Bulletin de la Société Royale des Sciences de Liège, Vol. 80, 2011, p. 175 - 179

Near-IR spectroscopy of OB stars with VLT/CRIRES*

Maria-Fernanda Nieva[1], Norbert Przybilla[2], Andreas Seifahrt[3,4], Keith Butler[5], Hans-Ulrich Käufl[6], Andreas Kaufer[7]

[1] Max-Planck-Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany
[2] Dr. Karl Remeis-Observatory & ECAP, Sternwartstr.7, D-96049 Bamberg, Germany
[3] Physics Department, University of California, Davis, CA 95616, USA
[4] Institut für Astrophysik, Georg-August-Universität Göttingen, Friedrich-Hund Platz 1, D-37077, Germany
[5] Universitätssternwarte München, Scheinerstr. 1, D-81679 München, Germany
[6] ESO Garching, Karl-Schwarzschild-Str. 2, D-85784 Garching, Germany
[7] ESO Santiago, Alonso de Córdova 3107, Casilla 19001, Santiago 19, Chile

Abstract: We have conducted a pilot observational programme in order to obtain very high resolution near-IR spectra ($R\sim 100\,000$) with wide wavelength coverage in the JHKL bands of early B-type stars with CRIRES on the VLT. The sample comprises a B0.2 V, a B0 III and a B1.5 III star, which have already been thoroughly analysed by us in previous work in the optical. The stars span a range of about 9000 K in effective temperature, thus covering different ions of several elements. A novel data reduction technique was carried out which facilitated telluric lines removal by precise modelling of the Earth's atmospheric spectrum. We investigate to what extent it is possible to derive atmospheric parameters and chemical abundances of early B-type stars from near-IR spectroscopy only. For this purpose we have extended our non-LTE spectral modelling to applications in the near-IR, based on our state-of-the-art model atoms that were thoroughly tested previously in the optical. Most H, He, C, N, O, Mg and Si lines in the near-IR (some of them resolved for the first time) could be reproduced, allowing atmospheric parameters and chemical abundances to be derived. Some remaining discrepancies between synthetic and observed strong lines, and some lines unidentified due to a lack of atomic data need to be investigated further. We have succesfully tested our modelling techniques and quantitative spectral analysis in the near-IR at high resolution and obtained excellent agreement with previous precision work in the optical. This will allow us to perform reliable spectral analyses of early B-type stars that suffer from strong optical extinction in the future, based on near-IR observations alone.

1 Introduction

The lifetimes of massive stars on the main sequence are so short ($\sim 10^6$–10^7 yr) that they are confined to their nursery[1]. Massive stars are expected to have the same chemical composition as their parent clouds, hence they are valuable metallicity indicators, a key to the understanding of star-formation processes, massive star evolution and galactic chemical evolution. Stars enshrouded by gas and dust

*Based on observations obtained at the European Southern Observatory, proposal 079.D-0810(A).
[1]Except for runaway or hypervelocity stars.

can suffer strong extinction of more than 10-20 mag in the visual. The dust and gas surrounding them becomes more transparent in the IR regime. Near-IR spectroscopy thus opens a new window to study stars in regions with high optical extinction.

Quantitative spectroscopic techniques make the derivation of stellar chemical abundances possible, however they rely on many model assumptions. Among the hot stars, less massive ($M \leq 20\,M_{\odot}$) and unevolved OB dwarfs and giants (luminosity class V to III) present much simpler radiative stellar atmospheres than hotter and more luminous stars. Weak stellar winds only affect the cores of the strongest spectral lines. Classical atmospheric models assuming plane-parallel geometry, homogeneity and even LTE have been shown to represent their atmospheric structure very well (see e.g. Nieva & Przybilla 2007, hereafter NP07). However, most of their spectral lines are still subject to non-LTE effects, nowadays well understood and constrained in the optical (see the review by Przybilla 2008) but still not thoroughly studied in the whole near-IR regime at high spectral resolution. Amplified non-LTE effects in the Rayleigh-Jeans tail of the stellar spectrum pose a challenge to the spectral modelling and analysis of the near-IR regime of massive stars (Lenorzer et al. 2004, Przybilla & Butler 2004). We concentrate here on early B-type stars, the least massive but potentially best-constrained objects among the massive stars in terms of quantitative spectral analysis.

So far, only a few groups have complemented the observational studies at lower resolution by implementing spectral modelling and quantitative analyses of massive stars in the near-IR. For example, Lenorzer et al. (2004) provided synthetic spectra based on the TLUSTY code for 9 H and 13 He lines for O-stars in the J, H and K bands. Repolust at al. (2005) analysed quantitatively 2 H and 8 He lines in OB main sequence to supergiant stars based on spectra of Hanson et al. (2005) by means of the FASTWIND code (Puls et al. 2005). Detailed chemical abundance studies and spectral modelling development require not only strong H and He but also weak metal lines to be resolved. For a slow-rotator like τ Sco, an $R = \lambda/\Delta\lambda \sim 75\,000$ is required. Hence, the detection of weak metal lines is not possible at intermediate or low spectral resolution. The advent of new and powerful instruments like CRIRES (CRyogenic high-resolution InfraRed Echelle Spectrograph, Käufl et al. 2004) on the Very Large Telescope allows us to study a large part of the spectrum ($\sim$1-5 μm) at extremely high resolution ($R = 100\,000$).

Our pilot observational programme aimed at obtaining very high resolution spectra of early B-type stars with wide wavelength coverage in the CRIRES range, similar to the objectives of the recent CRIRES-POP survey (Ramsay et al. 2011). The stars had already been carefully studied in the optical using FEROS spectra and our newest spectral modelling and analysis technique (NP07; Nieva & Przybilla 2006, 2008, hereafter NP06, NP08, respectively; Przybilla, Nieva & Butler 2008, PNB08). Our final goal is to derive atmospheric parameters and chemical abundances of early B-type stars in the near-IR regime only. We concentrate on the identification of all possible spectral indicators – H, He, C, N, O, Mg and Si lines – that are available in the cooler and hotter stars from different ions. We also test the capabilities of our spectral modelling technique to reproduce the spectral lines in the near-IR and test to what extent the quantitative analysis provides parameters and chemical abundances comparable to those from our previous precision analyses in the optical.

This work is of broader interest for current near-IR studies of hot stars in the Milky Way at lower spectral resolution than the one achieved in the present work because of the identification and modelling of many spectral features not observed so far. Further applications are e.g. for massive stars near the Galactic Centre, hot stars in ultra compact H II regions or reddened high-mass X-ray binary systems. The work also constitutes useful preparation for the science to be done with the next generation of extremely large telescopes (ELTs), which will apply adaptive optics techniques to resolve crowded fields of stars at near-IR wavelengths throughout the Milky Way and beyond. Moreover, the observational dataset will contribute to the upper HR diagramm of the spectral library CRIRES-POP (Lebzelter et al. 2010).

Table 1: Atmospheric parameters of the programme stars.

Parameter	τ Sco HD 149438	HR 3055 HD 63922	HR 3468 HD 74575
Sp.Type	B0.2 V	B0 III	B1.5 III
$T_{\rm eff}$ (K)	32000 ± 300	31200 ± 300	22900 ± 400
$\log g$ (cgs)	4.30 ± 0.05	3.95 ± 0.05	3.60 ± 0.05

2 The star sample

Three stars were selected for this study, one main sequence and two giant stars, spanning ~9000 K in effective temperature. The sample size is constrained by telescope time because of the large spectral coverage selected for the study. The stars have been thoroughly analysed by us in the optical based on high quality FEROS spectra ($S/N \sim$ 500-800, R ~ 48 000). They are a sub-sample of recent work that defines the present-day cosmic abundance standard locally (PNB08) and serve as reference to test model atoms for non-LTE line-formation calculations. They are located in OB associations and the field of the Solar Neighbourhood. Note that no massive star has so far been spectroscopically analysed to such an extent as the sample defining the present-day cosmic abundance standard. For the first time practically all observable H and He (NP07), carbon (NP06, NP08), nitrogen, oxygen, neon, magnesium, silicon and iron lines (PNB08) have been matched simultaneously in these stars in the visual by means of a hybrid non-LTE approach based on state-of-the-art model atoms. Some observed H and He lines have also been reproduced in the near-IR by NP07. The stellar parameters have been constrained to unprecedented accuracy by taking the Balmer and He lines and 5-6 independent ionization equilibria simultaneously into consideration. Table 1 provides ids, spectral types, effective temperatures $T_{\rm eff}$ and surface gravities $\log g$ of the stars as derived by NP08 and PNB08.

3 Data reduction of CRIRES spectra

The basic data reduction followed the standard recipes for long-slit infrared spectrographs. Observations were always performed in a single AB nodding pattern for all wavelength settings. Pairwise subtraction removed the atmospheric emission features and the individual A−B and B−A frames were divided by a normalized flatfield. The flatfielding step corrected the pixel-to-pixel gain variations of the chips but due to repeatability problems of the intermediate slit of CRIRES this step influenced the slope of the continuum which had to be corrected in a final step of the data reduction.

An ESOREX recipe of the CRIRES data reduction pipeline was used for optimal extraction of the 1D spectrum in each nodding position. The two 1D spectra of each setup and target combination were then cross-correlated to identify offsets in wavelength due to the slit curvature, shifted accordingly and co-added. In this step we removed the imprints of optical ghosts that are present in one of the two nodding positions in most J and H band settings and filtered cosmetic artefacts and outliers by an iterative procedure. The telluric absorption lines still contained in the processed 1D spectra could not be removed by dividing the spectrum by that of an early type standard star since this would have compromised the intrinsic features of our targets. Instead we have modelled the telluric features using the FASCODE algorithm (Clough et al. 1981, 1992), a line-by-line radiative transfer code for the Earth's atmosphere, and HITRAN (Rothman et al. 2005) as a database for molecular transitions. GDAS[2] atmospheric profiles were used as input for FASCODE and gave the necessary information for temperature, pressure, and humidity as a function of height in the atmosphere. The profiles were

[2]Global Data Assimilation System

retrieved from the NOAA website[3] for the two nights of observations. The amount of precipitable water vapour predicted by the models was adapted to achieve an optimal fitting in comparison to our measurements. The resulting spectra were smoothed with a Gaussian kernel to match the resolution of the science spectra. In a final step the telluric absorption features were then removed by dividing the science spectra by the model spectra. A more detailed discussion on the performance and limitations of using synthetic spectra to remove telluric absorption features is given in Seifahrt et al. (2010). The wavelength calibration is primarily based on the prediction of the physical instrument model implemented in the CRIRES data reduction pipeline. The initial wavelength calibration obtained with the pipeline was then refined by shifting the wavelength zero point and scaling the dispersion when fitting the telluric model to the observation. The final accuracy achieved for the majority of the settings is of the order of a 1/10 of a resolution element.

Continuum normalization is challenging for settings/chips in regions where broad hydrogen or helium lines are spread over 2-4 orders. Fortunately a sample of A supergiants (Przybilla et al., in prep.) that present sharper H lines and almost no He lines has also been observed in the same run. Division of the B-star spectra by the continuum derived from an A-supergiant around the broader lines allowed an improved normalization to be performed.

4 Stellar spectrum model calculation and analysis

The hybrid non-LTE approach solves the restricted non-LTE problem on the basis of prescribed LTE model atmospheres. Classical atmospheric models assuming plane-parallel geometry, homogeneity and even LTE are proven to represent very well the atmospheric structure of unevolved B-type stars (NP07). This approach also allows extensive non-LTE model atoms to be implemented, facilitating a highly detailed treatment of the atomic processes involved. We compute line-blanketed LTE model atmospheres using the ATLAS9 code (Kurucz 1993). Non-LTE population numbers and synthetic spectra are then obtained with recent versions of DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985). The coupled radiative transfer and statistical equilibrium equations are solved with DETAIL, employing the Accelerated Lambda Iteration (ALI) scheme of Rybicki & Hummer (1991). Synthetic spectra are calculated with SURFACE, using refined line-broadening theories. The non-LTE model atoms for hydrogen and He I/II adopted in the present work are described in detail by Przybilla & Butler (2004) and Przybilla (2005), respectively. Use of improved atomic data for electron impact excitations, in particular from *ab-initio* computations, allows consistent results from the hydrogen lines in the visual and near-IR to be derived throughout the entire range of early-A to O stars . The He I/II model atom has been successfully used to reproduce observed trends of the highly non-LTE-sensitive He I λ 10 830 Å transition in early-type main sequence stars (Przybilla 2005) and visual/near-IR spectra of extreme helium stars with B-type spectra (Przybilla et al. 2005, 2006b) and subluminous B stars (Przybilla et al. 2006a).

Photospheric lines in emission indicate the pure non-LTE nature of the transitions, i.e. the upper level is overpopulated due to the non-LTE effects. It is not possible to reproduce these lines with standard LTE techniques. So far two photospheric carbon lines in emission have been reported for the hotter stars and reproduced by us in the optical (NP06). An interesting result from this work is the finding of several photospheric lines in emission, which confirms the expected large non-LTE effects at these wavelengths. Direct application of existing non-LTE codes does not guarantee that all lines will be reproduced since the non-LTE effects are very sensitive to the choice of the input atomic data. Comparisons of model predictions based on stellar parameters and chemical abundances as derived in the visual to spectral line profiles in the near-IR are displayed in Fig. 1. The formation of some

[3]`http://www.ready.noaa.gov/ready/amet.html`

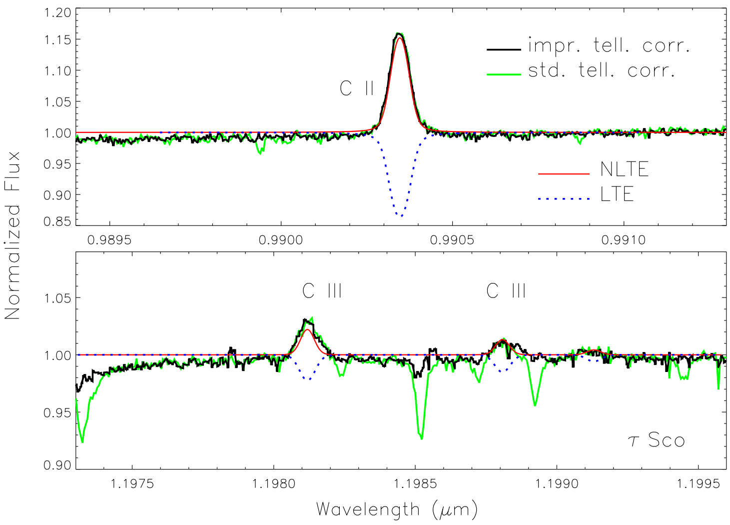

Figure 1: Example of observations vs. model predictions to C II/III lines. Our NLTE models agree very well with observation. LTE models are not able to reproduce the stellar spectrum. Different solutions for telluric line corrections are presented, one with standard values for parameters of the Earth's atmosphere (std.) and for the atmospheric conditions for the nights of the observations (improv.).

strong lines has to be investigated further in order to reproduce them by theory. Note that atomic data like line broadening parameters of some He lines in the near-IR are still not available. The strongest H lines may also be sensitive to stellar winds, unaccounted for in our approach. However, some lines like Brα in τ Sco pose a challenge, even when investigated with hydrodynamic non-LTE model atmosphere codes (see Przybilla & Butler 2004). More details can be found in a forthcoming paper (Nieva et al., in prep.)

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