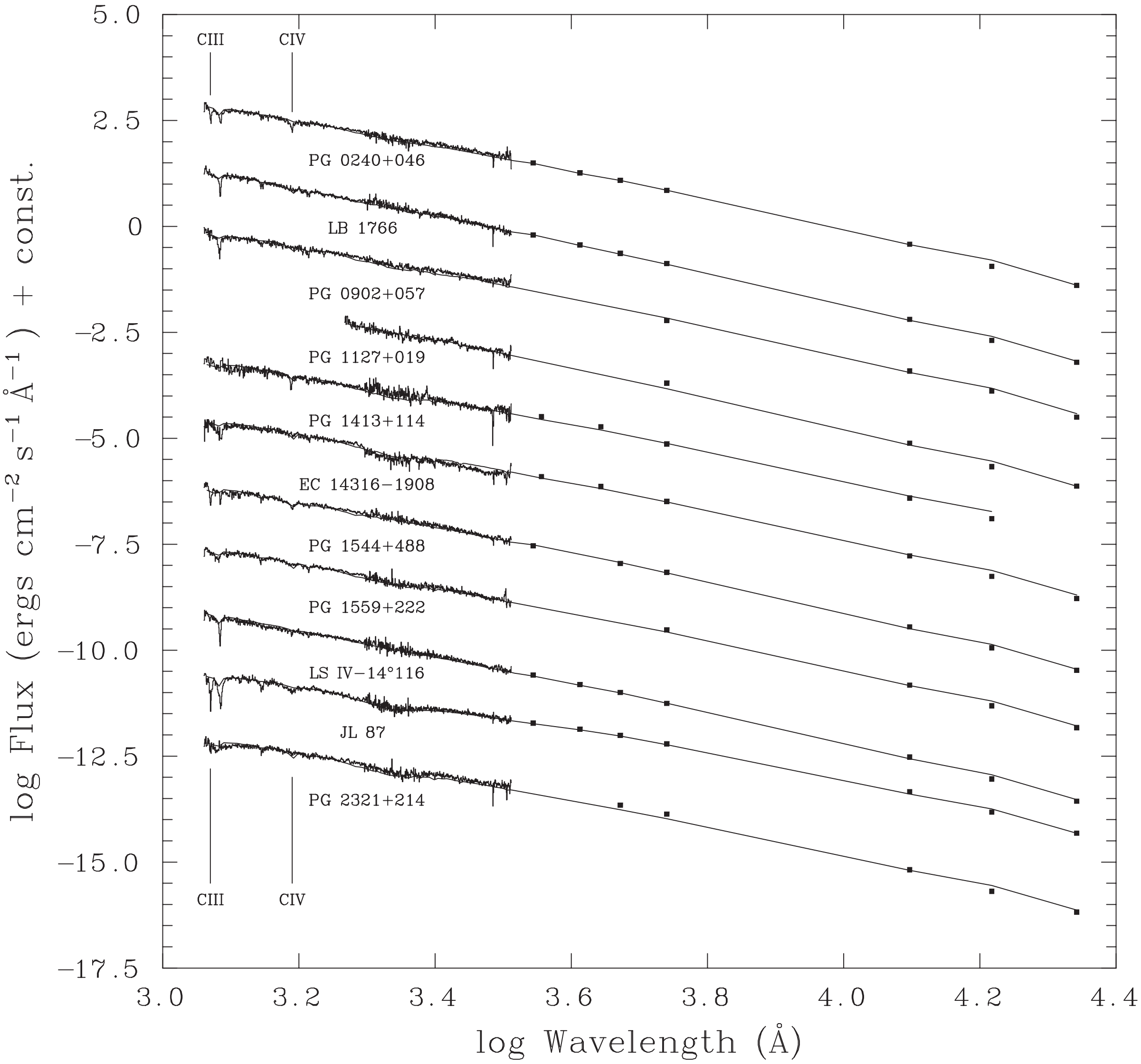

Fig. 1. Flux distribution of He-sdB stars with the model fits.

Table 1. IUE observations of He-sdB stars.

Star	LW Image	Exp [s]	SW Image	Exp [s]
PG 0240+046	LWP 18452	2699	SWP 39307	2099
LB 1766	LWP 31664	399	SWP 56159	299
PG 0902+057	LWR 06514	3599	SWP 56259	999
	LWP 31781	1499	–	–
PG 1127+019	LWP 10994	1199	–	–
PG 1413+114	LWP 10989	8999	SWP 31135	14 999
EC 14316–1908	LWP 23384	1320	SWP 45020	660
PG 1544+488	LWP 10992	899	SWP 31142	899
PG 1559+222	LWP 10993	6899	SWP 31143	5999
LS IV–14°116	LWP 10814	759	SWP 31029	759
JL 87	LWP 09467	419	SWP 29594	299
PG 2321+214	LWP 18329	1445	SWP 39208	1019

3. Photometry

Photometric measurements of He-sdB stars were collected from published photometry. The optical photometry includes Johnson *UBV* and Strömgren *uvby* measurements and these are listed in Table 2. Infrared Johnson *JHK* measurements, listed in Table 3 were collected from the 2MASS All-Sky Catalogue of Point Sources (Cutri et al. 2003).

For some of the stars there are no published *y* or *V* measurements; in such cases the *V* magnitude has been calculated from the $B_{\rm pg}$ magnitude using the transformation equation given by Thejll et al. (1994),

$$V = 6.628 \times 10^{\,0.024\,B_{\rm pg}}. \tag{1}$$

The transformed *V* magnitudes have a standard deviation of 0.3 mag. The errors in the photometric measurements listed in Tables 2 and 3 are derived from the source papers.

The photometric magnitudes used in the energy distribution analysis were converted into fluxes using

$$F_\lambda = 10^{0.4(C_\lambda - m_\lambda)}. \tag{2}$$

The scale factors C_λ used for converting the magnitudes to fluxes are taken from Heber et al. (1984) for the Strömgren *uvby* filters and from Johnson (1966) for the Johnson *UBVJHK* filters.

Table 2. Visible light photometry of of He-sdB stars.

Star	u	v	b	U	B	y/V
PG 0240+046	13.785 ± 0.021[1]	14.034 ± 0.018[1]	14.037 ± 0.016[1]	–	–	14.142 ± 0.014[1]
LB 1766	11.906 ± 0.112[2]	12.158 ± 0.053[2]	12.223 ± 0.023[2]	–	–	12.343 ± 0.012[2]
PG 0902+057	–	–	–	–	–	14.415 ± 0.300[3]
PG 1127+019	–	–	–	–	–	13.603 ± 0.300[3]
PG 1413+114	–	–	–	14.580 ± 0.360[4]	15.710 ± 0.024[4]	16.070 ± 0.015[4]
EC 14316–1908	–	–	–	11.860 ± 0.040[5]	12.990 ± 0.020[5]	13.210 ± 0.010[5]
PG 1544+488	12.500 ± 0.120[6]	–	12.770 ± 0.070[6]	–	–	12.800 ± 0.050[6]
PG 1559+222	–	–	–	–	–	14.786 ± 0.300[3]
LS IV–14°116	12.629 ± 0.025[2]	12.847 ± 0.011[2]	12.882 ± 0.003[2]	–	–	13.029 ± 0.001[2]
JL 87	12.082 ± 0.056[7]	12.095 ± 0.032[7]	12.034 ± 0.026[7]	–	–	12.049 ± 0.022[7]
PG 2321+214	–	–	13.530 ± 0.364[8]	–	–	13.560 ± 0.324[8]

References :
[1] Wesemael et al. (1992); [2] Kilkenny & Busse (1992); [3] V calculated using Eq. (1); [4] Beers et al. (1992); [5] Kilkenny et al. (1997); [6] Green (1980); [7] Hauck & Mermilliod (1998); [8] Bixler et al. (1991).

Table 3. Infrared photometry of He-sdB stars from the 2MASS survey (Cutri et al. 2003).

Star	J	H	K
PG 0240+046	14.755 ± 0.033	14.936 ± 0.052	14.844 ± 0.100
LB 1766	13.062 ± 0.027	13.181 ± 0.031	13.248 ± 0.038
PG 0902+057	14.742 ± 0.036	14.789 ± 0.049	15.116 ± 0.162
PG 1127+019	14.498 ± 0.029	14.751 ± 0.062	14.688 ± 0.111
PG 1413+114	16.609 ± 0.138	16.701 ± 0.316	–
EC 14316–1908	13.773 ± 0.026	13.848 ± 0.045	13.933 ± 0.060
PG 1544+488	13.460 ± 0.022	13.561 ± 0.030	13.666 ± 0.046
PG 1559+222	15.398 ± 0.054	15.482 ± 0.112	15.555 ± 0.219
LS IV–14°116	13.638 ± 0.027	13.799 ± 0.031	13.898 ± 0.051
JL 87	12.308 ± 0.026	12.388 ± 0.027	12.410 ± 0.026
PG 2321+214	14.289 ± 0.024	14.430 ± 0.038	14.434 ± 0.075

4. Models and χ^2 minimization

A grid of LTE model atmospheres was computed assuming plane-parallel geometry and hydrostatic equilibrium using the code STERNE (Jeffery & Heber 1992). The grid points were defined by $T_{\rm eff}$ = 20 000 (5000) 40 000, 50 000, $\log g$ = 5.0 (0.5) 6.0 and $n_{\rm He}$ = 0.100, 0.300, 0.699, 0.997. Solar metal abundances were assumed. Another model grid was used to study the effect of carbon enhancement in the model atmospheres, these comprised $T_{\rm eff}$ = 28 000 (2000) 40 000, $\log g$ = 5.0 (0.5) 6.0 and abundance ($n_{\rm He} + n_{\rm C}$) = 0.960+0.030, 0.990+0.010, 1.000+0.003.

The FORTRAN90 program FFIT (Jeffery et al. 2001) was used to calculate the effective temperature ($T_{\rm eff}$), reddening (E_{B-V}) and angular diameter (θ) from the observed flux distribution by fitting model fluxes using a χ^2 minimisation procedure (cf. Aznar Cuadrado & Jeffery 2001).

The best fit parameters for each star correspond to the minimum in the χ^2 surface. Aznar Cuadrado & Jeffery (2001) had noted that these surfaces should be treated carefully as they may have more than one minimum and FFIT can find wrong parameters if it ends up in a local minimum instead of the global minimum. We examined the quality of each final solution (Fig. 1) to ensure that it looked reasonable and to check whether it was consistent with previous measurements.

5. Errors

Aznar Cuadrado & Jeffery (2001) have shown that the $T_{\rm eff}$ is not very sensitive to $\log g$ in the range of 5.0–6.0 (cgs). We have therefore assumed a value for $\log g$ for our stars based on Paper I and previous analyses. The results do not change if $\log g$ is varied by ±0.3 dex. Also, $n_{\rm He}$ does not affect the parameters if it is varied by ±0.1. The best model fits were calculated

Table 4. Physical parameters of of He-sdB stars along with previous measurements from the literature. Values in square brackets are assumed.

Star	E_{B-V}	θ [rad] $\times 10^{-12}$	$T_{\rm eff}$ [K]	$\log g$ [cgs]	$n_{\rm He}$	Reference
PG 0240+046	0.07 ± 0.01	4.08 ± 0.09	34 600 ± 1 700	[5.5]	[0.70]	FFIT
[carbon-rich]	–	–	34 000 ± 150	5.40 ± 0.10	0.63 ± 0.01	Paper I
	–	–	36 200 ± 400	6.25 ± 0.10	0.66 ± 0.02	Aznar Cuadrado & Jeffery (2002)
	0.06	–	34 800 ± 1 850	–	–	Aznar Cuadrado & Jeffery (2001)
	–	–	37 000 ± 2 000	5.30 ± 0.30	0.55 ± 0.11	Thejll et al. (1994)
LB 1766	0.02 ± 0.01	7.98 ± 0.17	40 400 ± 1 300	[6.0]	[0.99]	FFIT
[carbon-poor]	–	–	40 000 ± 2 000	6.30 ± 0.30	0.99	Lanz et al. (2003)
PG 0902+057	0.08 ± 0.01	3.37 ± 0.10	47 000 ± 3 000	[6.0]	[0.99]	FFIT
[carbon-poor]	–	–	>40 000	–	–	Paper I
	–	–	44 000 ± 2 000	6.00 ± 0.10	0.97 ± 0.19	Thejll et al. (1994)
PG 1127+019	0.03 ± 0.01	3.82 ± 0.16	42 100 ± 2 000	[5.0]	[0.99]	FFIT
[carbon-rich]	–	–	39 900 ± 200	5.00 ± 0.10	0.99 ± 0.01	Paper I
PG 1413+114	0.12 ± 0.02	1.74 ± 0.07	40 300 ± 2 500	[5.5]	[0.99]	FFIT
[carbon-rich]	0.00	–	31 600	–	–	Beers et al. (1992)
EC 14316–1908	0.12 ± 0.02	6.06 ± 0.22	42 000 ± 3 000	[5.5]	[0.99]	FFIT
[carbon-poor]	0.12	–	77 000	–	–	Drilling & Beers (1995)
	0.08	–	33 900	–	–	Beers et al. (1992)
PG 1544+488	0.01 ± 0.01	7.51 ± 0.12	32 100 ± 1 000	[5.0]	[0.99]	FFIT
[carbon-rich]	–	–	36 000 ± 2 000	6.00 ± 0.30	0.98	Lanz et al. (2003)
	–	–	34 000 ± 300	5.10 ± 0.10	0.99 ± 0.01	Paper I
	–	–	31 000	5.10	≤ 0.99	Heber et al. (1988)
PG 1559+222	0.09 ± 0.02	2.92 ± 0.13	38 700 ± 2 100	[5.5]	[0.99]	FFIT
[carbon-poor]	–	–	–	–	–	–
LS IV–14°116	0.03 ± 0.01	6.90 ± 0.10	32 500 ± 700	[5.5]	[0.30]	FFIT
[carbon-poor]	–	–	32 500 ± 150	5.40 ± 0.10	0.21 ± 0.01	Paper I
	–	–	35 000	–	–	Ulla & Thejll (1998)
	0.01	–	33 000 ± 1 000	5.80 ± 0.20	0.20 ± 0.07	Viton et al. (1991)
JL 87	0.16 ± 0.01	15.00 ± 0.36	28 100 ± 1 100	[5.0]	[0.10]	FFIT
[carbon-rich]	–	–	29 000 ± 2 000	5.50 ± 0.30	0.09 – 0.16	Lanz et al. (2003)
	–	–	30 000	5.00	–	Magee et al. (1998)
	0.15	–	28 000 ± 1 000	5.20 ± 0.30	0.17 ± 0.05	Schulz et al. (1991)
PG 2321+214	0.13 ± 0.02	4.93 ± 0.22	38 400 ± 3 000	[5.5]	[0.99]	FFIT
[carbon-poor]	–	–	39 600 ± 150	5.30 ± 0.10	0.99 ± 0.01	Paper I
	0.10±0.03	–	43 000[1]	–	–	Ulla & Thejll (1998)

[1] Thejll, Husfeld & Saffer (unpublished) reported by Ulla & Thejll (1998).

without any interpolation in $\log g$ and $n_{\rm He}$. For some stars in this study there are no previous analyses for surface gravity and helium abundance, in such cases we have assumed $\log g = 5.5$ and $n_{\rm He} = 0.99$, which are the typical values for He-sdB stars (Paper I).

It is clear from optical and IUE spectra that some He-sdB stars are carbon-rich while others are carbon-poor. Hence we studied the effect of carbon enhancement in the atmosphere by adding 3%, 1% and 0.3% carbon in the model atmospheres. The results indicate that increasing the amount of carbon in the atmosphere does not significantly change the flux distribution in the wavelengths under study (1180–22 000 Å). The effect of the change in carbon abundance on $T_{\rm eff}$ is ≤600 K, which is quite small considering the errors associated with $T_{\rm eff}$ in the best model fit are around ±1500 K. Hence, we have used a solar carbon abundance for this analysis.

It has been established (Kudritzki 1979) that for $T_{\rm eff} \leq 35\,000$ K, departure from local thermodynamic equilibrium (LTE) does not significantly affect measurements of $T_{\rm eff}$ in high-gravity stars. For hotter stars, NLTE effects become increasingly important. However the relative temperature differences obtained from LTE analysis are still useful.

6. Results

The IUE spectra of He-sdB stars are shown in Fig. 1 combined with the photometric fluxes and model fits. The best fit parameters derived from FFIT are quoted in Table 4 along with the formal errors.

It is interesting to note that some He-sdB stars show strong CIII/CIV lines in their IUE spectrum (see Fig. 1) as well as in the optical spectrum (Paper I) indicating that they are carbon-rich. In other stars these strong carbon lines are absent. This reinforces the view that there are two distinct sub-classes within He-sdB stars, one which consists of stars which are carbon-rich and the other which comprises stars which are carbon-poor (Table 4).

7. Discussion

Some of our He-sdB stars have been analysed previously. For these, most of our results match quite well with those already in the literature (Table 4). PG 1413+114, EC 14316–1908 and PG 1559+222 do not have previous estimates for $\log g$ and $n_{\rm He}$ hence typical values for these parameters were assumed for the analysis. The optical spectra of these three stars show strong HeII lines indicating that they are hot ($\gtrsim$40 000 K) and enriched in helium.

PG 1413+114 is a He-sdB star from Jeffery et al. (1996). Beers et al. (1992) have also referred to it as a He-sdB star (BPS CS 22883–0015) and estimated $T_{\rm eff}$ = 31 600 K and E_{B-V} = 0.0. Such a low effective temperature is not consistent with the presence of the strong HeII lines. We derive a much higher effective temperature and interstellar reddening for this star in our analysis.

EC 14316–1908 is a He-sdB star from the Edinburgh-Cape survey of blue objects by Kilkenny et al. (1997). Beers et al. (1992) refer to it as a He-sdO star (BPS CS 22871–0019) and estimate $T_{\rm eff}$ = 33 900 K and E_{B-V} = 0.08. This star appears as two different object in SIMBAD. Drilling & Beers (1995) have estimated $T_{\rm eff}$ = 77 000 K and E_{B-V} = 0.12 by analysing the flux distribution of this star. The optical spectrum shows strong HeII but also some HeI which suggests that although this star is quite hot ($T_{\rm eff} \geq$ 40 000 K), it is not as hot as estimated by Drilling & Beers (1995). We derive the same interstellar reddening but a much lower effective temperature (42 000 K).

8. Conclusion

We have analysed a sample of eleven He-sdB stars and derived fundamental parameters from their flux distributions. The results confirm those obtained from analyses of optical spectra.

The IUE spectra of He-sdB stars reinforces the idea of two distinct subclasses of these stars. The carbon-rich He-sdB stars which show strong carbon lines in their optical and IUE spectra can be explained by the merger of CO+He white dwarfs (Saio & Jeffery 2002) as well as the flash-mixing model (Brown et al. 2001) whereas carbon-poor He-sdB stars can be explained by He+He white dwarf mergers (Saio & Jeffery 2000). Detailed abundance measurements will be required to determine which of these evolutionary channel(s) are responsible for the formation of these rare faint blue stars.

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