Spectral energy distributions and colours of hot subluminous stars

1 Introduction

Optical photometry and spectroscopy provide the observational basis for astronomy. Ongoing large photometric surveys provide a huge amount of photometric measurements in several optical passbands, which can be used to identify candidate hot subluminous stars, though spectroscopy is needed for proper spectral typing. However, optical photometry is much more than a mere target selection tool. Time-series photometry (light curves) are a crucial ingredient for asteroseismology of pulsating stars and to identify eclipses, reflection effects, and ellipsoidal variations, in compact binaries. Single-epoch observations, however, provide crucial information as well. Spectroscopic distances rely on at least one measured apparent magnitude. Ultraviolet and infrared surveys when combined with optical photometry allow us to construct broad spectral energy distributions (SED), which can be used to determine e.g. the effective temperature of a star, to identify an infrared excess hinting at the presence of a cool companion, and to quantify interstellar absorption from UV flux depression.

Here we shall not address light variation but restrict ourselves to colour-metric properties of hot subdwarf B (sdB) stars. Several investigations of hot subdwarf stars have made use of single-epoch photometry. With the advent of the International Ultraviolet Explorer (IUE) satellite crucial information to study hot stars arose and early attempts to analyse SEDs of sdB stars were carried out by Heber et al. (1984), Heber (1986), and Aznar Cuadrado & Jeffery (2001) by combining low resolution UV spectra from IUE with optical photometry. Colour-colour diagrams combining infrared and optical magnitudes are important tools to identify composite objects, such as sdB stars with F/G/K companions (see e.g. Stark & Wade 2003, Green et al. 2008).

Subdwarf B stars are core helium burning stars of half a solar mass and in the Hertzsprung Russell diagram they form the extreme horizontal branch. Because radial velocity surveys have shown that the fraction of close binaries amongst single-lined (SB1) sdB stars is as high as 50%, common envelope evolution plays an important role in the formation of sdB stars. About 30% of the sdB stars show composite colours, that is they have companions of spectral types F, G, or K. In many cases the companions to SB1 systems have been found to be white dwarfs, but low mass main-sequence stars (spectral type M) and brown dwarfs have been found as well (see Heber 2009, 2016, for reviews). Because it is often very difficult to clarify the nature of the companions from optical data alone, broad SEDs are the method of choice to constrain the companions’ properties and constrain their nature.

We describe a method to construct broad SEDs by combining measurements in various photometric systems from the ultraviolet to the infrared in Sect. 2.
SEDs and colours of sdB stars

2 Constructing observational SEDs

The SEDs of the program stars were constructed from photometric measurements ranging from the ultraviolet to the infrared collected from literature. To eliminate the steep slope of the SED we plot the flux density times the wavelength to the power of three ($F_\lambda \lambda^3$) as a function of wavelength throughout this paper.

2.1 Photometric data

The visual range is covered by SDSS [Alam et al. 2015] and APASS [Henden et al. 2016] data as well as magnitudes and colours in the Johnson-Cousins, Strömgren (see Fig. 1), and Geneva systems, which are collected using Vizier as well as the Subdwarf Database by Østensen (2006).

Ultraviolet fluxes are important to constrain the atmospheric parameters of a hot subdwarf and were extracted from observations by the International Ultraviolet Explorer (IUE), available in the MAST archive. Infrared photometry is of particular importance for binary systems that contain a cool companion because an IR excess is expected. Available infrared data were taken from ALLWISE [Wright et al. 2010; Cutri et al. 2013], 2MASS [Skrutskie et al. 2006], and UKIDSS [Lawrence et al. 2007] (see Fig. 1).

The photometric datasets are inhomogeneous, both with respect to bandwidth as well as to accuracy. Ultraviolet spectra from IUE cover the wavelength range from 1150Å to 3150Å at a spectral resolution of 6 Å. The optical spectral range is covered by several filters both narrow band (e.g. Strömgren) and wide-band (e.g. Sloan or Johnson), while the infrared is usually represented by five wide-band filters (J, H, K, W1, and W2).

2.2 Ultraviolet fluxes from IUE spectra

The IUE satellite provided UV spectra for two wavelength ranges; the short (SW, 1150-1975Å) and long (1910-3150Å) wavelength range. Each spectrograph offered both high and low resolution modes, with spectral resolutions of 0.2 and 6 Å respectively, as well as two entrance apertures each, a small circular aperture with a 3 arcsec diameter and a large rectangular aperture of 10 by 20 arcsecs. We discarded spectra at high-resolution as well as those taken through a small aperture, because the flux calibration is less accurate than that for the large-aperture, low-resolution spectra. Because we have to combine them with broad and intermediate band optical and infrared photometry we defined a suitable set of filters to derive UV-magnitudes from IUE spectra (see Fig. 2). Three box filters, which cover the spectral ranges 1300–1800Å, 2000–2500Å, and 2500–3000Å, are defined to extract magnitudes from the IUE spectra. The box filters were designed in order to avoid the boundaries of the SW and LW wavelength ranges because of the increasing noise level and the region around the Lyman-alpha line because of the contribution by interstellar gas absorption. The mid-UV filter was designed to include the UV absorption bump at $\approx 2200$Å of interstellar absorption (see Fig. 3), which is important to determine the interstellar reddening parameter E(B-V).

1 http://catserver.ing.iac.es/sddb/
2 http://archive.stsci.edu/
3 Synthetic SEDs and colours

The magnitude $m_{x}$ of an arbitrary photometric passband $x$ is defined as

$$m_{x} = -2.5 \log \left( \frac{\int_{0}^{\infty} r_{x}(\lambda)f(\lambda)\lambda d\lambda}{\int_{0}^{\infty} r_{x}(\lambda)f^{\text{ref}}(\lambda)\lambda d\lambda} \right) + m_{x}^{\text{ref}}$$  \hspace{1cm} (1)

where $r_{x}(\lambda)$ is the response function of the filter (see Fig. 1 for examples) and $f(\lambda)$ the flux at the photon-counting detector. The flux of a reference star (usually Vega) $f^{\text{ref}}$ is needed to set the zero point of the filter to a predefined magnitude $m_{x}^{\text{ref}}$. Note that we assume photon-counting detectors, which explains the additional factor $\lambda$ in the arguments of the integrals (see, e.g. Bessell et al. 1998, for details).

The stellar flux at Earth $f(\lambda)$ can be calculated from the model flux at the stellar surface $F(\lambda)$ and the angular diameter of the star $\Theta (= 2R_{\star}/d)$, which is two times the stellar radius $R_{\star}$ divided by the distance, from which we obtain $f(\lambda) = \Theta^{2}F(\lambda)/4$.

To account for interstellar extinction, the synthetic flux is multiplied with a reddening factor $10^{-0.4A(\lambda)}$. The extinction in magnitude at wavelength $\lambda$, $A(\lambda)$, as a function of the colour excess $E(B-V)$ and the extinction parameter $R_{V} = A(V)/E(B-V)$ (defaulted to 3.1) is taken from Fitzpatrick (1999) (see Fig. 3). The final expression to calculate a synthetic magnitude, therefore, reads as

$$m_{x} = -2.5 \log \left( \frac{\int_{0}^{\infty} r_{x}(\lambda)10^{-0.4A(\lambda)}F(\lambda)\lambda d\lambda}{4 \int_{0}^{\infty} r_{x}(\lambda)f^{\text{ref}}(\lambda)\lambda d\lambda} \right) + m_{x}^{\text{ref}}. \hspace{1cm} (2)$$

3.1 Grids of synthetic SEDs and colours

We aim at modelling the observed SEDs and colours of single sdB stars or SB1 binaries, as well as composite spectrum systems consisting of a hot subdwarf and a late-type main-sequence star.

3.1.1 SEDs of hot subdwarf stars

Subluminous B stars are known to show peculiar chemical abundance patterns (Heber 2009, 2016) characterized in general by depletions of light metals (C to Ca) and enrichment of heavy metals by very large factors with respect to solar composition. However, star-to-star scatter is large. Naslim et al. (2013) suggested an average abundance pattern, which we adopted for the model calculations. For the elements not listed in Naslim et al. (2013) the reference abundance is solar (Asplund et al. 2009).

In order to synthesize the SED of a hot subdwarf star a grid of model atmospheres was calculated using the ATLAS12 code (Kurucz 1996) with effective temperatures
ranging from 15000 K to 55000 K and surface gravities from 4.6 to 6.2. The helium abundance was fixed at a low value of one hundredth solar and the logarithmic "metallicities" \( z \) are scale factors with respect to the abundance pattern of Naslim et al. (2013). The synthetic spectra cover the wavelength range form 300 Å to 100000 Å (far UV to mid infrared). The logarithmic metallicity \( z \) is allowed to vary between -1 and +1 (a tenth or ten times the typical composition of a subdwarf B star). Please note that iron and nickel are the dominant absorbers and have the greatest influence on the metallicity \( z \) because they have many absorption lines in the FUV and their absolute abundance is high. As demonstrated in Fig. 4, the metallicity essentially affects the UV spectral range, most significantly the short wavelength UV box filter. Hence it might be possible to derive the metallicity of the sdB if such UV measurements were available.

Recently, several improvements have been implemented in the ATLAS12 code (Irrgang, in prep.), the most important of which is the treatment of high series members of the hydrogen and ionized helium line series, following Hubeny et al. (1994). This is of particular importance to model the Balmer jump.

3.1.2 SEDs of cool stars

For cool stars a grid of PHOENIX models calculated by Husser et al. (2013) is used. The synthetic SEDs cover the wavelength range from 500–55000 Å. The parameter range is confined to effective temperatures between 2300 K and 12000 K, surface gravities between 2 and 5 dex, and the helium content is set at the solar value.

3.1.3 Combining SEDs of sdB and cool stars

In order to combine the spectra of the two components the surface ratio \( S \) needs to be determined, which adds another parameter, from which the angular diameter of the companion \( \Theta_c \) can be derived.

4 Photometric analysis methodology

To facilitate objective and efficient photometric analyses, we have developed a grid-based fitting routine. It is based on \( \chi^2 \) minimization tools provided by the Interactive Spectral Interpretation System (Houck & Denicola 2000) to find the global best-fit in the multi-parameter space.

The six parameters considered to model SEDs and colours of the sdB stars are
- the angular diameter \( \Theta \)
- the effective temperature: \( T_{\text{sdB eff}} \)
- the surface gravity: \( \log g_{\text{sdB}} \)
- Helium Abundance: \( \log(n(\text{He})/n(\text{all})) \)
- "Metallicity" \( z \) (scaled typical abundance pattern (Naslim et al. 2013))
- the interstellar reddening parameter E(B-V)

Adopting the canonical mass for the sdB star, we also derive the stellar distance.
4.1 Composite spectra

In the case of binary stars we may observe a composite spectrum, which increases the parameter space by the parameters describing the companion as well as the surface ratio $S$ of both stars.

- Effective temperature: $T_{\text{eff}}$
- Surface gravity: $\log g^c$
- Metallicity: $[\text{Fe/H}]$

However, usually the surface gravity and metallicity of the cool star are unconstrained. Therefore, they were kept fixed to $\log g=4.5$ and 1/10 solar metallicity.

4.2 Determination of uncertainties

Uncertainties are derived from the $\chi^2$ statistics. The parameter under consideration is increased/decreased – while all remaining parameters are fitted to account for possible correlations – until a certain increment $\Delta \chi^2$ from the minimum $\chi^2$ is reached. The value chosen for $\Delta \chi^2$ determines the confidence level of the resulting interval. For instance, $\Delta \chi^2 = 1$ yields single-parameter 1$\sigma$ uncertainties.

The photometric data were compiled from various sources and, thus, are quite inhomogeneous, in particular with respect to the stated uncertainties. The following strategy was employed to cope with this: (i) Data flagged in catalogs as uncertain and obvious outliers are omitted. (ii) Magnitudes and colours without given errors are assigned typical uncertainties of 0.05 and 0.025 mag, respectively. (iii) To account for systematic shortcomings (e.g. in the system response curves, synthetic SEDs, or calibration of the data), a generic error of 0.015 mag is added in quadrature to all observed values. (iv) Eventually, all uncertainties are rescaled by a common factor to ensure a reduced $\chi^2$ of 1 at the best fit.

5 Results

We present preliminary results for two sdB stars, the apparently single HD205805 and the composite spectrum sdB binary PG0749+658. These stars were chosen because extensive, high-quality photometric observations in all relevant wavelength regimes are available.

5.1 HD 205805 – a benchmark single sdB star

HD 205805 is one of the brightest sdB stars and, therefore, ample photometric measurements are available for the optical regime including Strömgren indices, in particular the H$\beta$ index, which employs a narrow band filter centered at the H$\beta$ line to measure its strength. An ultraviolet spectrum has also been observed by IUE as well as infrared fluxes. HD 205805 is one of a handful of sdB stars that have such good photometric data coverage and, therefore provides our benchmark for SED and colour fitting.

High resolution optical spectra taken with the FEROS spectrograph at the ESO 2.2m telescope became also available through the ESO archive. We analysed five FEROS spectra using an updated version of the grid of synthetic hydrogen and helium spectra calculated from metal-line blanketed LTE models described by Heber et al. (2000). The resulting atmospheric parameters are $T_{\text{eff}}=25338\pm463$ K, $\log g=5.21\pm0.21$ and a helium to hydrogen ratio of $\log (n_{\text{He}}/n_{\text{H}})=-1.93\pm0.03$ by number.

The SED fit and the corresponding confidence map for the error estimation of $T_{\text{eff}}$ are shown in Figs. [9] and [8], respectively. The resulting parameters ($T_{\text{eff}}=25338^{+463}_{-423}$ K, $\log g=5.21\pm0.21$) are in perfect agreement with those derived from spectroscopy. The metal abundance parameter ($z=0.09^{+0.17}_{-0.28}$) points to a normal sdB composition for HD205805 consistent with the metal abundances derived by Geier (2013). The resulting interstellar reddening towards HD 205805 is very low ($E(B-V)=0.016 \pm 0.005$ mag).

5.2 The composite spectrum sdB binary PG 0749+658

The sdB star PG0749+658 was classified as sdB-O by Green et al. (1986). A spectral analysis of the optical spectrum resulted in an effective temperature $T_{\text{eff}}=24600$K, surface gravity $\log g=5.54$ (Saffer et al. 1994). Its composite nature was realised by Allard et al. (1994) from BVRI photometry and the faint companion was classified as spectral type K5.5, but no significant radial velocity variations were found. Maxted et al. (2001) and Aznar Cuadrado & Jeffery (2002) determined the effective temperatures for both components from the SED to be $T_{\text{eff}}=25050\pm675$ K and $T_{\text{eff}}^c=5600\pm300$ K, while Aznar Cuadrado & Jeffery (2002) analysed the composite spectrum of PG0749+658 and derived similar tem-
Fig. 6. HD 205805: Fit of the SED (top panel) simultaneously with available colours in the Strömgren, Johnson, Geneva photometric systems. The magnitudes $B_T$ and $V_T$ are from the Tycho catalog and $H_P$ is the Hipparcos magnitude. Residuals are shown in the right hand (colours) and lower (fluxes) panels as magnitudes.

Fig. 7. Same as Fig. 6 but for the composite spectrum of PG 0749+658. The bump in the H band is caused by the onset of H$^-$ absorption.
temperatures $T_{\text{eff}} = 25400 \pm 500 \, \text{K}$ and $T_{\text{eff}}^c = 5000 \pm 500 \, \text{K}$. The corresponding gravities were found to be $5.7 \pm 0.11$ and $4.58 \pm 0.24$ for the sdB and the late-type companion, respectively. Heber et al. (2002) derived a considerably lower effective temperature of $T_{\text{eff}} = 25050 \, \text{K}$ for the sdB component from the optical SED and attempted to resolve the binary spatially using the Wide Field and Planetary Camera 2 on-board the Hubble Space Telescope, but found it to be unresolved to a limiting angular separation $< 0.2''$, which at a distance of 580 pc translates into a separation $< 116 \, \text{AU}$. Ohl et al. (2000) determined metal abundances from FUV spectra obtained with FUSE and showed that the sdB is somewhat metal poor in comparison to the typical sdB abundance pattern.

The fit of the observed SED of PG 0749+658 is shown in Fig. 7 and the resulting parameters are listed in Table 1. The resulting temperatures of both stars are lower than those derived from spectroscopy. The resulting gravity of the sdB is consistent with the spectroscopic one derived by Safer et al. (1994) to within error limits, but lower than that of Aznar Cuadrado & Jeffery (2002).

### Table 1. Results of the analyses of the SED (see Fig. 7) of PG 0749+658. The resulting interstellar redening parameter is zero to within error limits ($E(B-V) < 0.01 \, \text{mag}$).

|       | $T_{\text{eff}}$ [K] | $\log g$ | $z$ | $\Theta / 10^{-11}$ |
|-------|----------------------|----------|-----|---------------------|
| sdB   | $23250^{+569}_{-391}$ | $5.290^{+0.19}_{-0.23}$ | $-0.16^{+0.09}_{-0.57}$ | $2.53^{+0.07}_{-0.00}$ |
| comp. | $4805 \pm 59$        | $4.5^+$  | $-1^+$ | $10.7 \pm 0.4$     |

*: fixed value

### 6 Outlook

HD 205805 and PG 0749+658 are amongst the best cases, both in terms of available data quality and wavelength coverage. For most of the other known sdB stars, available datasets are less complete. Hence we can not expect to achieve similar accuracy for the parameters derived from SED fitting, in particular the surface gravity $\log g^{\text{sdB}}$ will likely be unconstrained as well as the metal abundance parameter $z$ when no IUE data are available. Because of their large systematic uncertainties, FUV and NUV fluxes from the GALEX mission are not sufficient to replace UV magnitudes from IUE (Kawka et al. 2015).

Using mock datasets we shall investigate the quality requirements for observed photometric datasets to derive atmospheric parameters to be conclusive.

### 6.1 The sample of sdB binaries with known orbits

Kupfer et al. (2015) and Kawka et al. (2015) compiled a list of close binary sdB stars with known orbits and studied their properties (see Fig. 9).

We restrict ourselves to the single-lined spectroscopic binaries. Because the companions are unseen, they could be white dwarfs, low mass main sequences stars, or substellar objects. From light variations (reflection effect or ellipsoidal variations) and the mass function, the nature of the companions could be inferred only for about half of the sample (Kupfer et al. 2015).

Hence, we embarked on an analysis of their SEDs in order to better constrain the nature of the companions. We compiled available photometric data from the data archives and constructed the SEDs as described in Sect. 2. The sample contains 142 stars. Twenty-six are reflection effect systems, hence the companions are normal stars, but were excluded from the study because of their light variability. Kupfer et al. (2015) suggested that 52 stars host a white dwarf companion. We could model the SEDs of 50 of them by a single synthetic SED, confirming the white dwarf nature of the companion. However, two binaries showed infrared excess and where modelled with a composite SED. The companions are most likely main-sequence stars. For the stars for which the nature of the companion was unclear, we were able to reproduce their observed SED with a single synthetic sdB one in fifty cases, but ten binaries require a composite SED, indicating that the companion is likely a late-type main-sequence star. In the case of the single-SED binaries addi-
SEDSs and colours of sdB stars

6.2 Gaia, SkyMapper, and other photometric surveys

Because subdwarf O and B stars are hot the Balmer jump is an important diagnostic tool, which requires measurements of optical UV (e.g. u, u’ or U) or NUV magnitudes. Several ongoing surveys will provide such photometric data, in particular SkyMapper, which measures the Strömgren u-band, and the Gaia space mission, which will measure spectrophotometry in 30 bands with fine sampling of the Balmer jump. All-sky NIR surveys will be important to study composite spectrum sdB binaries and constrain the properties of both components.

This will put us into an excellent position to constrain the properties of the known (>5000) hot subdwarfs (Geier et al. 2017), out of which we expect 50% to be close binaries as well as to enlarge the sample enormously from new discoveries, in particular from Gaia.

7 Acknowledgements

Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This publication makes use of data products from the AAVSO Photometric All Sky Survey (APASS). Funded by the Robert Martin Ayers Sciences Fund and the National Science Foundation. This work is based in part on data obtained as part of the UKIRT Infrared Deep Sky Survey. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 212
Allard, F., Wesemael, F., Fontaine, G., Bergeron, P., & Lamontagne, R. 1994, AJ, 107, 1565
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Aznar Cuadrado, R. & Jeffery, C. S. 2001, A&A, 368, 994
Aznar Cuadrado, R. & Jeffery, C. S. 2002, A&A, 385, 131
Bessell, M. S., Castelli, F., & Plez, B. 1998, A&A, 333, 231
Cutri, R. M. & et al. 2013, VizieR Online Data Catalog, 2328
Fitzpatrick, E. L. 1999, PASP, 111, 63
Geier, S. 2013, A&A, 549, A110
Geier, S., Kupfer, T., Heber, U., et al. 2017, A&A, 602, C2
Green, E. M., Fontaine, G., Hyde, E. A., For, B.-Q., & Chayer, P. 2008, in Astronomical Society of the Pacific Conference Series, Vol. 392, Hot Subdwarf Stars and Related Objects, ed. U. Heber, C. S. Jeffery, & R. Napiwotzki, 75
Green, R. F., Schmidt, M., & Liebert, J. 1986, ApJS, 61, 305
Heber, U. 1986, A&A, 155, 33
Heber, U. 2009, ARA&A, 47, 211
Heber, U. 2016, PASP, 128, 082001
Heber, U., Hunger, K., Jonas, G., & Kudritzki, R. P. 1984, A&A, 130, 119
Heber, U., Moehler, S., Napiwotzki, R., Thejll, P., & Green, E. M. 2002, A&A, 383, 938
