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Resolving subdwarf B stars in binaries by HST imaging⋆,⋆⋆,⋆⋆⋆,†

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Abstract. The origin of subluminous B stars is still an unsolved problem in stellar evolution. Single star as well as close binary evolution scenarios have been invoked but until now have met with little success. We have carried out a small survey of spectroscopic binary candidates (19 systems consisting of an sdB star and late type companion) with the Planetary Camera of the WFPC2 onboard Hubble Space Telescope to test these scenarios. Monte Carlo simulations indicate that by imaging the programme stars in the R-band about one third of the sample (6–7 stars) should be resolved at a limiting angular resolution of $0\farcs1$ if they have linear separations like main sequence stars ("single star evolution"). None should be resolvable if all systems were produced by close binary evolution. In addition we expect three triple systems to be present in our sample. Most of these, if not all, should be resolvable. Components were resolved in 6 systems with separations between $0\farcs2$ and $4\farcs5$. However, only in the two systems TON 139 and PG 1718+519 (separations $0\farcs32$ and $0\farcs24$, respectively) do the magnitudes of the resolved components match the expectations from the deconvolution of the spectral energy distribution. These two stars could be physical binaries whereas in the other cases the nearby star may be a chance projection or a third component. Radial velocity measurements indicate that the resolved system TON 139 is a triple system, with the sdB having a close companion that does not contribute detectably to the integrated light of the system. Radial velocity information for the second resolved system, PG 1718+519, is insufficient. Assuming that it is not a triple system, it would be the only resolved system in our sample. Accordingly the success rate would be only 5% which is clearly *below* the prediction for single star evolution. We conclude that the distribution of separations of sdB binaries deviates strongly from that of normal stars. Our results add further evidence that close binary evolution is fundamental for the evolution of sdB stars.

Key words. stars: early-type – stars: binaries: spectroscopic – stars: evolution

1. Introduction

Subluminous B (sdB) stars dominate the populations of faint blue stars of our own Galaxy and are found in both the disk (field sdBs) and globular clusters (Moehler et al. 1997). Observations of elliptical galaxies with the Ultraviolet Imaging Telescope (Brown et al. 1997) and the Hubble Space Telescope (Brown et al. 2000) have shown that these stars are sufficiently common to be the dominant source for the "UV upturn phenomenon" observed in elliptical galaxies and galaxy bulges (see also Greggio & Renzini 1990, 1999). Their space distribution and kinematical properties indicate that the field stars belong to the intermediate to old disk population (de Boer et al. 1997; Altmann & de Boer 2000).

However, important questions remain concerning their formation process and the appropriate evolutionary timescales. This is a major drawback for the calibration of the observed ultraviolet upturn in elliptical galaxies as an age indicator.

It is now generally accepted that the sdB stars can be identified with models for Extreme Horizontal Branch (EHB) stars burning He in their core, but with a very

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⋆⋆⋆ Based on data obtained at ESO (ESO proposal No. 58.D-0478, 65.H-0253(A)).

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tiny (<2% by mass) inert hydrogen envelope (Heber 1986; Saffer et al. 1994). 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) as confirmed by evolutionary calculations (Dorman et al. 1993).

How stars evolve to the EHB configuration is controversial. The problem is how the mass loss mechanism in the progenitor manages to remove all but a tiny fraction of the hydrogen envelope at *precisely* the same time as the He core has attained the minimum mass ($\approx$0.5 $M_{\odot}$) required for the He flash.

Both non-interacting (scenario i), and interacting (scenarios ii and iii) evolutionary scenarios have been proposed to explain the origin of the sdB stars (see Bailyn et al. 1992).

(i) Enhanced mass loss on the red giant branch (RGB) before or during the core helium flash may remove almost the entire hydrogen-rich envelope. This is usually modelled by increasing the η factor in the Reimers (1975) formula to estimate mass loss rates for RGB stars. It has been conjectured that the mass loss rates increase with increasing metallicity, implying that metal rich populations should produce more sdB stars than metal poor ones. Birthrate estimates for sdB stars indicate that only 2% (Heber 1986) or even less (0.25% to 1%, Saffer & Liebert 1995) of the RGB stars need to experience such enhanced mass loss. Evidence that this is possible comes from the existence of RR Lyrae stars of population I which must also have lost half of their mass during evolution. In both cases the physical reason for such strong mass loss is not yet understood.

(ii) Mengel et al. (1976) suggest that sdBs could be formed from binaries in which mass transfer starts on the red giant branch and results in a reduction of the hydrogen envelope prior to the helium core flash. Hence all sdBs star are predicted to be found in close binary systems.

(iii) An alternative scenario was proposed by Iben (1990), who pointed out that sdBs can be formed from mergers of helium white dwarf binary systems. Iben & Tutukov (1992) estimate that 80% of the sdBs could have been formed by mergers. Hence the frequency of sdBs still being in binaries should be at most 20%.

Several dozens of objects with composite spectra consisting of an sdB and a dwarf G-K star have been discovered (e.g. Ferguson et al. 1984; Theissen et al. 1993, 1995; Allard et al. 1994) which implies that the binary frequency of sdBs is 50% or more (Allard et al. 1994). The observed large binary frequency rules out the merger scenario (iii) and we are left with scenarios (i) and (ii), i.e. either the sdB binaries are mostly wide systems that did not interact so that the sdB precursors have evolved independently from the companion (i), or they are close systems formed by interaction of the sdB precursor with the companion star (mass exchange, ii).

The high spatial resolution of the *Planetary Camera* (PC) on board the *Hubble Space Telescope* (HST) allows to perform a crucial test. As we will show in this paper, it should be possible to resolve a significant fraction of the known composite spectrum systems containing an sdB star if scenario (i) is correct, i.e. if the systems have a distribution of separations like normal main sequence binaries (Duquennoy & Mayor 1991). The interacting scenario (ii), however, predicts that all sdB stars reside in short period ($P \leq 100$ d) binaries and consequently none of the systems should be resolvable even with the PC. In order to measure their distribution of separations we have imaged 23 sdB binary candidates with the PC by taking advantage of the snap shot mode of HST observations.

2. Observations and data analysis

2.1. Target selection and optical spectroscopy

For the snapshot observations a target list of fifty of the brightest sdB star binary candidates was extracted from an updated version of the Kilkenny et al. (1988) catalogue, supplemented by two stars which we discovered in the course of follow-up spectroscopy of hot stars from the Hamburg-ESO survey (see Edelmann et al. 2001a). 23 stars from this target list were actually observed with the *Wide Field Planetary Camera 2* (WFPC2) onboard the HST during our snapshot project, i.e. they were scheduled for observation to fill small gaps in the HST schedule. All stars have published photometry (see Tables B.1 and B.2), but only 16 have published optical spectroscopy. Therefore additional spectra were obtained at the Calar Alto and ESO observatories (see Appendix A for details and plots of the spectra in Figs. A.1 and A.2). As can be seen from Fig. A.1 spectral features (Ca I, Ca II, Mg I and/or Fe I) indicative of a cool star are clearly present in the spectra of PG 1309−078, PG 0942+461, HE 0430−2457, HE 2213−2212, and PG 2148+095 in addition to the Balmer and helium lines of the sdB. Hence these objects are spectroscopic binaries consisting of an sdB star and a cool companion. PG 0942+461 has already been observed by Mitchell (1998), who, however, did not note the binary nature of the star. We do not find any evidence for a cool companion in the spectra of the sdB stars PG 1558−087 and KPD 2215+5037 (see Fig. A.2). We also re-analysed a published spectrum of PG 2259+134 (Theissen et al. 1993) and do not find any spectroscopic evidence for a cool companion. PG 0105+276 turns out to be not an sdB star but a helium-rich sdO star and does not show any spectroscopic evidence for a cool companion. Therefore our sample consists of 19 composite spectrum objects plus four stars showing only photometric evidence for a companion. One of these four stars (PG 0105+276) also does not belong to the programme sample since it is an sdO star.

2.2. WFPC2 data

We observed the candidate binary systems with the PC chip of the WFPC2. If the cool companion is a main sequence star, both components should be of comparable brightness in the R band and we therefore used the

Table 1. Programme stars: coordinates, observation dates, and exposure times for the WFPC2 and references for the spectroscopic classification observations.

star	α_{1950}	δ_{1950}	l	b	obs. date	exp. time [s]	reference
PB 6107	$00^{\rm h}39^{\rm m}31^{\rm s}$	$+04^\circ53'17''$	$118\overset{\circ}{.}59$	$-57\overset{\circ}{.}64$	990627	3.5	Moehler et al. (1990)
PHL 1079	$01^{\rm h}35^{\rm m}48^{\rm s}$	$+03^\circ23'00''$	$144\overset{\circ}{.}96$	$-57\overset{\circ}{.}22$	981204	4	Theissen et al. (1995)
HE 0430−2457	$04^{\rm h}30^{\rm m}59^{\rm s}$	$-24^\circ57'37''$	$223\overset{\circ}{.}49$	$-40\overset{\circ}{.}55$	980417	8	this paper
PG 0749+658	$07^{\rm h}49^{\rm m}39^{\rm s}$	$+65^\circ50'13''$	$150\overset{\circ}{.}44$	$+30\overset{\circ}{.}99$	990329	1.8	Saffer (1991)
PG 0942+461	$09^{\rm h}42^{\rm m}02^{\rm s}$	$+46^\circ08'38''$	$173\overset{\circ}{.}11$	$+48\overset{\circ}{.}89$	980530	10	Heber et al. (1991)
TON 1281	$10^{\rm h}40^{\rm m}57^{\rm s}$	$+23^\circ24'55''$	$213\overset{\circ}{.}62$	$+60\overset{\circ}{.}89$	990623	5	Jeffery & Pollacco (1998)
TON 139	$12^{\rm h}53^{\rm m}39^{\rm s}$	$+28^\circ23'31''$	$77\overset{\circ}{.}21$	$+88\overset{\circ}{.}57$	980103	1.8	Green (1997)
PG 1309−078	$13^{\rm h}09^{\rm m}09^{\rm s}$	$-07^\circ49'18''$	$311\overset{\circ}{.}60$	$+54\overset{\circ}{.}44$	980505	8	Ferguson et al. (1984)
PG 1421+345	$14^{\rm h}21^{\rm m}29^{\rm s}$	$+34^\circ27'53''$	$58\overset{\circ}{.}36$	$+69\overset{\circ}{.}01$	990605	14	Ferguson et al. (1984)
PG 1449+653	$14^{\rm h}49^{\rm m}42^{\rm s}$	$+65^\circ17'58''$	$104\overset{\circ}{.}84$	$+47\overset{\circ}{.}63$	990619	7	Moehler et al. (1990)
PG 1511+624	$15^{\rm h}11^{\rm m}25^{\rm s}$	$+62^\circ21'00''$	$99\overset{\circ}{.}21$	$+47\overset{\circ}{.}96$	990513	14	Moehler et al. (1990)
PG 1601+145	$16^{\rm h}01^{\rm m}47^{\rm s}$	$+14^\circ32'58''$	$27\overset{\circ}{.}15$	$+43\overset{\circ}{.}51$	000613	12	Ferguson et al. (1984)
PG 1636+104	$16^{\rm h}36^{\rm m}40^{\rm s}$	$+10^\circ24'54''$	$27\overset{\circ}{.}00$	$+34\overset{\circ}{.}04$	000612	8	Ferguson et al. (1984)
TON 264	$16^{\rm h}47^{\rm m}05^{\rm s}$	$+25^\circ15'13''$	$45\overset{\circ}{.}16$	$+37\overset{\circ}{.}12$	990529	10	Theissen et al. (1993)
PG 1656+213	$16^{\rm h}56^{\rm m}12^{\rm s}$	$+21^\circ15'05''$	$41\overset{\circ}{.}25$	$+33\overset{\circ}{.}90$	980301	12	Ferguson et al. (1984)
PG 1718+519	$17^{\rm h}18^{\rm m}35^{\rm s}$	$+51^\circ55'05''$	$79\overset{\circ}{.}00$	$+34\overset{\circ}{.}94$	990427	7	Theissen et al. (1995)
PG 2148+095	$21^{\rm h}48^{\rm m}41^{\rm s}$	$+09^\circ30'39''$	$66\overset{\circ}{.}78$	$-32\overset{\circ}{.}84$	990411	4	this paper
HE 2213−2212	$22^{\rm h}13^{\rm m}38^{\rm s}$	$-22^\circ12'26''$	$32\overset{\circ}{.}63$	$-54\overset{\circ}{.}50$	981207	8	this paper
BD $-7^\circ5977$	$23^{\rm h}15^{\rm m}12^{\rm s}$	$-06^\circ44'56''$	$71\overset{\circ}{.}55$	$-59\overset{\circ}{.}65$	981125	0.3	Viton et al. (1991)
stars without spectroscopic evidence for a cool companion							
PG 0105+276	$01^{\rm h}05^{\rm m}32^{\rm s}$	$+27^\circ36'53''$	$127\overset{\circ}{.}46$	$-34\overset{\circ}{.}84$	980226	14	this paper, new type: He-sdO
PG 1558−007	$15^{\rm h}58^{\rm m}39^{\rm s}$	$-00^\circ43'26''$	$9\overset{\circ}{.}34$	$+36\overset{\circ}{.}51$	990424	7	this paper
KPD 2215+5037	$22^{\rm h}15^{\rm m}25^{\rm s}$	$+50^\circ37'48''$	$99\overset{\circ}{.}71$	$-4\overset{\circ}{.}91$	961213	7	this paper
PG 2259+134	$22^{\rm h}59^{\rm m}16^{\rm s}$	$+13^\circ22'31''$	$86\overset{\circ}{.}36$	$-41\overset{\circ}{.}31$	000615	10	Theissen et al. (1993), this paper

$F675W$ filter of the WFPC2. We obtained four observations of each target, which were offset relative to the first one by (−11,−5.5), (−16.5,−16.5), (−5.5,−11) pixels. We first rebinned the data linearly to a step size of 0.5 pixels and then aligned them according to the offset pattern mentioned above. We then determined the median value of the four aligned images to avoid cosmic ray hits and hot pixels and used these median-averaged images for visual inspection. All flux measurements are performed on manually cleaned average images to ensure proper flux conservation.

The median-averaged images were first inspected by eye to see if any companion could be detected. Only 6 stars (cf. Fig. 1) showed obvious nearby stars and the angular separations and brightness differences can be found in Table 2. The brightness differences were determined using the command `INTEGRATE/APERTURE` from `MIDAS`, which performs an aperture photometry with a given radius. Aperture photometry is difficult for TON 1281, TON 139, and PG 1718+519, due to the small distance of the components. The sky background was determined in an empty region using the same aperture as for the stars.

To get a more quantitative estimate of possible companions we fitted two-dimensional Gaussians with variable angle of the major axis to *all* shifted and co-added target images and compared the results to fits obtained for archive point-spread functions (PSFs; $F675W$ filter, PC chip). The archive PSFs define a good correlation between the length of the two axes, which is shared by most target PSFs (see Fig. 2). Besides the resolved binaries (where stray light can affect the determination of the axis ratio) four stars deviate from the main correlation between major and minor axis (see Fig. 3): PG 2148+095 (2.03/1.26), KPD 2215+5037 (2.38/1.61), TON 264 (2.35/1.83), and PG 0749+658 (2.36/1.87).

Table 2. Separation and estimated brightness differences for the components of the 6 resolved binaries. The photometric data available for HE 0430−2457 do not allow to estimate a temperature or distance of the sdB.

system	separation angular	separation linear [AU]	brightness difference $\Delta F675W$
PG 0105+276	$3\overset{''}{.}37$	3700	$0\overset{\rm m}{.}9$
	$4\overset{''}{.}48$	4900	$1\overset{\rm m}{.}6$
HE 0430−2457	$1\overset{''}{.}25$		$2\overset{\rm m}{.}1$
TON 1281	$0\overset{''}{.}22$	250	$3\overset{\rm m}{.}7$
TON 139	$0\overset{''}{.}32$	300	$0\overset{\rm m}{.}8$
PG 1558−007	$2\overset{''}{.}80$	2500	$3\overset{\rm m}{.}1$
PG 1718+519	$0\overset{''}{.}24$	230	$0\overset{\rm m}{.}8$

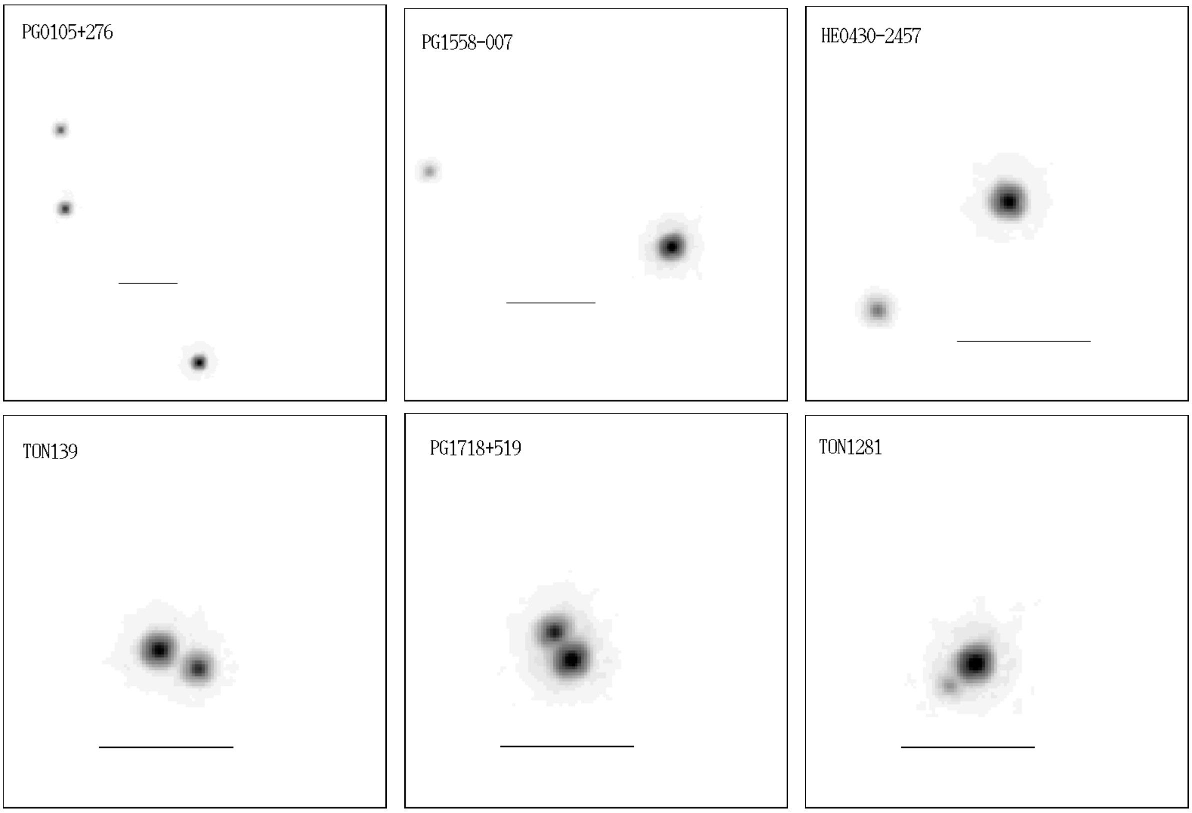

Fig. 1. The images of the resolved binaries. The bar in each image corresponds to 1″.

We used DAOPHOT (Stetson 1987) to obtain an average PSF from those target stars that share the axis-relation of the archive PSFs. This "target PSF" was then used to deconvolve all systems that are either resolved by eye or show deviations from the axis-relation defined by the archive PSFs. No additional components were resolved in this process, but we could verify the brightness differences between the components of the resolved systems listed in Table 2, which were reproduced by DAOPHOT also for small separations.

For 13 of our target stars a homogeneous set of ground-based R_{C} measurements exist (Allard et al. 1994, see Table B.2). Comparing those data to the instrumental $F675W$ magnitudes integrated within an aperture of 0$''\!.$5 radius

$$F675W = -2.5 \log \frac{\mathrm{flux}_{0''\!.5} - \mathrm{sky}_{0''\!.5}}{\text{exposure time}}$$

we find that most of the stars lie on a line with slope 1 (except KPD 2215+5037 and PG 1601+145, see Fig. 4). From the 11 stars on the line we determine a zeropoint of $21^{\mathrm{m}}\!.21 \pm 0^{\mathrm{m}}\!.02$. From the WFPC2 data handbook we determine a zeropoint of $21^{\mathrm{m}}\!.9$ (gain 14, including an aperture correction of $-0^{\mathrm{m}}\!.1$) that has to be corrected to Cousins R by adding $-0^{\mathrm{m}}\!.65$ (assuming a spectral type of A5 for the combined spectra of our binary stars), yielding a final zeropoint of $21^{\mathrm{m}}\!.25$, in agreement with our empirically determined zeropoint. Since our empirically derived zeropoint automatically takes into account the unusual flux distribution of our binary stars we decided to use it to calculate R_{HST} given in Table B.2.

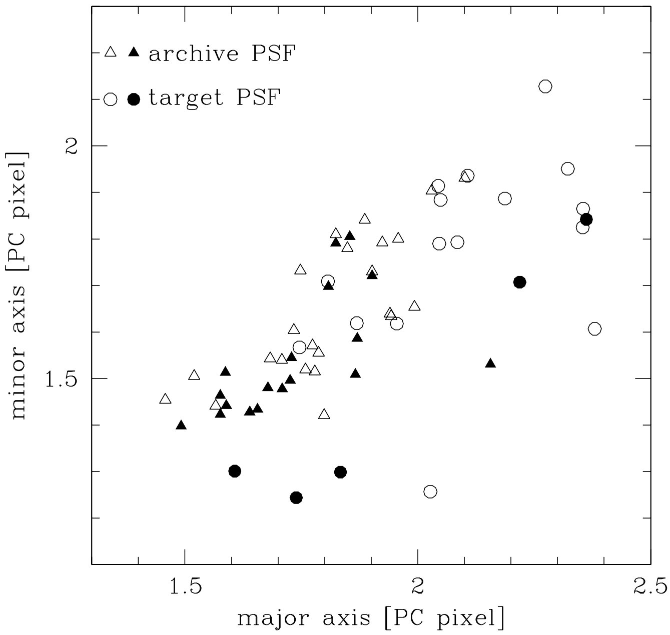

Fig. 2. The major and minor axes of the point spread functions for the target stars (circles, filled symbols mark brightest star of resolved binaries) and of archive point-spread functions (triangles, filled ones mark stars with positions on the PC chip close to our targets).

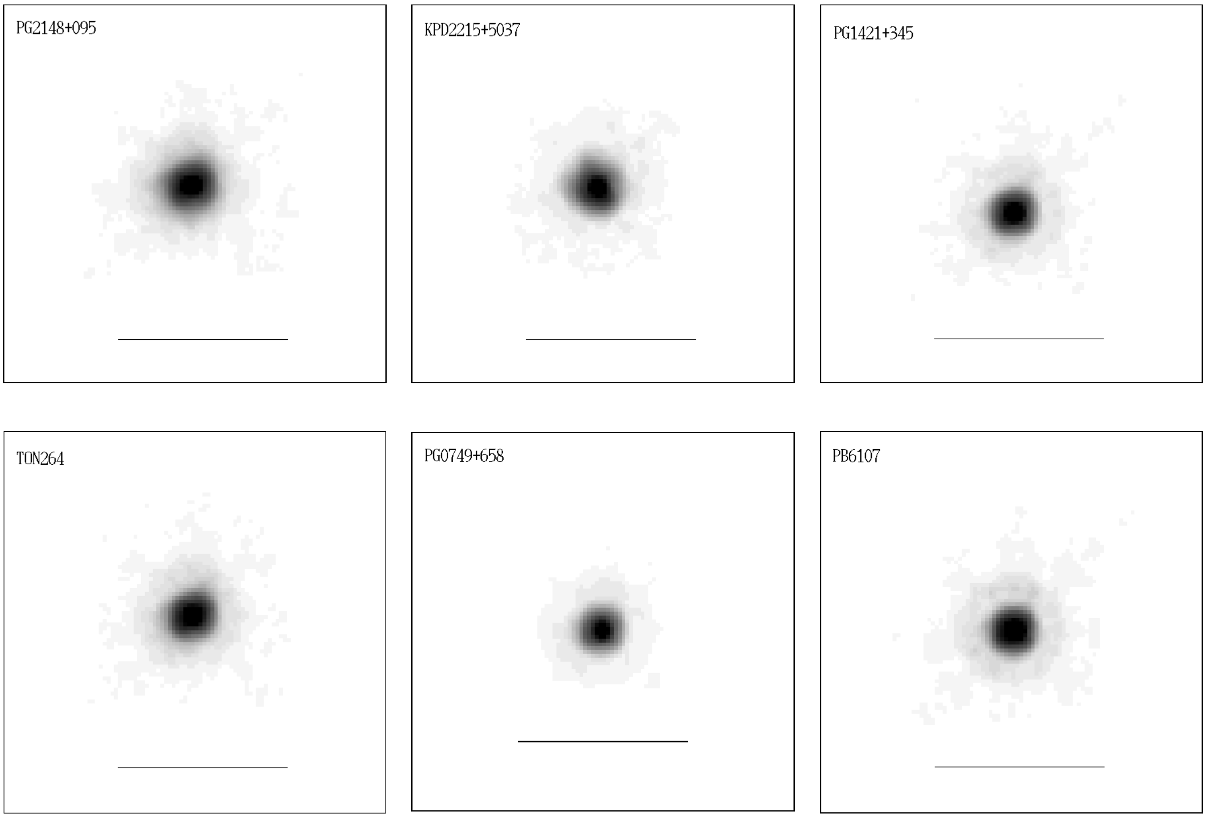

Fig. 3. The images of the unresolved stars (PG 2148+095, KPD 2215+5037, TON 264, PG 0749+658) which show deviations from the standard PSF shape (see text). The images of PB 6107 and PG 1421+345 are well matched by the standard PSF shape and are displayed for comparison. Note that – in contrast to all other stars displayed here – there is no spectroscopic evidence for binarity of KPD 2215+5037. The bar in each image corresponds to $1''$.

3. Spectral energy distribution

To obtain an upper limit to our resolution we tried to estimate the R brightness of the cool companion by fitting the available photometric data of those stars that have sufficient measurements. In order to disentangle the flux of the hot star from that of the cool star we analyse the composite spectral energy distribution. For this purpose ultraviolet, optical and infrared (spectro-) photometry is collected from literature and archives (IUE, 2MASS). To determine the contribution of the hot star we fit synthetic spectra (Kurucz 1992) to the bluest part of the observed spectral range, i.e. IUE data plus u or u/U plus v/B (if no UV data were available) and determine the effective temperature of the sdB star. In doing so we assume that the companion does not contribute to the flux in this wavelength range (cf. Fig. 5). While this is probably true for the IUE data, some contamination may be present in the u/U- and v/B-band and consequently the temperature determination for the sdB star can be compromised.

However, for some stars photometric data are so incomplete that no meaningful fit can be obtained. Aside from the $F675W$ measurements discussed here PG 0942+461 and HE 2213−2212 have only JHK photometry from 2MASS, which are insufficient for a fit. While HE 0430−2457 has BVR photometry it is still not possible to constrain the sdB star's temperature with these data as $B-V$ is insensitive to $T_{\rm eff}$ at sdB temperatures. To convert the magnitudes into flux values we used the data given in Table 3.

By comparing the measured flux in the R band to the model flux of the sdB star we derive the flux ratio of the hot vs. the cool star in the system. For those systems which should have a rather bright companion according to their photometric data we verified the flux ratio in R between sdB and cool companion from two colour diagrams similar to those used by Ferguson et al. (1984), which is best suited for components of comparable brightness (for details see Ferguson et al. 1984). With this method we found that the companion of TON 1281 is bright enough to affect also the u filter, yielding a temperature of 25 000 K to 27 000 K for the sdB instead of the 22 000 K given in Table 4 and a brightness difference ΔR of $0\overset{\mathrm{m}}{.}2$ to $-0\overset{\mathrm{m}}{.}1$. Also for PG 1601+345 we find a much smaller brightness difference ($0\overset{\mathrm{m}}{.}1$) and higher temperature (29 500 K) from this method than from our photometric fits. In this case the B filter is already affected by the cool companion. For reasons of consistency we keep the values from the photometric fits for these two stars in Table 4. For all other stars with brightness differences $\leq 0\overset{\mathrm{m}}{.}8$ the results from both

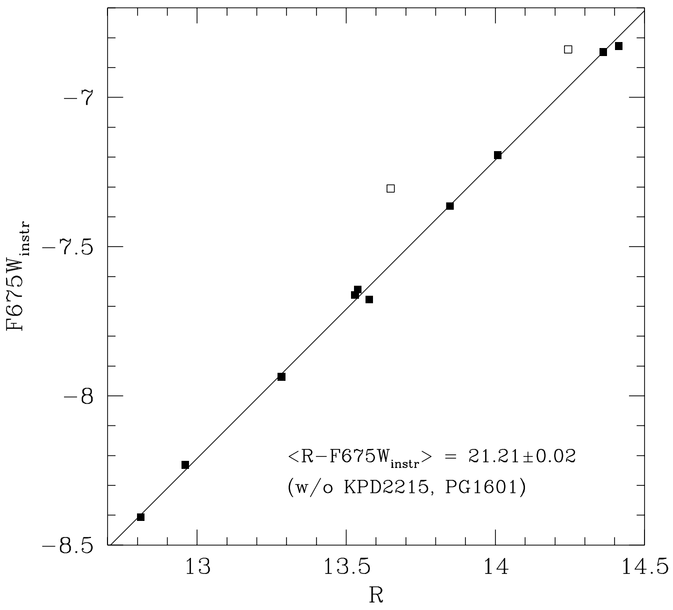

Fig. 4. The instrumental $F675W$ magnitudes compared to the $R_{\rm C}$ data from Allard et al. (1994). The open symbols are KPD 2215+5037 and PG 1601+145. The line marks the relation $R_{\rm C} = -2.5\log\frac{\mathrm{flux}_{0\overset{\prime\prime}{.}5}-\mathrm{sky}_{0\overset{\prime\prime}{.}5}}{\text{exposure time}}+21.21$.

Table 3. Flux for a star with $m_\lambda = 0$. The data are taken from Lamla (1982, p. 59, *uvby*; p. 82 $BVR_{\rm C}I_{\rm C}$), Zombeck (1990, $JHK_{\rm UT98}$) and from the 2MASS Team (priv. comm., $JHK_{\rm 2MASS}$).

filter	flux [erg/(cm^2 s Å)]	$\lambda_{\rm c}$ [Å]
u	1.169×10^{-8}	3500
v	8.444×10^{-9}	4110
b	5.826×10^{-9}	4670
y	3.700×10^{-9}	5470
U	4.187×10^{-9}	3600
B	6.597×10^{-9}	4400
V	3.607×10^{-9}	5500
$R_{\rm C}$	2.254×10^{-9}	6400
$I_{\rm C}$	1.196×10^{-9}	7900
$J_{\rm 2MASS}$	2.91×10^{-10}	12 510
$H_{\rm 2MASS}$	1.11×10^{-10}	16 280
$K_{\rm 2MASS}$	3.83×10^{-11}	22 030
$J_{\rm UT98}$	3.18×10^{-10}	12 500
$H_{\rm UT98}$	1.18×10^{-11}	16 500
$K_{\rm UT98}$	4.17×10^{-11}	22 000

methods were the same. To correct for interstellar reddening we used the reddening-to-infinity maps of Schlegel et al. (1998) which give somewhat higher values than the older data of Burstein & Heiles (1982). KPD 2215+5037, PG 1558−007, and PG 2259+134 all lie in regions of quite high reddening according to Schlegel et al. (1998) and show no spectroscopic evidence for a cool companion (see Appendix A). The observed apparent infrared excess can be explained by high interstellar reddening alone, without invoking the presence of a cool companion. We also find no evidence for a companion from available photometry of PG 1656+213, although there is spectroscopic evidence (Ferguson et al. 1984). However there are are no flux measurements redwards of V available and B and V fluxes are inconsistent. Therefore we keep PG 1656+213 as a programme star.

Aznar Cuadrado & Jeffery (2001) present an extensive discussion of sdB parameters derived from energy distributions, which also includes some of the stars discussed in this paper. In Table 5 we present the temperatures given in their paper and other values collected from literature in comparison to the ones derived here. As can be seen from Table 5 differences of ±10% in $T_{\rm eff}$ between different authors are quite common.

The temperatures derived from the photometric data and from line profile fits for the stars in regions with high reddening agree moderately well (compare Tables 4 and A.1). The discrepancies may be due to small scale variations in reddening that affect the temperatures derived from photometry but not those derived from line profile fits.

From the photometric fit we can derive the apparent R magnitudes of the sdB and of the cool star and correct both for interstellar extinction. The uncertainty in $T_{\rm eff}$ of about ±10% evident from Table 5 causes an estimated uncertainty in the derived brightness for both components of $\pm0\overset{\rm m}{.}2$. Knowing the absolute R magnitude of the sdB stars then allows to determine their distance. We use the mean M_V derived by Moehler et al. (1997) for hot subdwarfs in the globular cluster NGC 6752. They found two groups of hot subdwarfs, a cooler one with a mean effective temperature of 22 000 K and $< M_V > = 3\overset{\rm m}{.}2$ (5 stars), and a hotter one with $<T_{\rm eff}> = 29\,000$ K and $< M_V > = 4\overset{\rm m}{.}2$ (12 stars). From Kurucz (1992) model atmospheres for [M/H] = 0 we find $V - R = -0\overset{\rm m}{.}120$ for $T_{\rm eff} = 22\,000$ K and $-0\overset{\rm m}{.}152$ for 29 000 K. We therefore use $M_R = 3\overset{\rm m}{.}3$ for stars cooler than 25 000 K and $M_R = 4\overset{\rm m}{.}4$ for hotter stars.

Using the archive point spread functions we estimated the minimum separation that we can resolve for a given brightness difference by adding two PSFs with a defined brightness difference and angular separation and examining the resulting image by eye. We find the following resolution limits: $\Delta\alpha_{\rm lim}$ (ΔR) = $0\overset{\prime\prime}{.}2$ ($2\overset{\rm m}{.}0$), $0\overset{\prime\prime}{.}1$ ($1\overset{\rm m}{.}5$), $0\overset{\prime\prime}{.}07$ ($1\overset{\rm m}{.}0$), $0\overset{\prime\prime}{.}05$ ($0\overset{\rm m}{.}5$). Using the distances determined above we can now derive upper limits for the linear separation of the unresolved binaries (cf. Table 4), ranging from 50 AU to 210 AU.

Table 2 shows that the brightness differences between the components in TON 1281 and HE 0430−2457 are too large to reproduce the spectral energy distribution of TON 1281 and the photometry of HE 0430−2457, respectively. The large brightness difference of $3\overset{\rm m}{.}1$ (from the WFPC2 data) for PG 1558−007 agrees with the lack of photometric and spectroscopic evidence for a companion. In the remaining two cases (PG 1718+519, TON 139) the brightness differences in Table 2 are somewhat larger than those derived from the spectral energy distribution. To see whether we can in principle accommodate the HST observations by fits to the photometric data we repeated the

Table 4. Estimated temperature of sdB stars, resulting reddening-free brightness of subdwarf B star ($R_{\rm sdB,0}$) and companion ($R_{\rm comp,0}$), distance d, brightness difference ΔR, and upper limit for linear separation $a_{\rm lim}$ derived from upper limit of angular separation $\Delta\alpha_{\rm lim}$. The reddening estimates are from the maps of Schlegel et al. (1998) and we used $A_R = 2.6 \cdot E_{B-V}$. The three different temperatures for PG 1511+624 result from the three available SWP spectra. If no evidence for a companion can be found from available photometry no entry is given in Col. 4.

Star	$T_{\rm eff,sdB}$ [K]	A_R	$R_{\rm comp,0}$	$R_{\rm sdB,0}$	$M_{R,\rm sdB}$	d [pc]	ΔR	$\Delta\alpha_{\rm lim}$	$a_{\rm lim}$ [AU]
PB 6107	23 000	$0^{\rm m}.086$	$14^{\rm m}.4$	$13^{\rm m}.0$	$3^{\rm m}.3$	870	$1^{\rm m}.4$	$0''.1$	87
PG 0105+276	32 000	$0^{\rm m}.156$	$15^{\rm m}.8$	$14^{\rm m}.4$	$4^{\rm m}.4$	1100	$1^{\rm m}.4$	$0''.1$	110
PHL 1079	25 000	$0^{\rm m}.104$	$14^{\rm m}.9$	$13^{\rm m}.4$	$4^{\rm m}.4$	630	$1^{\rm m}.5$	$0''.1$	63
PG 0749+658	22 000	$0^{\rm m}.125$	$14^{\rm m}.4$	$12^{\rm m}.1$	$3^{\rm m}.3$	580	$2^{\rm m}.3$	$0''.2$	116
TON 1281	22 000	$0^{\rm m}.065$	$14^{\rm m}.4$	$13^{\rm m}.6$	$3^{\rm m}.3$	1150	$0^{\rm m}.8$	$0''.07$	80
TON 139	20 000	$0^{\rm m}.026$	$13^{\rm m}.6$	$13^{\rm m}.2$	$3^{\rm m}.3$	950	$0^{\rm m}.4$	$0''.05$	48
PG 1309−078	24 000	$0^{\rm m}.138$	$15^{\rm m}.5$	$14^{\rm m}.2$	$3^{\rm m}.3$	910	$1^{\rm m}.3$	$0''.1$	91
PG 1421+345	24 000	$0^{\rm m}.044$	$16^{\rm m}.0$	$14^{\rm m}.9$	$3^{\rm m}.3$	2100	$0''.1$	210	
PG 1449+653	28 000	$0^{\rm m}.042$	$14^{\rm m}.7$	$14^{\rm m}.0$	$4^{\rm m}.4$	830	$0^{\rm m}.7$	$0''.07$	58
PG 1511+624	31 000	$0^{\rm m}.047$	$15^{\rm m}.7$	$14^{\rm m}.8$	$4^{\rm m}.4$	1200	$0^{\rm m}.9$	$0''.07$	84
	28 000		$15^{\rm m}.8$	$14^{\rm m}.8$	$4^{\rm m}.4$	1200	$1^{\rm m}.0$	$0''.07$	84
	33 000		$15^{\rm m}.6$	$14^{\rm m}.9$	$4^{\rm m}.4$	1260	$0^{\rm m}.7$	$0''.07$	88
PG 1558−007	23 000	$0^{\rm m}.468$		$13^{\rm m}.1$	$3^{\rm m}.3$	910			
PG 1601+145	25 000	$0^{\rm m}.133$	$15^{\rm m}.2$	$14^{\rm m}.6$	$4^{\rm m}.4$	1100	$0^{\rm m}.6$	$0''.07$	77
PG 1636+104	20 000	$0^{\rm m}.156$	$14^{\rm m}.5$	$13^{\rm m}.7$	$3^{\rm m}.3$	1200	$0^{\rm m}.8$	$0''.07$	84
PG 1656+213	17 000	$0^{\rm m}.172$		$14^{\rm m}.6$	$3^{\rm m}.3$	1800			
TON 264	26 000	$0^{\rm m}.146$	$16^{\rm m}.0$	$14^{\rm m}.1$	$4^{\rm m}.4$	870	$1^{\rm m}.9$	$0''.2$	174
PG 1718+519	27 000	$0^{\rm m}.081$	$14^{\rm m}.1$	$14^{\rm m}.3$	$4^{\rm m}.4$	950	$-0^{\rm m}.2$	$0''.05$	48
PG 2148+095	26 000	$0^{\rm m}.169$	$14^{\rm m}.5$	$13^{\rm m}.0$	$4^{\rm m}.4$	520	$1^{\rm m}.5$	$0''.1$	52
KPD 2215+5037	35 000	$0^{\rm m}.871$		$12^{\rm m}.8$	$4^{\rm m}.4$	480			
PG 2259+134	30 000	$0^{\rm m}.341$		$14^{\rm m}.4$	$4^{\rm m}.4$	1000			
BD $-7^\circ 5977$	29 000	$0^{\rm m}.093$	$10^{\rm m}.2$	$11^{\rm m}.9$	$4^{\rm m}.4$	320	$-1^{\rm m}.7$	$0''.2$	64

Table 5. Effective temperatures for sdB stars derived from energy distributions by various authors. The sources are Aznar Cuadrado & Jeffery (2001, ACJ01), Allard et al. (1994, A94), Theissen et al. (1993, T93; 1995, T95), Ulla & Thejll (1998, UT98).

star	$T_{\rm eff}$ [K] derived by					
	this paper	ACJ01	T93	A94	T95	UT98
PB 6107	23 000			25 000		
PG 0105+276	32 000	35 850		32 000		
PHL 1079	25 000		26 350		30 000	30 000
PG 0749+658	22 000	25 050		23 500		
TON 1281	22 000	23 275		29 500		
TON 139	20 000					18 000
PG 1449+653	28 000	28 150		28 000		
PG 1511+624	31 000:			33 000		
PG 1636+104	20 000			21 000		
TON 264	26 000			28 500		
PG 1718+519	27 000	29 950	23 500	25 000	30 000	
PG 2148+095	26 000	22 950		26 000		25 000
KPD 2215+5037	35 000			24 500		
PG 2259+134	30 000	28 300	28 500		22 500	

fits, this time enforcing the brightness difference in the R band obtained from the HST data. The results are shown in Fig. 5 (in comparison to the original fits). Obviously the companion of PG 1718+519 is sufficiently bright to affect also the u filter, thereby rendering our assumption that this filter is unaffected by the cool companion obsolete. The fits for TON 139 do not show much difference. We conclude that the spectral energy distribution of TON 139 and PG 1718+519 are consistent with the R band flux ratio measured with the HST WFPC2 camera.

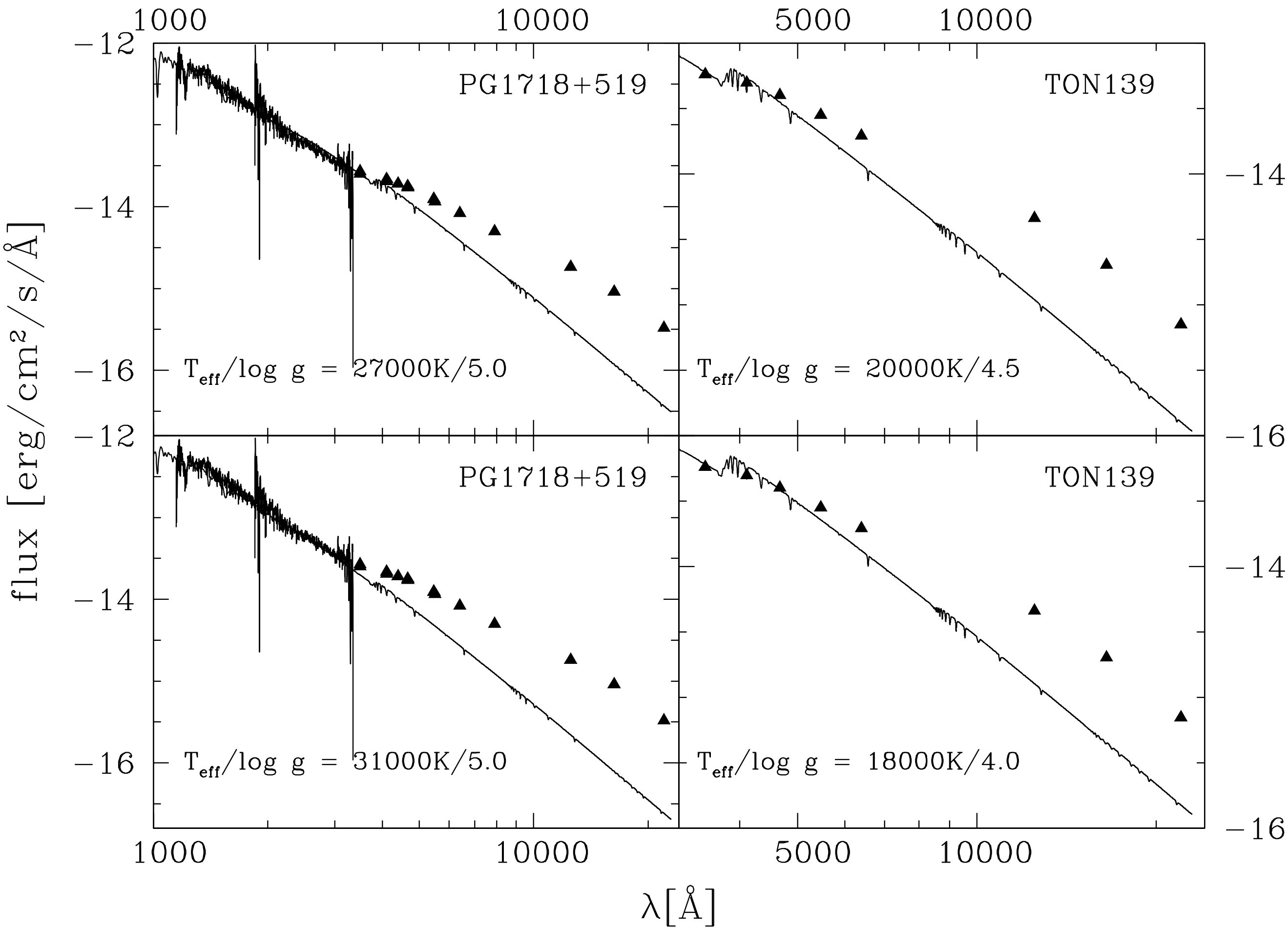

Fig. 5. Fits of ATLAS9 model spectra (Kurucz 1992, [M/H] = 0) to the photometric data of PG 1718+519 (left panel, including IUE spectra) and TON 139 (right panel). The upper panels show the fits obtained assuming that the bluest photometric data points (IUE spectra and u for PG 1718+519, u and v for TON 139) are not affected by the cool companion. The lower panels show fits that reproduce the brightness differences measured on the WFPC2 images.

3.1. The sdO star PG 0105+276

Since the He-sdO PG 0105+276 does not belong to the programme sample, we discuss it separately. It is the only programme star that is resolved into three components. However, the two companions are quite distant from the primary ($3\farcs37$ and $4\farcs48$, respectively). The light of these companions can explain at least qualitatively the IR excess observed by ground based aperture photometry. The spectrum of PG 0105+276, however, does not show any signature of a cool companion, probably because due to the orientation and the small width of the slit no light of the distant companions was included. The diaphragm used in the photometry was large ($18''$) and included the companions' light.

The brightness differences measured on the WFPC2 image ($0\overset{\mathrm{m}}{.}9$, $1\overset{\mathrm{m}}{.}6$) for PG 0105+276 are smaller than the one derived from the photometric fit ($1\overset{\mathrm{m}}{.}4$), i.e. one companion is brighter than expected. However, as discussed in Appendix A, the true temperature (from line profile fitting) is much higher than the one obtained from the spectral energy distribution (63 000 K vs. 35 000 K) making the companion's luminosity obtained from photometry a lower limit only.

4. Simulation of separability in binary systems

In order to interpret our results with respect to the different evolutionary scenarios we simulate binary systems containing main sequence (MS) companions and sdBs with period distributions found for normal main sequence binaries (Duquennoy & Mayor 1991). Assuming that the sdB mass is $0.5\,M_{\odot}$ and the MS companion mass is $1\,M_{\odot}$ we convert the period distribution published by Duquennoy & Mayor (1991) to physical separations using Kepler's Harmonic law. The orientation of the axis of the system is then chosen to be random in space and the projected separation, or $a \sin i$, is calculated, given the distance to the system which is found from the apparent and absolute brightness of the system. The orbits are assumed to be circular.

Based on the spectroscopic distances derived above (see Table 4) we then simulate a huge number of such binary systems. For three stars (HE 0430−2457, PG 0942+461, and HE 2213−2212) the magnitude ratio of the components could not be determined and therefore the distances are unknown. We adopted the mean value of the other stars ($\Delta R = 1\overset{\mathrm{m}}{.}1$), which is consistent with their spectral appearance (see Fig. A.1). The numerical simulation predicts a mean value of $a \sin i = 0\overset{''}{.}04$ and that, out of the 19 observed systems, we should resolve six systems at a resolution limit of $0\overset{''}{.}1$, one of which should show a separation greater than $1\overset{''}{.}0$.

Since the orbital motion for an eccentric orbit is lower during phases of large separation, the time averaged distance is larger than the semi major axis. Thus eccentric orbits would increase the detectability. Duquennoy & Mayor (1991) also provide a distribution of ellipticities for normal stars. If the sdB systems did not experience phases of binary interaction, the distribution of eccentricity should correspond to that of normal stars. We used Duquennoy & Mayor's distribution corrected for selection effects. For each eccentricity the ratio of the time averaged distance to a was calculated and finally the mean over the Duquennoy & Mayor distribution was computed. We find the average distance of the companions to increase by 17%. Another mechanism that tends to increase the separation of the components in a sdB binary is mass loss during post-main sequence evolution in order to reduce the mass of the sdB progenitor to its present value of half a solar mass. Assuming that the sdB evolved from a $1\,M_{\odot}$ main sequence progenitor it must have lost $0.5\,M_{\odot}$ due to a stellar wind during its post-main sequence evolution. Assuming that the wind emanates in a spherical symmetric manner and does not interact with the companion the increase in separation can be calculated according to $\frac{\dot{a}}{a} = -\frac{\dot{M}_{\mathrm{s}}}{M_{\mathrm{s}}+M_{\mathrm{c}}}$ (Pringle 1985), with a being the separation and M_{s} and M_{c} the masses of the sdB progenitor and that of the cool star, respectively. As a result the separation increases by 33%.

We repeated the Monte Carlo simulations for increased separations. Even when we consider both elliptical orbits and evolution of the orbits due to a stellar wind as described above the prediction increased only slightly to 7 resolvable stars in our sample.

Hence we predict that 6 to 7 stars should be resolvable in our sample if the systems have separations consistent with the Duquennoy & Mayor (1991) distribution.

5. Chance projections and triple systems

In the vicinity of five programme stars we found an additional object within a radius of $3\overset{''}{.}0$[1]. We have demonstrated above that only in two cases (TON 139 and PG 1718+519) the relative brightnesses are consistent with the expectations from the deconvolution of the spectral energy distribution. The remaining three cases must then be chance projections or triple systems. Since the programme stars lie at high galactic latitudes (except KPD 2215+5037, see Table 1), we expect chance coincidences to be rare. Indeed, we do not find any additional object in the PC field ($40'' \times 40''$) except for the low galactic latitude object KPD 2215+5037.

According to Abt & Levy (1976) 16% of multiple systems of normal stars are triples. If the fraction of triple systems is the same for our sample, we expect three programme stars to be triple. Most of these, if not all, should be resolvable. Besides TON 139 and PG 1718+519 we find in three cases companions to the sdB stars which are too faint to match the spectral energy distribution. These could be triple systems consisting of an unresolved sdB binary and a distant third star.

[1] Note that PG 0105+276, which is resolved in three components (see Fig. 1), is an sdO star and does not belong to our sdB sample.

6. Radial velocities

Important additional information can be obtained from radial velocity measurements. A systematic search for radial velocity variations of our programme stars is needed. Such projects have already been started by Saffer et al. (2001) and Maxted et al. (2001) who observed six of our programme stars (PB 6107, PHL 1079, PG 0749+658, TON 1281, PG 1449+653 and PG 2148+095). None of them showed significant radial velocity changes.

Saffer et al. (2001) find in their survey of 21 composite spectrum sdB stars that the velocity variations of the individual components as well as the velocity difference between the two components are very small (less than a few $\mathrm{km\,s^{-1}}$) or undetectable, and conclude that the binaries have likely periods of many months to several years. Green et al. (2001) estimate from these measurements that the current periods average 3–4 years with separations 540–650 $R_{\odot}$.

We have obtained multiple precise radial velocities for TON 139 and a single measurement of PG 1718+519 using the MMT Blue Channel spectrograph at 1 Å resolution from 4000–4930 Å (see Table 6). The radial velocities of the cool companions were determined by cross correlation against super-templates of main sequence spectral types from F6 to K5. The sdB velocities were derived using a preliminary attempt at subtracting out the cool star companion spectrum. For details of the data reduction and analysis see Saffer et al. (2001). Improved sdB velocities using better cool star template spectra for the subtractions will be determined by Green et al. (2002, in prep.).

For TON 139 the cool star's velocity is constant, whereas the sdB velocity is changing by more than $50\,\mathrm{km\,s^{-1}}$. This can be explained if an additional companion is orbiting the sdB star. This companion has to be so faint that it does not contribute to the light in the R band. Hence we have to conclude that the resolved system TON 139 is a triple system. A radial velocity study of PG 1718+519, the second resolved system in our sample, is not available yet. The single measurement listed in

Table 6. Heliocentric radial velocities for the sdB- and the cool star components of TON 139 and PG 1718+519.

star	date UT	HJD-2450000	exposure time [s]	S/N	$v_{\rm rad}$ [km s^{-1}] (sdB component)	$v_{\rm rad}$ [km s^{-1}] (cool companion)
TON 139	1996-01-14	96.91396	600	95.6	-6.3 ± 4.9	19.9 ± 0.6
TON 139	1996-03-11	153.84515	300	71.9	-7.4 ± 7.8	20.2 ± 0.7
TON 139	1996-06-09	243.75586	600	66.5	-13.1 ± 8.4	21.8 ± 0.8
TON 139	1997-01-28	476.96939	1800	69.4	-20.2 ± 7.9	20.2 ± 0.9
TON 139	1997-07-04	633.66734	500	72.7	32.6 ± 6.7	22.4 ± 0.7
TON 139	1998-01-22	836.03834	750	82.9	-22.1 ± 9.1	20.7 ± 0.6
TON 139	mean				-3.6 ± 20.2	20.8 ± 1.0
PG1718+519	1997-09-10	701.71120	1400.0	82.0	-69.2 ± 10.1	-68.0 ± 0.9

Table 6 gives identical radial velocities for the sdB and the cool companion. This argues against a third faint component orbiting the sdB star in a narrow orbit as was found for TON 139. Additional radial velocity measurements are urgently needed to clarify the nature of PG 1718+519. Assuming that PG 1718+519 is not triple, this would be the only resolved binary system in our sample of 19 objects.

7. Conclusions

In total we have resolved six systems out of a sample of 23 stars. Of those 23 stars, however, four do not really belong to the intended sample of sdB stars showing evidence for a cool companion: PG 1558−007, KPD 2215+5037, and PG 2259+134 show no photometric or spectroscopic evidence for a companion. The observed infrared excess can be explained by interstellar reddening rather than by a cool companion.

PG 1558−007 does have a resolved near-by star (linear separation 1500 AU), which, however, is too faint to contribute detectably to the combined light in the R band. PG 0105+276 is a helium-rich sdO star (with two possible distant companions at 3700 AU and 4900 AU).

Of the remaining four resolved systems the nearby stars are in two case (TON 1281, HE 0430−2457) too faint to reproduce the photometric and/or spectroscopic observations of the stars.

Only in the two systems TON 139 and PG 1718+519 (separations $0\farcs32$ and $0\farcs24$, respectively) do the magnitudes of the resolved components match the expectations. These two stars could be physical binaries whereas in the other cases the nearby star may be a third component or a chance projection. Radial velocity measurements indicate, however, that the resolved system TON 139 is also triple.

Hence, the observed sdB binary sample was reduced to 19 objects with two bona-fide resolved systems, which have apparent separations of $0\farcs24$ and $0\farcs32$. From the numerical simulations we would expect to resolve six to seven systems if sdB stars have the same binary characteristics as normal stars, out of which one system is expected to have $a \sin i > 1''$ and two should have separations between $0\farcs1$ and $0\farcs2$. The discrepancy becomes even more pronounced if one recalls that our photometric fit procedure tends to underestimate the brightness of the companion (and thus to overestimate the limiting angular separation that can still be resolved). In addition we expect three triple systems to be present in our sample. Most of these, if not all, should be resolvable. Such systems could explain some of the more distant companions as well as the radial velocity measurements of TON 139.

This success rate (1 resolved binary out of 19 candidates) is clearly *below* the prediction of numerical simulations assuming single star evolution (about 30%), using the distribution of binary separations given by Duquennoy & Mayor (1991). This indicates that the distribution of separations of sdB binaries strongly deviates from that of normal stars.

If, on the other hand, all sdB stars were produced by close binary evolution, none of the binary systems should have been resolved (even at the high spatial resolution of the WFPC2 camera). Our low success rate is thus closer to that predicted by the close binary evolutionary scenario. Recent radial velocity surveys (Saffer et al. 2001; Maxted et al. 2001) revealed that a large fraction of single-lined sdB stars are indeed close binaries with periods below 10 days. Our results could be explained if most of the programme stars were close binaries. Therefore, our study provides further evidence that close binary evolution indeed is fundamental to the evolution of sdB stars. A survey for radial velocity variations in all of our programme stars will be tale telling.

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Appendix A: Spectroscopic observations and data reduction

The observational setups and observing dates for the new spectra are given in Table A.1. The reduction of the

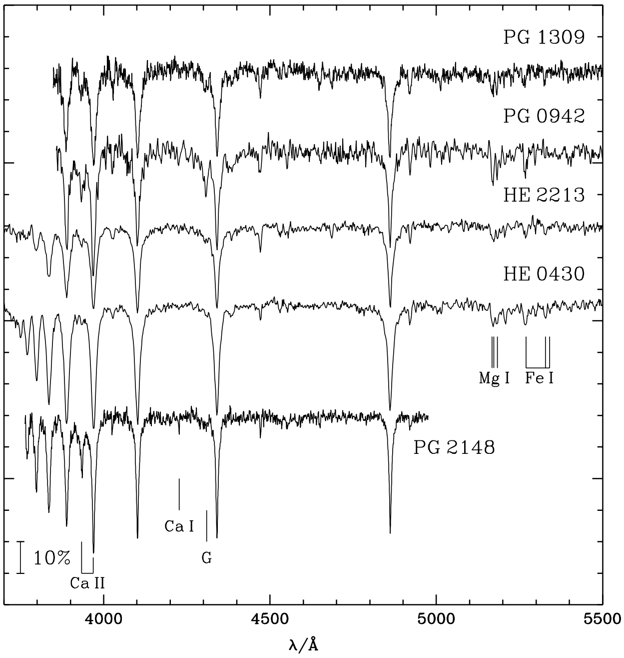

Fig. A.1. Comparison of normalized spectra of four programme stars to PG 1309−078, which is already known to be a spectroscopic binary containing an sdB. The spectral features indicative of a cool companion are marked.

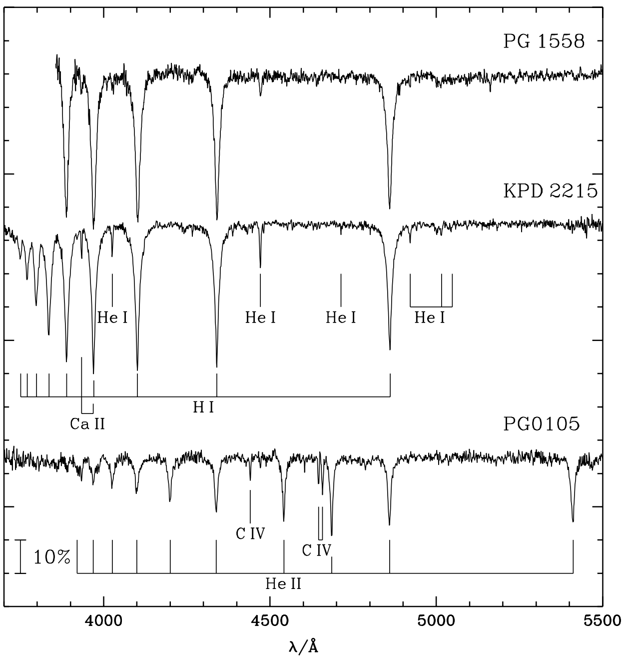

Fig. A.2. Optical spectra of the sdB stars PG 1558−007 and KPD 2215+5037 as well as of the sdO star PG 0105+276. The spectra of the former are dominated by hydrogen lines, that of the latter by He II lines.

spectra of PG 0105+276, HE 0430−2457, PG 0942+461, HE 2213−2212, and KPD 2215+5037 are described by Edelmann et al. (2001b). PG 2148+095 was observed and reduced as described by de Boer et al. (1995), the reduction of PG 1309−078 and PG 1558−007 was performed in the same way as described in Moehler et al. (1997).

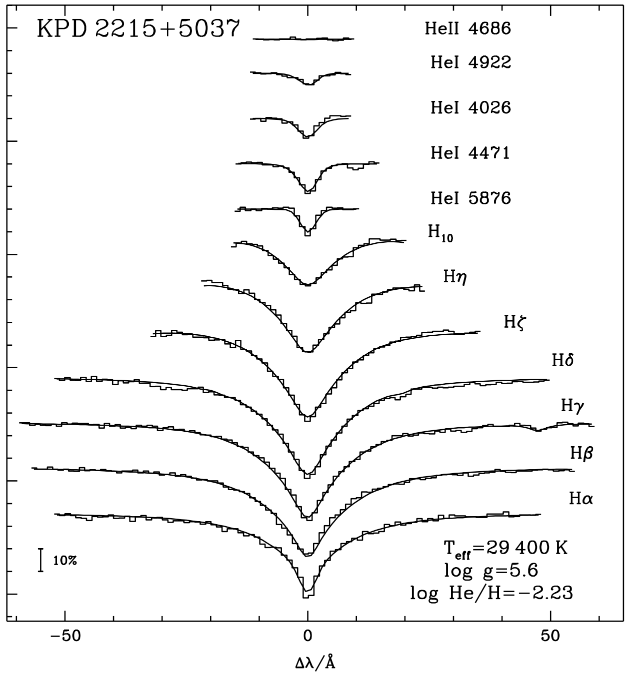

Fig. A.3. Spectral fit for the sdB star KPD 2215+5037. Hϵ is excluded from the fit because of contamination by interstellar Ca II.

Figure A.2 shows the spectra of the stars that show no spectroscopic or photometric evidence for a cool companion (PG 1558−087, KPD 2215+5037, and PG 0105+276). The Ca II absorption lines in the spectra of these stars (see Fig. A.2) are probably of interstellar nature. Our spectrum clearly shows that PG 0105+276 is a helium rich sdO star (see Fig. A.2) inconsistent with the photometric classification as sdB+K7 by Allard et al. (1994, where all three stars seen in Fig. 1 were included in the measurements) but in accordance with the early spectroscopic classification by Green et al. (1986).

We derived the atmospheric parameters $T_{\rm eff}$, log g and helium abundance simultaneously for the single stars by matching a grid of synthetic spectra derived from H and He line blanketed NLTE model atmospheres (Napiwotzki 1997) to the data. For temperatures below 27 000 K we used the metal line blanketed LTE model atmospheres of Heber et al. (2000). The synthetic spectra were convolved beforehand with a Gaussian profile of the appropriate *FWHM* to account for the instrumental profile. Results are given in Table A.1 and Fig. A.3 displays the fit for KPD 2215+5037 as an example.

Appendix B: Photometric data for our programme stars

In Tables B.1 and B.2 we compile the photometric data collected from literature and used in the photometric deconvolution.

Table A.1. New optical spectroscopy and atmospheric parameters of single programme stars.

star	telescope and spectrograph	wavelength range [Å]	spectral resolution [Å]	obs. date	$T_{\rm eff}$ [K]	log g [cgs]	log(He/H)
PG 0105+276	CA 3.5m TWIN	3600–7400	3.1	1997/08/31	63 000	5.4	+0.5
HE 0430−2457	ESO 1.5m B&C	3600–7450	5.5	1996/10/22			
PG 0942+461	CA 3.5m B&C	3860–5560	5.0	1989/01/23			
PG 1309−078	ESO 1.5m DFOSC	3860–6780	5.4	2000/06/21			
PG 1558−007	ESO 1.5m DFOSC	3860–6780	5.4	2000/06/21	20 300	5.0	−2.6
PG 2148+095	ESO 1.5m B&C	3730–4970	3.0	1991/07/10-15			
HE 2213−2212	ESO 1.5m B&C	3600–7400	5.5	1996/10/23			
KPD 2215+5037	CA 3.5m TWIN	3260–7450	3.1	1997/08/29	29 400	5.6	−2.2
PG 2259+134		Theissen et al. (1993)			31 900	5.9	−1.7

Table B.1. Strömgren photometry and UV spectrophotometry for our programme stars. Strömgren photometry is taken from Green (1980, G80), Kilkenny (1984, K84; 1987, K87), Moehler et al. (1990, M90), Theissen et al. (1993, T93), Wesemael et al. (1992, W92). The IUE data were obtained from the IUE final archive (`http://archive.stsci.edu/iue/`).

Star	y	$b-y$	$u-b$	m_1	c_1	Ref.	IUE SWP	IUE LWP
PB 6107	$12^{\rm m}.897$	$+0^{\rm m}.032$	$+0^{\rm m}.112$	$+0^{\rm m}.052$		W92		
	$12^{\rm m}.889$	$+0^{\rm m}.026$		$+0^{\rm m}.092$	$-0^{\rm m}.094$	M90		
	$12^{\rm m}.89$	$+0^{\rm m}.01$	$+0^{\rm m}.10$	$+0^{\rm m}.05$		G80		
	$12^{\rm m}.907$	$+0^{\rm m}.018$		$+0^{\rm m}.093$	$-0^{\rm m}.109$	K87		
PG 0105+276	$14^{\rm m}.481$	$+0^{\rm m}.022$	$-0^{\rm m}.194$	$+0^{\rm m}.023$		W92	56 271	
PHL 1079	$13^{\rm m}.278$	$+0^{\rm m}.003$	$+0^{\rm m}.106$		$-0^{\rm m}.109$	K84	42 338	21 098
PG 0749+658	$12^{\rm m}.135$	$-0^{\rm m}.032$	$+0^{\rm m}.131$	$+0^{\rm m}.087$		W92		
TON 1281	$13^{\rm m}.371$	$+0^{\rm m}.094$	$+0^{\rm m}.175$	$+0^{\rm m}.065$		W92	56 384	
TON 139	$12^{\rm m}.796$	$+0^{\rm m}.111$	$+0^{\rm m}.364$	$+0^{\rm m}.055$		W92		
PG 1309−078	$14^{\rm m}.11$	$+0^{\rm m}.07$	$+0^{\rm m}.06$	$+0^{\rm m}.18$		G80		
PG 1449+653	$13^{\rm m}.580$	$+0^{\rm m}.041$	$+0^{\rm m}.047$	$+0^{\rm m}.034$		W92	34 298	
PG 1511+624	$14^{\rm m}.421$	$+0^{\rm m}.049$	$-0^{\rm m}.002$	$+0^{\rm m}.005$		W92	39 370, 57 359, 57 361	18 491
PG 1558−007	$13^{\rm m}.528$	$-0^{\rm m}.011$	$+0^{\rm m}.244$	$+0^{\rm m}.091$		W92		
PG 1636+104	$14^{\rm m}.090$	$+0^{\rm m}.169$	$+0^{\rm m}.426$	$+0^{\rm m}.056$		W92		
PG 1656+213							39 422	18 542
TON 264	$14^{\rm m}.070$	$+0^{\rm m}.008$	$-0^{\rm m}.053$	$+0^{\rm m}.070$		W92	39 422	18 542
PG 1718+519	$13^{\rm m}.686$	$+0^{\rm m}.102$	$+0^{\rm m}.307$	$+0^{\rm m}.084$		W92	41 571	20 308
	$13^{\rm m}.694$	$+0^{\rm m}.131$		$+0^{\rm m}.094$	$-0^{\rm m}.095$	T93		
PG 2148+095	$13^{\rm m}.037$	$+0^{\rm m}.028$	$+0^{\rm m}.087$	$+0^{\rm m}.066$		W92	56 148	
KPD 2215+5037	$13^{\rm m}.739$	$-0^{\rm m}.026$	$+0^{\rm m}.034$	$+0^{\rm m}.068$		W92		
PG 2259+134	$14^{\rm m}.478$	$-0^{\rm m}.038$		$+0^{\rm m}.082$	$-0^{\rm m}.089$	M90	44 821, 56 182	23 244
PG 2259+134	$14^{\rm m}.545$	$-0^{\rm m}.069$	$-0^{\rm m}.011$	$+0^{\rm m}.088$		W92		
BD −7°5977							31 030	10 815

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Table B.2. *BVRI* (Allard et al. 1994), *UBVI* (Ferguson et al. 1984), HST *R* (this paper) and infrared broadband photometry (UT98: Ulla & Thejll 1998, 2MASS: 2MASS 2nd incremental data release, `http://irsa.ipac.caltech.edu/applications/2MASS/BasicSearch/`) for our programme stars.

Star	V	$B-V$	$V-R$	$R-I$	$R_{\rm HST}$	J	H	K	Ref.
PB 6107	$12^{\rm m}.881$	$-0^{\rm m}.038$	$+0^{\rm m}.070$	$+0^{\rm m}.096$	$12^{\rm m}.80$				
PG 0105+276	$14^{\rm m}.448$	$-0^{\rm m}.087$	$+0^{\rm m}.086$	$+0^{\rm m}.127$	$14^{\rm m}.36$	$14^{\rm m}.347$	$13^{\rm m}.821$	$13^{\rm m}.721$	2MASS
PHL 1079					$13^{\rm m}.24$	$12^{\rm m}.55$	$12^{\rm m}.23$	$12^{\rm m}.04$	UT98
HE 0430−2457	$14^{\rm m}.155$[1]	$-0^{\rm m}.046$[1]	$+0^{\rm m}.085$[1]		$14^{\rm m}.07$	$13^{\rm m}.619$	$13^{\rm m}.315$	$13^{\rm m}.208$	2MASS
PG 0749+658	$12^{\rm m}.121$	$-0^{\rm m}.106$	$+0^{\rm m}.021$	$+0^{\rm m}.072$	$12^{\rm m}.14$				
PG 0942+461					$13^{\rm m}.96$	$13^{\rm m}.612$	$13^{\rm m}.172$	$13^{\rm m}.084$	2MASS
TON 1281	$13^{\rm m}.439$	$+0^{\rm m}.094$	$+0^{\rm m}.156$	$+0^{\rm m}.176$	$13^{\rm m}.27$	$12^{\rm m}.758$	$12^{\rm m}.503$	$12^{\rm m}.448$	2MASS
TON 139					$12^{\rm m}.65$	$12^{\rm m}.10$	$11^{\rm m}.92$	$11^{\rm m}.93$	UT98
PG 1309−078					$14^{\rm m}.05$	$13^{\rm m}.558$	$13^{\rm m}.259$	$13^{\rm m}.162$	2MASS
PG 1449+653	$13^{\rm m}.611$	$-0^{\rm m}.035$	$+0^{\rm m}.073$	$+0^{\rm m}.110$	$13^{\rm m}.57$				
PG 1511+624	$14^{\rm m}.527$	$-0^{\rm m}.022$	$+0^{\rm m}.113$	$+0^{\rm m}.142$	$14^{\rm m}.38$	$14^{\rm m}.114$	$13^{\rm m}.813$	$13^{\rm m}.883$	2MASS
PG 1558−007	$13^{\rm m}.541$	$-0^{\rm m}.064$	$+0^{\rm m}.012$	$+0^{\rm m}.110$	$13^{\rm m}.55$				
PG 1601+145	$14^{\rm m}.424$	$+0^{\rm m}.028$	$+0^{\rm m}.180$	$+0^{\rm m}.347$	$14^{\rm m}.37$	$13^{\rm m}.918$	$13^{\rm m}.578$	$13^{\rm m}.600$	2MASS
PG 1636+104	$14^{\rm m}.039$	$+0^{\rm m}.193$	$+0^{\rm m}.191$	$+0^{\rm m}.196$	$13^{\rm m}.85$				
TON 264	$14^{\rm m}.074$	$-0^{\rm m}.083$	$+0^{\rm m}.066$	$+0^{\rm m}.136$	$14^{\rm m}.02$				
PG 1718+519	$13^{\rm m}.733$	$+0^{\rm m}.113$	$+0^{\rm m}.156$	$+0^{\rm m}.132$	$13^{\rm m}.53$	$13^{\rm m}.008$	$12^{\rm m}.716$	$12^{\rm m}.664$	2MASS
PG 2148+095	$13^{\rm m}.021$	$-0^{\rm m}.024$	$+0^{\rm m}.060$	$+0^{\rm m}.096$	$12^{\rm m}.98$	$12^{\rm m}.18$	$12^{\rm m}.34$	$12^{\rm m}.06$	UT98
HE 2213−2212					$14^{\rm m}.01$	$13^{\rm m}.686$	$13^{\rm m}.292$	$13^{\rm m}.236$	2MASS
KPD 2215+5037	$13^{\rm m}.664$	$-0^{\rm m}.093$	$+0^{\rm m}.015$	$+0^{\rm m}.052$	$13^{\rm m}.91$				
PG 2259+134					$14^{\rm m}.70$	$15^{\rm m}.795$	$15^{\rm m}.220$	$14^{\rm m}.523$	2MASS
BD −7°5977	$10^{\rm m}.55$[2]	$+0^{\rm m}.51$[2]			$10^{\rm m}.05$	$8^{\rm m}.97$	$8^{\rm m}.48$	$8^{\rm m}.38$	UT98
						$9^{\rm m}.017$	$8^{\rm m}.526$	$8^{\rm m}.448$	2MASS

Star	V	$B-V$	$U-B$	$V-I$	$R_{\rm HST}$	J	H	K	Ref.
PG 1421+345	$14^{\rm m}.78$	$-0^{\rm m}.14$	$-0^{\rm m}.89$	$+0^{\rm m}.63$	$14^{\rm m}.59$	$14^{\rm m}.035$	$13^{\rm m}.716$	$13^{\rm m}.678$	2MASS
PG 1601+145	$14^{\rm m}.50$	$+0^{\rm m}.01$	$-0^{\rm m}.92$	$+0^{\rm m}.41$					
PG 1656+213	$14^{\rm m}.88$	$-0^{\rm m}.20$	$-0^{\rm m}.73$		$14^{\rm m}.73$				

[1] Altmann (priv. comm.).
[2] Derived from Tycho photometry ($V_{\rm T} = 10^{\rm m}.6$, $(B-V)_{\rm T} = +0^{\rm m}.6$) using the transformation given in Perryman (1997).

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