Parameters of normal and peculiar massive single and multiple stars

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A precise characterization of stars through their fundamental parameters and chemical fingerprints is a basic and non-trivial step that complements the study of the stellar structure and evolution, allowing us to understand their nature in more detail. The large variety of massive stars present in nature prevents us to study them in a unique way and challenges standard spectral modeling and analyses. We summarize investigations from the past 12 years on the analysis of different kind of massive stars, from the *simplest* single objects to multiple systems. The scope of this review is to provide the broader community with tools (biased towards our experience) to judge results from spectroscopic studies to complement analyses of stellar variability using photometric observations.

1 Introduction

Massive stars comprise objects with masses larger than $8\,M_\odot$ (spectral types O and early-B), whereas here we extend the discussion to masses larger than $3\,M_\odot$ (mid to late B-types). The spectral characteristics of massive stars vary with their temperature and luminosity. From the spectral analysis perspective, the relatively *simplest* stars to be studied are the late-O and early-B type main sequence stars[1] because, in comparison to early- and mid-O stars or OB supergiants or Be stars, they have no strong winds and their atmospheres can be assumed to be in plane parallel geometry. And in comparison to many mid/late B-type stars, they do not present signatures of diffusion in their atmospheres. However, for many applications with different astrophysical interests, we have to analyze earlier-O, OB supergiants, Be and late B-type, chemically peculiar, magnetic, pulsating, fast-rotating stars, and pre- to post-main-sequence stars.

The large variety of massive stars challenges the basic assumptions of standard atmospheric models and spectral analysis techniques that have been often used to estimate their fundamental parameters and chemical composition. Most standard models and methods have been optimized to study single stars with homogeneous, plane-parallel atmospheres in local thermodynamic and in hydrostatic equilibrium. Such studies oversee, e.g. an oblateness of the stars due to a high rotational velocity, or the presence of a disk surrounding them, the effects of spots on stellar surfaces due strong magnetic fields, mass-loss produced by winds, elemental abundance stratification due to diffusion, deformation of spectral lines due to stellar pulsations, the presence of spectroscopic companions which affects the spectral line continuum and

[1]Late-O and early-B type main sequence stars require actually robust spectral modeling and a comprehensive analysis technique.

shape when they cannot be resolved, the sphericity in the stellar atmosphere of supergiant stars, departures from local thermodynamic equilibrium (non-LTE).

The reason why a unique tool to automatically analyze the spectrum of such a variety of objects is not implemented at the moment is the large quantity of variables or parameters entering in the analysis, which will translate in a spectral grid with a prohibitive number of points. A more feasible approach to reliably study each kind of star is with a tailored model atmosphere and analysis technique that tackles the star's intrinsic restrictions and incorporates the most realistic physical background for each particular case. Dedicated spectral grids can then be computed for each type of objects when the range in all intervening parameters is known.

The final scope is to derive the stars' atmospheric parameters to reliably place them in a Kiel diagram (surface gravity $\log g$ vs. effective temperature $T_{\rm eff}$). In cases where fundamental parameters can also be derived (with additional information, like e.g. parallaxes, or evolutionary masses and some photometric quantities), the objects can be placed in a Hertzsprung-Russell diagram and basic relationships between fundamental stellar parameters can be checked. Related to the atmospheric and fundamental parameters is the determination of the stars' spectroscopic distances, that − when compared with other independent distance indicators − allows us to constrain the accuracy of the stellar parameters. Spectral energy distributions from the UV to the IR allows us to derive the extinction and reddening for a particular star, which is relevant for the spectroscopic distance determination.

A subsequent work after the stellar parameter determination is the chemical analysis, which also differs among the various kind of stars because of e.g., temperature constraints, where lines of different species/ionization stages vary their strength, different blends appear in different parts of the spectrum, or some lines in absorption can turn to emission. The projected rotational velocity will also determine which lines can be analyzed in isolation and which blends can be consistently taken into account. A detailed chemical analysis can yield on accurate elemental abundances when the four basic conditions are met: i) the stellar atmospheric models are applicable to the stars, ii) the spectra have a good quality (spectral lines should be resolved and measurable at good S/N), iii) the analysis methodology takes into account a good selection of spectral lines that can be well reproduced by the modeled spectra and iv) the atmospheric (and when possible fundamental) parameters have been consistently derived.

This manuscript is biased towards our experience on the spectral modeling and analysis of normal and peculiar massive single and recently also multiple stars. It exposes some successes but also challenges to current modeling capabilities, and it is intended as a guideline for colleagues working in other areas to judge the accuracy of fundamental parameters and chemical abundances derived in the literature before they are applied to different fields in astrophysics, and in particular, in the interpretation of stellar variability based, e.g., on BRITE data. A special emphasis is put on the single OB stars on the main sequence, because they allow us to derive most parameters and chemical abundances at highest accuracy and precision, and therefore, we can consider them as reference objects. Shorter descriptions are dedicated to particular classes of more complex objects for which we have recently extended our spectral analysis.

2 Late-O and early B-type on the main sequence: the *simplest* stars

For over a decade, we have improved the spectral modeling and analysis technique for stars with spectral classes from O9 to B2 and luminosity classes V to III – the so-called OB subgroup because of their similar spectral characteristics. Given that standard stellar model atmospheres like e.g. ATLAS9 (Kurucz, 1993) meet most requirements to reproduce their atmospheric structures well (Nieva & Przybilla, 2007), our efforts were invested into realistic level population and line-formation computations in non-LTE by building and testing different configurations of new input atomic data to provide with robust model atoms for different elements (see Przybilla et al. 2016 for updated references). The codes used for the non-LTE level population and line-formation calculations are DETAIL (Giddings, 1981) and SURFACE (Butler & Giddings, 1981)[2]. Our new spectral modeling in combination with a self-consistent spectral analysis that accounts for multiple ionization equilibria, applied to high-quality observations, resulted in a drastic minimization of stellar parameter and chemical abundance uncertainties, particularly reducing several systematic effects previously unaccounted for. A comprehensive study and first applications of our work on single and normal early B-type dwarfs and giants are discussed by Nieva & Przybilla (2012, 2014, hereafter NP12 and NP14) and Nieva (2013). These studies allow us to put constraints not only on their atmospheric parameters and chemical composition at high precision and accuracy, but also to derive spectroscopically other stellar parameters like radius, luminosity, mass and to explore whether theoretical relations between them hold using our observationally derived parameters. For such stars, uncertainties in effective temperature, surface gravities and chemical abundances as low as 1-2%, 15% and 25%, respectively (NP12) and in evolutionary masses, radii and luminosities better than 5%, 10%, 20%, respectively and in absolute visual and bolometric magnitudes lower than 0.20 mag (NP14) are achieved. Moreover, practically a perfect match between the observed and the computed spectrum per star for one set of parameters confirm the robustness of models and analysis.

Figure 1 shows a precise location of a sample of single early B-type stars (NP12) in the Kiel diagram in comparison to detached eclipsing binaries (DEBs). Figure 2 shows their mass-radius relation and Fig. 3 their mass-luminosity relation (NP14), indicating that the derived stellar parameters lie within theoretically expected values and agree with more accurate results from DEBs. The empirical relation between absolute magnitudes and spectral types in NP14 shows an offset with respect to classical older calibrations from the literature (Cox, 2000). The latter are often adopted, affecting the computation of e.g. the stellar luminosities. The overall level of accuracy reached for this kind of objects can hardly be reproduced for more complex stars or systems. We therefore use their results as references for further studies.

3 BA and OB supergiants

Supergiants of spectral types late-B and early-A are descendants of OB stars on the main sequence. Their atmospheres can be well represented with ATLAS9, DETAIL and SURFACE, as described in Przybilla et al. (2006). The spectral analysis of early-O

[2]For this type of stars, stellar structures computed with ATLAS9 in LTE and stellar fluxes computed with ATLAS9 and DETAIL are practically identical to those calculated with TLUSTY (Hubeny & Lanz, 1995) in NLTE. This is discussed in detail in Nieva & Przybilla (2007). We prefer to use ATLAS9, DETAIL and SURFACE because the model atmosphere calculations are very fast and model atoms much more complex and robust than those used in TLUSTY can be employed.

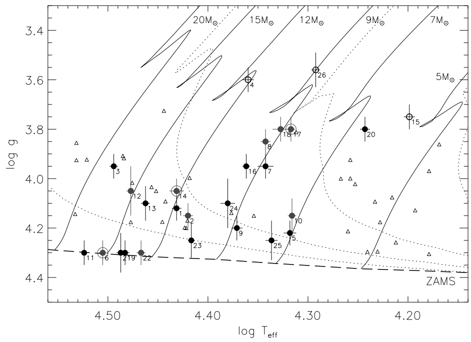

Fig. 1: $T_{\rm eff}$ and $\log g$ of a sample of early B-type stars on the main sequence (black dots). Open thick circles are objects beyond core H-exhaustion. Wide circles surrounding the dots mark magnetic stars. Data from double-lined detached eclipsing binaries are shown as small triangles. Evolutionary tracks and isochrones from Ekström et al. (2012) are shown. See NP12 and NP14 for details.

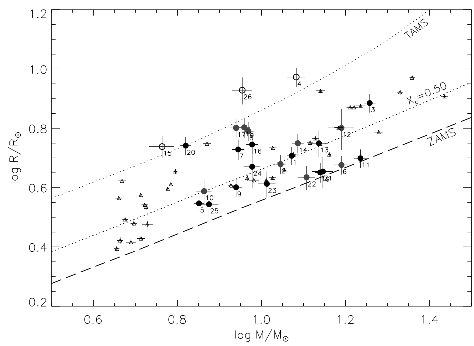

Fig. 2: Mass-radius relationship for the sample stars in Fig. 1 with the same symbol encoding. Abscissa values are evolutionary masses. The ZAMS and two additional loci for 50% core-H depletion and for the TAMS are indicated by the thick/thin-dotted lines from the stellar evolution code as in Fig. 1. Error bars are shown also for the detached eclipsing binaries. See NP14 for details.

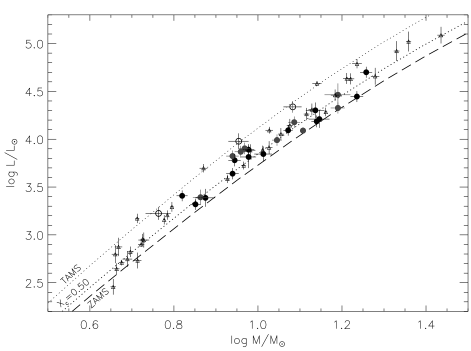

Fig. 3: Mass-luminosity relationship for the sample stars in Fig. 1. Symbol and loci encoding are the same as in Figs. 1 and 2 (NP14).

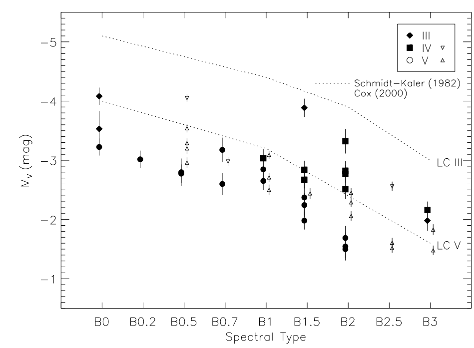

Fig. 4: Absolute visual magnitudes of the sample stars in Fig. 1, encoding their luminosity class according to the legend, vs. spectral type. Older reference values are also indicated (NP14).

stars and OB supergiants are beyond our modeling capabilities, however other robust (pseudo-)hydrodynamic codes in non-LTE that treat simultaneously the spherically symmetric stellar atmospheric structure and the stellar wind like Cmfgen (Hillier & Miller, 1998) and Fastwind (Puls et al., 2005) are suited for their study.

4 Fast-rotating stars

For intrinsically fast-rotating stars, we encounter several limitations in the analysis. If the star rotates so fast that its shape is affected (oblated), the assumptions of plane-parallel or even spherical symmetry are no longer valid on the global scale. Furthermore, depending on the star's inclination, we will observe spectral lines formed in different parts of the atmosphere, with different local temperatures. This is more evident in cases of fast-rotators seen pole-on, where the lines are sharp, but nevertheless it is difficult to fit the whole spectrum with one temperature only and the assumption of establishing ionization balance for all available species simultaneously is no longer valid. If the projected rotational velocity is large, only a few spectral lines can be analyzed and many blends have to be accounted for self-consistently. If the S/N ratio is not high enough, the definition of the line continuum is one of the largest sources of systematics because the spectral lines get smeared out and appear weaker (see Korn et al. (2005) for a discussion on this). The analysis of fast-rotating stars is challenging and their limitations have to be analyzed on a case-by-case basis. One of the most difficult tasks, when the stars have large projected rotational velocities, is identifying systematic asymmetries that can be caused by a companion in a spectroscopic binary (or multiple) system. Stellar parameters and chemical abundances derived from these kind of objects should be treated extremely carefully, because they are prone to large systematic errors. Maeder et al. (2014, their Table 1) provide with an example of a reassessment of a sub-sample of objects from the Massive Star FLAMES Survey studied by Hunter et al. (2009), resulting in the identification of stars with previously unnoticed double or asymmetric spectral lines, which cause their natural exclusion from the interpretation of results because they were analyzed with standard techniques.

5 Be stars

Be stars are main-sequence or subgiant spectral type B stars characterized by Balmer emission (e.g., Hα, but also other Balmer and eventually metal lines) that originates in a circumstellar disk. As most Be-stars are fast-rotators, the same limitations exposed in Sect. 4 apply to their analysis. Additionally, the clear signatures of lines formed in the disk cannot be reproduced self-consistently with any stellar atmosphere code at present. However, there are cases where the photospheric lines can be successfully reproduced, constraining reliably the stellar parameters and even metal abundances. An exploration of the extent of applicability of our spectral models and methods to such stars is ongoing (in collaboration with T. Rivinius).

6 Mid- and late B-type stars

Mid- and late B-type stars present fewer metal lines and less elements with different ionization stages traced in the spectra (1 or 2), in contrast to hotter stars (4 to 6). In many cases, in addition, the stars have a large projected rotational velocity, which can turn their analysis quite challenging. The identification of a companion forming a spectroscopic binary system by resolving line-asymmetries is also a challenge for many of these stars (Zwintz et al., in prep.). Many objects show chemical peculiarities due to atmospheric diffusion, while others present normal chemical abundances. The spectra of pre- to post-main-sequence stars close to the Zero Age Main Sequence are indistinct.

7 Chemically peculiar stars

Chemically peculiar stars are stars with distinctly unusual metal abundances in their surface layers. The stars present selective diffusion of different elements in their at-

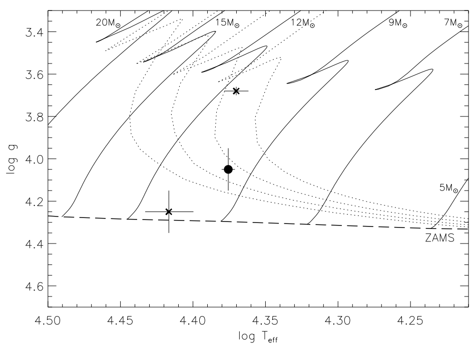

Fig. 5: CPD $-57^{\circ}3509$ in the Kiel diagram. Black dot: result from our self-consistent analysis. St. Andrew's crosses: results by Hunter et al. (2009, higher-gravity) and McSwain et al. (2009, lower gravity) assuming solar helium abundance. Adapted from Przybilla et al. (2016).

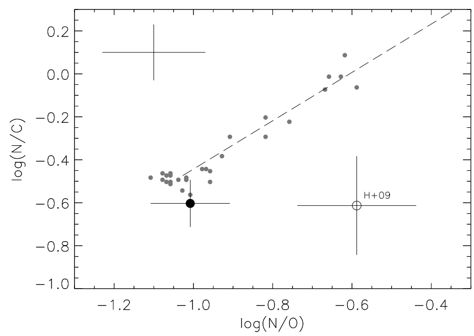

Fig. 6: CPD $-57^{\circ}3509$ in the N/O-N/C diagram (by mass). Black dot: Przybilla et al. (2016). Open circle: Hunter et al. (2009). Grey dots: early B-type stars from NP12. Dashed line: analytical approximation to the nuclear path for CN-cycled material using initial values from NP12 (Przybilla et al., 2010).

mospheres causing some elements to be more or less abundant in the outer layers. Helium-strong stars constitute the hottest and the most massive chemically peculiar stars of the upper main sequence. The chemical abundances and metallicities of such stars should be accounted for iteratively in every step of the analysis by computing dedicated model spectra, because their peculiar abundances are not considered in pre-computed grids of model spectra. A clear example of the consequence of not taking the peculiar abundances into account in the stellar parameter and final chemical composition determination, in contrast to a self-consistent analysis is shown in Figs. 5 and 6 (Przybilla et al., 2016). Analyses assuming solar helium abundances can result in very different atmospheric parameters. Therefore, a self-consistent analysis is recommended for this kind of stars. The same methodology used in Przybilla et al. (2016) was consequently applied to other He-strong stars in González et al. (2017), Castro et al. (2017), and Briquet et al. (in prep.).

Other less-massive chemically peculiar stars (mid- to late B-type) like He-weak or HgMn stars may pose an extra challenge in their spectral analysis caused by elemental abundance stratification in their atmospheres. Clear signatures of He abundance stratification are noticed e.g. in κ Cancri, even when the modeled spectra are computed in non-LTE, whereas oxygen seems not to be stratified, therefore the ionization balance using lines of O I and O II formed in different depths in the atmosphere is met when considering non-LTE line formation (Maza et al., 2014).

8 Pulsating and magnetic stars

Strongly-pulsating stars present spectral lines with noticeable asymmetries. As model atmosphere codes usually do not include modes of stellar pulsations in their computations, such asymmetries cannot be reproduced typically. We notice, however, that some spectral lines are more symmetric because they are formed in regions where the pulsations affect the atmosphere less. In a case-by-case study, it is possible to derive atmospheric parameters through the analysis of the most symmetric lines. An

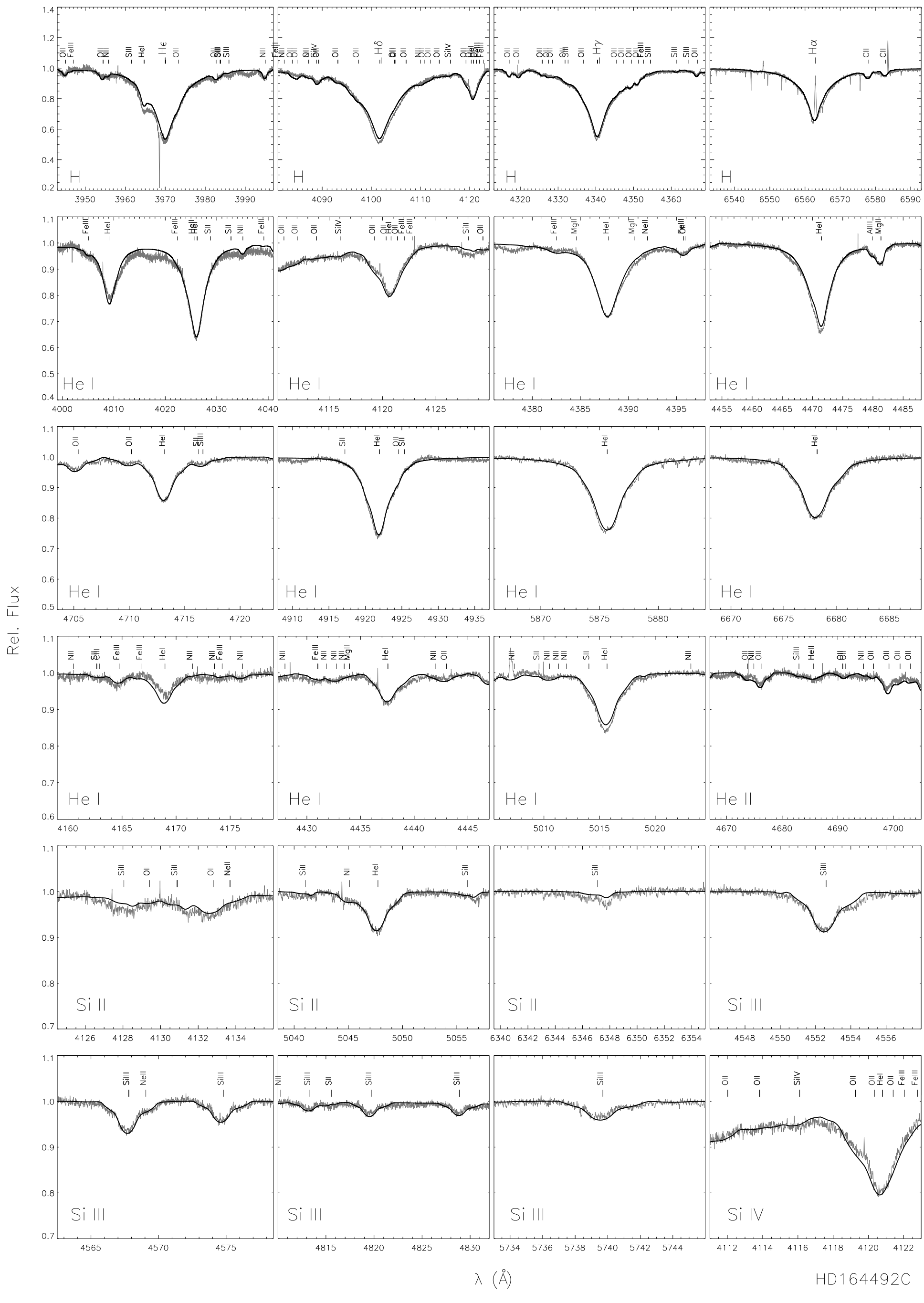

Fig. 7: Comparison of a synthetic and composite observed spectrum for the triple system HD 164492 C. Details of the analysis are discussed in González et al. (2017).

example can be found in Briquet et al. (2011). Note, however, the difference in $\log g$ resulting from the spectroscopic and from the asteroseismic analysis, which should be further investigated. We were also able to reproduce the spectra of several magnetic stars, with magnetic field strengths ranging from very weak to very strong. Some examples are discussed in Fossati et al. (2015), Przybilla et al. (2016), González et al. (2017), Castro et al. (2017), Briquet et al. (in prep.), within the "B fields in OB stars" (BOB) collaboration.

9 Multiple systems

We briefly discuss the spectral line fitting of a triple system formed by a close spectroscopic binary composed by a normal early B-type star and a chemically peculiar late B-type star and a tertiary He-strong star. Details of a dedicated spectral and spectropolarimetric analysis are described in González et al. (2017). The number of parameters involved in the spectral fitting is much larger than in the case of single stars. The composite spectrum is fitted by spectral models of the two brighter components, the normal early B-type and the He-strong star, because the flux contribution of the chemically peculiar late B-type is about 4-5%. The challenge of the analysis consists in the constraint that the spectroscopic solution should provide consistent ages, spectroscopic distances, mass ratio of the primary system and flux scaling factors. And additionally, because of the chemically peculiar composition of the He-strong star, dedicated grids of model spectra have to be computed to derive parameter combinations for $T_{\rm eff}$, $\log g$, microturbulence, projected rotational velocity, macroturbulence, helium abundance and individual metal abundances per star. Within the whole procedure, several parameters are interrelated with each other, therefore the analysis is intensively iterative. Figure 7 shows our best fit to the composite spectrum of one orbital phase. The Balmer lines do not allow to distinguish the contribution of the two components, but the He I lines and the stronger Si III lines show the contribution of the faster-rotator He-strong star on the spectral line wings. The faintest star cannot be constrained from the composite spectra, but only partially from its disentangled spectrum, from which $T_{\rm eff}$ can be estimated. Its surface gravity is challenging to be estimated from the Balmer lines, instead, it is constrained from its location in the HR diagram on the same isochrone than the other components (González et al., 2017).

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