QUANTITATIVE SPECTROSCOPY OF OB STARS: FROM DWARFS TO SUPERGIANTS

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Abstract. We discuss recent progress made in the spectral modelling of OB stars from the main sequence to evolved phases as BA-type supergiants. Non-LTE line-formation computations can now reproduce observed spectra over the entire optical and near-IR wavelength range with high confidence, facilitating stellar atmospheric parameters and elemental abundances to be determined at high accuracy and precision. An overview is given how the fundamental stellar parameters of single stars determined in our new approach compare to high-precision data derived from detached eclipsing massive binary stars. Finally, the observational constraints for a sample of Galactic objects are put in context with state-of-the-art evolution models for rotating massive stars.

1 Introduction

Massive OB-type stars on the main sequence and their evolved progeny, BA-type supergiants have been identified as highly valuable probes of present-day elemental abundances since long (*e.g.*, Kilian 1992; Gies & Lambert 1992; Venn 1995). Their enormous luminosities make BA-type supergiants accessible to quantitative spectroscopy in galaxies even well beyond the Local Group (*e.g.*, Kudritzki *et al.* 2012). A full characterisation of stellar parameters and elemental abundances allows various astrophysical topics to be addressed, ranging from *e.g.* observational constraints on stellar evolution (Przybilla *et al.* 2010) over the chemical composition of the interstellar dust (Nieva & Przybilla 2012), galactochemical evolution (Kudritzki *et al.* 2012) to the cosmic distance scale (Kudritzki *et al.* 2008).

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We give here an overview of recent improvements achieved in the quantitative spectroscopy OB main-sequence stars and BA-type supergiants. Fundamental stellar parameters determined from an application of the new models and analysis methodology on *single* stars will be compared to high-precision data derived from detached eclipsing massive binaries (DEBs, Torres *et al.* 2010). In a second step the evolutionary status in particular of the BA-type supergiants – either evolving redwards from the main sequence for the first time or experiencing a blue-loop phase – will be discussed, which is currently debated (*e.g.*, Saio *et al.* 2013).

2 Observations and analysis

The observational sample consists of bright, sharp-lined, apparently single and chemically inconspicuous stars that show no indications for the presence of a circumstellar disk. The main-sequence sample comprises a total of 29 early B-type stars discussed in detail by Nieva & Simón-Díaz (2011, NS11) and Nieva & Przybilla (2012, NP12). The objects are either associations members or field stars, at distances out to ~ 400 pc from the Sun. These are complemented by 35 BA-type supergiant stars (Firnstein & Przybilla 2012, FP12), at distances out to ~ 4 kpc.

High-S/N and high-resolution echelle spectra (with $S/N > 250$ –500 typically, and resolving power $R = \lambda/\Delta\lambda \geq 40\,000$) were obtained with FEROS on the ESO/MPG 2.2 m telescope at La Silla, FOCES on the 2.2 m telescope on Calar Alto, FIES on the 2.5 m Nordic Optical Telescope on La Palma, or taken from the ELODIE (Observatoire de Haute-Provence) and ESO archives (UVES/VLT). All spectra have a wide wavelength coverage (~ 3900 –7000 Å, and often out to 9000 Å), which is required to access all important spectroscopic indicators.

Model calculations were carried out using a hybrid non-LTE approach as discussed in detail by Przybilla *et al.* (2006, 2011) and Nieva & Przybilla (2007, 2008). In brief, hydrostatic, plane-parallel and line-blanketed LTE model atmospheres were computed with ATLAS9 (Kurucz 1993). Non-LTE line formation computations were then performed on these model structures using updated versions of the DETAIL and SURFACE codes (Giddings 1981; Butler & Giddings 1985). State-of-the-art non-LTE model atoms (see Table 1) relying on data from *ab-initio* computations – avoiding rough approximations wherever possible – were utilised in this step, see Przybilla (2010) for an overview of the importance of these input data. Thus, most of the astrophysically important chemical species were treated in non-LTE. Missing species were considered in LTE for completeness.

The stellar parameter and abundance determination employs an iterative analysis methodology (Przybilla *et al.* 2006; NP12). Numerous spectroscopic indicators such as multiple ionization equilibria and Stark-broadened profiles of the Balmer and Paschen lines are used simultaneously to derive effective temperatures T_{eff} and surface gravities $\log g$. Both, high accuracy and precision can be achieved, with 1σ -uncertainties reduced to ~ 1 –2% in T_{eff} (facilitating a thorough re-calibration of photometric T_{eff} -scales: FP12; Nieva 2013, see also these proceedings) and to 0.05–0.10 dex in $\log g$, when the analysis is performed in a

Table 1. Model atoms for non-LTE calculations.

Ion	Model atom
H	Przybilla & Butler (2004)
He I/II	Przybilla (2005)
C I-IV	Przybilla <i>et al.</i> (2001b), Nieva & Przybilla (2006, 2008)
N I/II	Przybilla & Butler (2001), updated
O I/II	Przybilla <i>et al.</i> (2000), Becker & Butler (1988), updated
Ne I/II	Morel & Butler (2008), updated
Mg I/II	Przybilla <i>et al.</i> (2001a)
Al II/III	Przybilla (in prep.)
Si III/IV	Becker & Butler (1990), updated
S II/III	Vrancken <i>et al.</i> (1996), updated
Ar I/II	Butler (in prep.)
Ti II	Becker (1998)
Fe II/III	Becker (1998), Morel <i>et al.</i> (2006), corrected

self-consistent way. Absolute elemental abundances can then be constrained with unprecedented accuracy and precision: to $\sim 25\%$ for systematic and $\sim 10\text{--}20\%$ for random 1σ -errors. The quality of the stellar parameter determination was verified in addition by simultaneously matching the measured stellar spectral energy distributions (employing UV spectrophotometry obtained with the IUE satellite and ground-based optical and near-IR photometry) with the model fluxes. Spectroscopic distances were compared to Hipparcos distances, where feasible. A quality criterion for the elemental abundance determination was the absence of systematic trends of abundances with T_{eff} or $\log g$. Finally, the model spectra were compared with the observed spectra, finding a good to excellent match throughout the entire analysed wavelength range, see Figure 1 for an example.

An application of the new models and analysis methodology to the disentangled spectra of double-lined OB-type DEBs would be highly valuable. On the one hand, this would facilitate the chemical composition of DEBs to be determined, about which little is known at present (see Pavlovski *et al.* 2011, and also these proceedings). On the other hand, this would allow to test our non-LTE model atoms at high detail, because of the availability of very tight and independent constraints on the atmospheric parameters of the DEB components.

3 Fundamental parameters and a comparison to data from DEBs

Once the basic atmospheric parameters T_{eff} and $\log g$ are known, evolutionary masses M of stars can be determined by comparison with the loci of stellar evolution tracks in the $T_{\text{eff}}\text{--}\log g$ plane. From these, spectroscopic distances (*i.e.* distance moduli) to the stars can be derived following the same strategy as in NP12, which also requires a determination of the interstellar reddening from a comparison of model and observed colours. Finally, bolometric corrections can

Fig. 1. Comparison of the model spectrum (black) with a high-resolution spectrum of HD 92207 (grey line). The major spectral features are identified, short vertical marks designate Fe II lines. With few exceptions, excellent agreement between theory and observation is found ($H\gamma$ is affected by the stellar wind). From Przybilla *et al.* (2006).

be computed from the model fluxes, providing stellar luminosities L and radii R . Alternatively, distances of the BA-type supergiants may be derived from application of the flux-weighted gravity–luminosity relationship (Kudritzki *et al.* 2003, 2008).

We refer to forthcoming papers by Nieva & Przybilla and Firnstein & Przybilla for a discussion of the detailed results on fundamental parameters of OB stars and BA-supergiants, respectively. A preliminary summary of results on early B-stars is given in Figures 2 and 3. These show the mass-radius and mass-luminosity relationships as established from the quantitative analysis of single stars, in comparison with data derived from double-lined DEBs (Torres *et al.* 2010). We want to draw the attention to the extremely small error bars of the DEB data – both components of the DEBs have M and R determined to $\pm 3\%$, or better. Our sample stars fit well into the trends, with error bars coming typically within a factor 2–4 to that of the DEBs. The precision in luminosity even reaches similar values as that obtained for DEBs. This opens up the possibility to improve on the number statistics and in particular to trace the regions close to the ZAMS in the M – R and M – L relations for the more massive objects, which so far is not covered by DEBs.

We also find a good agreement between our single star and the DEB data on early B-type dwarfs (luminosity class V) when establishing functional relationships, *e.g.* between spectral type and stellar mass, stellar radii or absolute visual or bolometric magnitudes, see Figure 4 for an example. Interestingly, these high-precision data differ from relations promoted in the astrophysical standard

Fig. 2. Mass-radius relationship for early B-stars in the solar neighbourhood. Black dots denote bona-fide main-sequence objects and open thick circles objects near/beyond core-H exhaustion. Data from double-lined detached eclipsing binary stars (Torres *et al.* 2010) are shown for comparison (small triangles). In addition to the zero-age main sequence (ZAMS), two additional loci, for 50% core-H depletion and for the terminal-age main sequence (TAMS), are indicated by the thick/thin-dotted lines, as predicted by the stellar evolution models of Ekström *et al.* (2012). Error bars are 1σ -uncertainties.

Fig. 3. Mass-luminosity relationship, see Figure 2 for details on the symbol encoding.

literature, like the Landolt-Börnstein (Schmidt-Kaler 1982) or Allen’s Astrophysical Quantities (Cox 2000). The actual values are significantly smaller than the recommended reference values. Our sparse data on early B-type stars of other luminosity classes indicate that similar discrepancies occur there. We conclude, that the reference literature on fundamental stellar parameters of OB stars requires to be revised.

Fig. 4. Masses of early-B stars (full symbols) as a function of spectral type. Encoding of the luminosity class according to the legend, open triangles denote data derived from detached eclipsing binary stars (Torres *et al.* 2010). Error bars denote 1σ -uncertainties. The functional relationship for dwarfs (luminosity class V) as advocated in the astrophysical reference literature is indicated. From Nieva & Przybilla (in prep.).

4 Constraints on evolutionary status

While the evolutionary status of main-sequence stars can be determined without ambiguity, that of BA-type supergiants is not clarified at present. Are they the direct progeny of main-sequence OB stars (*i.e.* are they crossing the Hertzsprung-Russell-diagram for the first time towards the red), or have they gone through the red supergiant stage before (*i.e.* are they on a blue loop)? A fresh view on this topic may be obtained from an accurate and precise determination of stellar parameters and elemental abundances, in particular for carbon, nitrogen and oxygen.

An indication for the absence of systematic error from stellar analyses (*i.e.* a quality criterion for their accuracy) may indeed be deduced objectively. It turns out that the locus of N/C *vs.* N/O abundance ratios depends only on nuclear physics (the CNO cycles), and is essentially independent of the initial stellar masses, rotation velocities and nature of the mixing processes (Przybilla *et al.* 2010). Indeed, only our recent investigations recover the predicted nuclear path tightly, see Figure 5. However, additional information is required to deduce indications for the evolutionary status of BA-type supergiants.

One possibility is to put surface N/C-ratios in the context of the surface gravity. This is depicted in Figure 6. From left to right, the theoretical evolution proceeds from the main sequence via the BA-type supergiant regime to the red supergiant stage, potentially entering a blue loop (where $\log g$ develops towards higher values again), as for the $9 M_{\odot}$ models. For the majority of the supergiants it seems that they have evolved directly from the main sequence when compared to the stellar evolution models of Ekström *et al.* (2012). Their level of enrichment

Fig. 5. N/C vs. N/O abundance ratios (by mass) in early-B dwarfs/giants (NS11; NP12; diamonds) and BA-supergiants (Przybilla *et al.* 2010, FP12, circles). The predicted tight trend from analytical considerations and various rotating Geneva evolution models (lines) is recovered for the first time. The symbol size is proportional to stellar mass.

Fig. 6. Evolution of surface N/C abundances as a function of $\log g$. The same objects as in Figure 5 are shown. Geneva evolution tracks (Ekström *et al.* 2012) for stars of 9 and $20 M_{\odot}$ are displayed, bracketing the investigated mass range. Two cases are considered, stars initially rotating at 40% breakup velocity (full), and non-rotators (dotted lines).

with CNO-processed matter is compatible with the predictions from rotational mixing in stars with initial rotation velocities of smaller or about to 40% of the breakup velocity, implying a first redward evolution after the main-sequence stage. This, on the other hand, is contradicted by the pulsational properties of BA-type

supergiants (Saio *et al.* 2013), where the observed pulsations are expected to occur only in a post-red supergiant stage. We conclude that no definite statement on the evolutionary status of the majority of BA-type supergiants can be drawn at present.

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