Active OB stars: structure, evolution, mass loss, and critical limits
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Fundamental parameters of "normal" B stars in the solar neighborhood

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Abstract. Understanding phenomena of activity in stars, like pulsations or magnetism, benefits from systematic comparisons of some key physical parameters of active with those of "normal" stars. Here we concentrate on a careful derivation of fundamental parameters of a well selected sample of 27 "normal" B stars in nearby OB associations and in the field. A quantitative spectral analysis methodology based on hybrid non-LTE techniques is applied to high-resolution and high-S/N spectra. Results derived from the pure spectroscopic analysis are compared to other data/indicators of stellar parameters in order to prove the reliability of the method. Very good agreement is obtained among all of them. Besides the fundamental parameters, the chemical composition of the stars is also determined at high precision, turning out to be highly homogeneous. A comparative study of the present results with those of well known active massive stars will help to improve our understanding of the driving mechanisms of activity.

Keywords. stars: abundances, stars: atmospheres, stars: early-type, stars: fundamental parameters

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1. Introduction

In order to improve our understanding of the driving mechanisms of activity in stars, systematic comparisons of fundamental parameters like temperature, mass, age, radius, luminosity, chemical composition of "normal" and active – pulsating or magnetic – stars have to be performed. Once the parameters are determined at high precision, further comparisons of the observed characteristics of the stars surface with predictions of stellar evolutionary models may help us to understand the nature of the stars.

There are different methods to derive fundamental parameters of massive OB stars. Eclipsing binaries offer a direct method to determine masses, radii and distances based on the measurement of Doppler shifts in the spectrum and the geometrical configuration of the system. For single stars, interferometry is the most direct method to derive the star's radius. However, the nearest OB main sequence stars have an angular diameter below the measurement threshold of the current interferometers. Indirect methods are based on e.g. photometry, spectrophotometry, spectroscopy or asteroseismology. Photometric calibrations may provide only rough estimates of parameters that need to be confirmed with other, more accurate techniques. Spectrophotometry is also used to determine temperatures e.g. via the Balmer jump (see e.g. Adelman *et al.* 2002). The method can be used for early B-type stars, however it is more precise for stars of spectral class late-B or A, where the jump is larger and more sensitive to temperature changes. Photometric and spectrophotometric analyses depend on details of model atmospheres. On the other hand, asteroseismology also offers the possibility to derive fundamental parameters like

Table 1. Spectroscopic indicators for for $T_{\rm eff}$ and $\log g$ determination.

HD	H	He I	He II	C II	C III	C IV	O I	O II	Ne I	Ne II	Si III	Si IV	Fe II	Fe III
36512	x	x	x	x	x	x		x		x	x	x		x
149438	x	x	x	x	x	x		x	x	x	x	x		x
63922	x	x	x	x	x	x		x		x	x	x		x
34816	x	x	x	x	x			x	x	x	x	x		x
36822	x	x	x	x	x	x		x	x	x	x	x		x
36960	x	x	x	x	x			x	x	x	x	x		x
36591	x	x	x	x	x			x	x	x	x	x		x
205021	x	x	x	x	x			x	x	x	x	x		x
61068	x	x	x	x	x			x	x	x	x	x		x
35299	x	x		x	x		x	x	x	x	x	x	x	x
216916	x	x		x	x		x	x	x	x	x	x	x	x
74575	x	x		x	x		x	x	x	x	x	x	x	x
886	x	x		x	x		x	x	x		x	x	x	x
29248	x	x		x	x		x	x	x		x	x	x	x
16582	x	x		x	x		x	x	x		x	x	x	x
122980	x	x		x	x		x	x	x		x		x	x
35708	x	x		x	x		x	x	x		x	x	x	x
3360	x	x		x	x		x	x	x		x	x	x	x
160762	x	x		x			x	x	x		x		x	x
209008	x	x		x			x	x	x		x		x	x

mass, age, effective temperature and surface gravity. The interpretation of the observed frequency spectrum relies on stellar model assumptions, e.g. chemical composition, convection and rotation (see Briquet *et al.* 2010 for an example of an asteroseimic study of a O9V star).

Among the indirect methods, quantitative spectroscopy has become a very powerful technique to derive reliable fundamental parameters of massive stars. In the past years we have improved the spectral modeling and analysis of unevolved early B-type stars, being able to derive unprecedentedly accurate stellar atmospheric parameters from the spectrum only. The method can be applied to objects that are not deformed due to high rotation rates. Here, we go one step further to show that also the fundamental parameters derived by means of our techniques are highly reliable and can be used as reference for further studies of active stars. Moreover, a first systematic comparison of chemical patterns of "normal" and active stars using our techniques has already been undertaken as discussed in Przybilla & Nieva (these proceedings), showing promising results.

2. The sample: "normal" stars

An original sample of 27 well studied "normal" early B-type stars in OB associations and the field of the solar neighbourhood was selected from previous analyses of chemical abundances (references in Nieva & Przybilla, in prep.). The observational material comprises high-resolution (~40 000–48 000) and high S/N (~250-800) spectra with broad wavelength coverage obtained with FEROS on the ESO 2.2m telescope in La Silla, with FOCES on the 2.2m telescope at Calar Alto/Spain and also collected from the ELODIE archive (1.93 m telescope of the Observatoire de Haute-Provence). This material

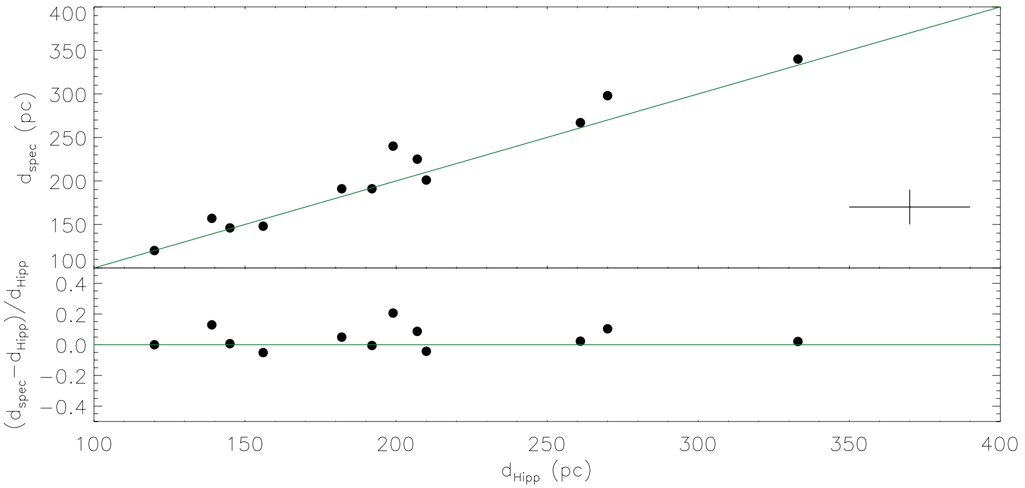

Figure 1. Spectroscopic vs. Hipparcos distances.

constitutes one of the highest quality for the quantitative spectral analysis of early B-type stars in the solar neighbourhood so far. After careful visual inspection of the spectra, 7 stars were identified as spectroscopic binaries or chemically peculiar stars and were removed from the sample. The final star sample containing 20 objects is listed in Table 1. Despite the stars were considered as “normal” in the past decades, half of them turned out to be of the β-Cephei type and some are magnetic, e.g. τ Sco (HD 149438).

3. Spectral Models and Analysis

Among the OB stars, early B-type stars on the Main Sequence are the best-constrained objects in terms of quantitative spectral analysis. In contrast to their hotter (early O) and luminous (OB supergiant) siblings, their atmospheric structure is much less sensitive to non-local thermodynamic equilibrium effects (non-LTE) and stellar winds. Classical atmospheric models assuming plane-parallel geometry, homogeneity and LTE are proven to represent their atmospheric structure very well (see e.g. Nieva & Przybilla 2007). However, most of their spectral lines are still subject to pronounced non-LTE effects nowadays well understood and constrained in the optical (see Przybilla 2008).

The model atmospheres are computed here with the Atlas9 code (Kurucz 1993b) and line blanketing is realised by means of opacity distribution functions ODFs (Kurucz 1993a). Non-LTE level populations are computed with Detail (Giddings 1981), that can treat even complex ions in a realistic way. The synthetic spectra are calculated with Surface (Butler & Giddings 1985), using refined line-broadening theories. Non-LTE spectra of all elements are computed using our most recent model atoms (see Przybilla, Nieva & Butler 2008 for references).

The analysis method is based on the use of different spectroscopic indicators, i.e. several Balmer lines and multiple ionization equilibria. The aim is to reproduce simultaneously all indicators via an iterative line-fitting procedure in order to derive atmospheric parameters and chemical abundances self-consistently. The stellar parameters primarily derived with this technique are the effective temperature $T_{\rm eff}$, surface gravity $\log g$, microturbulence ξ, macroturbulence ζ, projected rotational velocity $v \sin i$ and elemental abundances ε(X). Table 1 lists the star sample with the respective spectroscopic indicators, denoting with boxes established ionization equilibria. Within this method, the most relevant sources

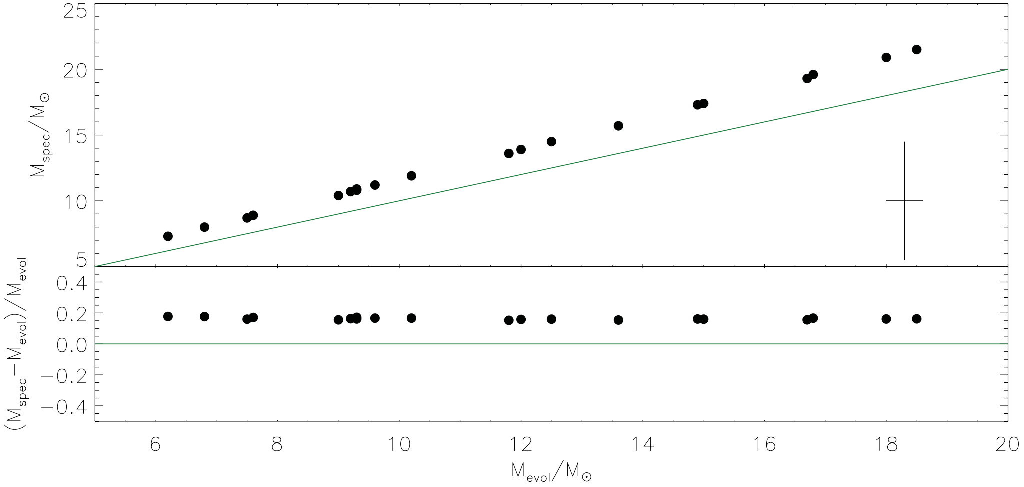

Figure 2. Spectroscopic vs. evolutionary masses.

of systematic errors were identified and consequently minimized (see Nieva & Przybilla 2008, 2010 for a discussion on this). Furthermore, the atmospheric parameters serve to compute the whole emergent stellar flux and to derive photometric quantities, like bolometric correction, colour excess and absolute magnitude, in an intermediate step to compute luminosity L, mass M, distance d and radius R.

4. Testing spectroscopic fundamental parameters

Stellar parameters derived spectroscopically can be tested against results obtained by other means. Here, we discuss tests for surface gravities, masses, effective temperatures, bolometric corrections, luminosities and chemical composition.

The determination of spectroscopic distances depends strongly on the surface gravity, more than on other quantities like evolutionary mass, effective temperature (through the model atmosphere flux at the stellar surface) and dereddened apparent magnitude (Ramspeck *et al.* 2001). Therefore, surface gravities can be tested by comparing the spectroscopic distances with distances derived from Hipparcos parallaxes (new reduction by van Leeuwen 2007), as shown in Fig. 1. The spectroscopic and *Hipparcos* distances agree very well within the uncertainties.

The spectroscopic masses depend on the gravity, the distance (therefore, also indirectly on the evolutionary mass) and the effective temperature. The distance allow to determine the luminosity, and radii are derived from from L and $T_{\rm eff}$. The spectroscopic masses can be compared with masses derived from stellar evolutionary tracks (e.g. Meynet & Maeder 2003), as displayed in Fig. 2. They show a constant offset of $\sim$ 15%, that may be due to the different metallicity of the evolutionary models ($Z = 0.020$) and the star sample ($Z = 0.014$), among other reasons that need to be investigated. However, the offset is relatively small when compared to a variable factor of typically 0–2 for stars up to $25\,M_\odot$ (e.g. Repolust *et al.* 2004).

Other tests – not shown here – prove the reliability of the results concerning the effective temperatures, bolometric corrections, luminosities and chemical composition. Effective temperatures derived from multiple ionization equilibria coincide with those determined via spectral energy distributions from the UV to the IR, but are by far more precise. Bolometric corrections for the hotter stars agree with values from Vacca *et al.*

(1996) and Martins *et al.* (2005). The mass-luminosity relation of the sample agrees very well with theory (Maeder 2009, p. 625ff.). Furthermore, the chemical composition of the star sample is highly homogeneous, in agreement with recent findings by Przybilla, Nieva & Butler (2008). Details on the remaining comparisons not shown here can be found in Nieva (in prep.) and Nieva & Przybilla (in prep.).

5. Conclusions

The determination of fundamental parameters can be performed following different, direct or indirect methods. No matter which technique we use, it is necessary to cross-check the results with independent methods or measurements in order to test their reliability. Further comparisons between observational constraints and stellar evolutionary model predictions are only meaningful when the derived stellar parameters are reliable and describe the physical properties of the stars consistently. Here, we presented a very well studied sample of “normal” early B-type stars representative for the solar neighbourhood. The sample has very high-quality spectra and has been carefully inspected before the analysis. Several stellar – atmospheric and fundamental – parameters derived by means of our self-consistent spectroscopic method have been successfully tested against independent measurements, indicators and model predictions. This study offers a solid basis for further investigations by comparing some key properties of “normal” and active stars (see Przybilla & Nieva, these proceedings).

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