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Quantitative spectroscopy of hot stars: accurate atomic data applied on a large scale as driver of recent breakthroughs

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Abstract. OB-type stars present hotbeds for non-LTE physics because of their strong radiation fields that drive the atmospheric plasma out of local thermodynamic equilibrium. We report on recent breakthroughs in the quantitative analysis of the optical and UV-spectra of OB-type stars that were facilitated by application of accurate and precise atomic data on a large scale. An astrophysicist's dream has come true, by bringing observed and model spectra into close match over wide parts of the observed wavelength ranges. This allows tight observational constraints to be derived from OB-type stars for a wide range of applications in astrophysics. However, despite the progress made, many details of the modelling may be improved further. We discuss atomic data needs in terms of laboratory measurements and also *ab-initio* calculations. Particular emphasis is given to quantitative spectroscopy in the near-IR, which will be the focus in the era of the upcoming extremely large telescopes.

Keywords. atomic data, radiative transfer, stars: abundances, stars: atmospheres, stars: early-type, stars: fundamental parameters

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OB-type stars are important targets for addressing a wide range of astrophysical questions as their high luminosity allows high-resolution spectra to be obtained even if they are situated at large distances. The atmosphere of an OB star is exposed to an intense radiation field that drives the plasma out of local thermodynamic equilibrium (non-LTE). This leads to a complication in the spectral analysis as the usually adopted Saha-Boltzmann formulae for the description of excitation and ionization are no longer applicable. Instead, a detailed treatment of the individual atomic processes (de-)populating the energy levels and the radiation field is required, i.e. a simultaneous solution of the radiative transfer and statistical equilibrium equations. Among other factors, the extent to which all relevant processes are included and the accuracy and precision of the atomic data employed in the modelling – the model atoms – determine the quality and realism of the synthetic spectra to be compared with observation (see e.g. Przybilla 2010).

We have adopted a hybrid non-LTE approach for the modelling of the atmospheres of OB-type stars (and their evolved progeny) in the mass range ∼7–18 $M_\odot$, as described in detail by Przybilla *et al.* (2006a) and Nieva & Przybilla (2007, 2008). The modelling combines hydrostatic, plane-parallel, and line-blanketed LTE model atmospheres with non-LTE line formation, which allows highly detailed model atoms to be used. The model atoms and line-formation input rely substantially on high precision and accurate data from laboratory measurements and *ab-initio* computations. The latter comprise applications of the multi-configuration Hartree-Fock method (e.g. Froese Fischer & Tachiev

2004) and the R-matrix method in the close-coupling approximation as employed within the Opacity and IRON Projects (Seaton 1987, Hummer *et al.* 1993), own work (e.g. Przybilla & Butler 2004) and numerous diverse studies in the literature.

The models facilitate high-quality observations of the OB stars under consideration to be closely matched over wide parts of the optical wavelength region once the atmospheric parameters are tightly constrained. Examples of the high quality of the fits are given by Nieva & Przybilla (2012). As a consequence, elemental abundances in individual OB stars can be constrained to a precision of ~0.05-0.10 dex and an accuracy of ~0.07-0.12 dex, coming close to corresponding values in photospheric abundance studies for the Sun. First results on an extension of the modelling to the UV, based on high-quality HST/STIS spectra (Schaffenroth 2015), and the near-IR, based on high-resolution VLT/CRIRES data (Nieva *et al.* 2011) for a sub-set of objects are highly promising. The latter wavelength regime will be of particular interest in the era of extremely large telescopes.

Data requirements. Despite all the progress made, quantitative spectroscopy of hot stars still requires large amounts of data for non-LTE modelling and line-formation computations to be provided. A summary of the most desired data sorted by processes follows.

Radiative bound-bound and bound-free. Extended laboratory measurements of oscillator strengths for iron-group elements at UV wavelengths are required to benchmark large-scale *ab-initio* computations that are needed for improved non-LTE modelling of UV spectra. *Ab-initio* data on photoionization cross-sections are missing for most of the relevant ions (ionization stages II-V) of the iron-group elements other than iron.

Collisional bound-bound and bound-free. Ab-initio data for electron-impact excitation for most of the lighter elements (carbon, nitrogen and oxygen, α-process elements, but also including hydrogen and helium) are missing for transitions to and among energy levels with principal quantum number $n \gtrsim 5$-7. Even basic data are missing for most ions of the iron-group elements that could be used to replace simple approximations. Few measurements and *ab-initio* computations on electron-impact ionization are available. Reliable computations are challenging, and they would be required in particular for ionization of excited levels, where collisions are effective because of favourable threshold energies.

Line broadening. Reliable Stark broadening data are missing for many stronger transitions in the spectra of hot stars. These comprise in particular (resonance) lines of CNO and α-elements in the UV, (diffuse) He I lines involving upper levels with $n \geqslant 6$ in the optical, and hydrogen Brackett and Pfund lines and many of the helium lines in the near-IR. The lack of data on helium lines in particular limits comprehensive spectrum synthesis for helium-rich objects, see e.g., Przybilla *et al.* (2005, 2006b).

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