A spectroscopic atlas of the A7 Ib supergiant ι Carinae in the near-IR

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High-quality spectral atlases provide the basis for the exploration of the line features in stellar spectra and provide benchmarks for the comparison of models with observations. Currently, we face a dearth of high-resolution spectral atlases of the near-IR wavelength range, with only two such atlases available, for the Sun and for Arcturus. The CRIRES-POP project aims at making available high-quality atlases covering the 1-5μm range for strategic targets throughout the Hertzsprung-Russell diagram. Here, we discuss the preparation of a high-resolution ($R \approx 100\,000$), high-signal-to-noise ratio ($SNR > 200$) near-IR spectral atlas of the A7 Ib supergiant ι Car. Using BRITE-Constellation data we find that the star is not variable, facilitating a meaningful spectral atlas to be constructed from nearly 200 spectral exposures collected throughout a year of service observations with CRIRES on the ESO VLT. Emphasis is given on the different reduction steps in the atlas preparation, and on problems encountered in the process.

1 Introduction

Massive stars are key drivers of galactic evolution throughout their short life cycles. Their strong stellar winds and spectacular ends as core-collapse supernovae enrich the interstellar medium with heavy elements. Moreover, their kinetic and radiation output drives star formation in their neighbourhood (e.g. Kennicutt, 2005).

On the observational side, massive A-type supergiants (A-SGs) play a particular role, because they are among the visually brightest normal stars in spiral and irregular galaxies due to their high intrinsic luminosities combined with their small bolometric corrections (e.g. Przybilla et al., 2006; Kudritzki et al., 2008). These objects will remain interesting science targets for extragalactic stellar astronomy in the era of ground-based observations with extremely large telescopes like the European-Extremely Large Telescope (E-ELT) or the Thirty Meter Telescope (TMT) because they are comparatively bright in the near-infrared (NIR) as well, and because they are easy to be identified from their colours (with red supergiants being the other objects of choice). The step towards the NIR becomes necessary in order to use the full potential of the ELTs for diffraction-limited observations via adaptive optics techniques. A second driver for observations in the NIR is to overcome the limitations that extinction poses to studies of objects throughout the Galactic disk in the optical, and towards the Galactic Centre in particular.

The NIR spectra of A-SGs contain information on most of the astrophysically interesting chemical species, encompassing the light elements (He, CNO), iron-group species and α- and s-process elements. Therefore, they are suited to study both stellar

Table 1: Properties of ι Car

Property	Value	Reference	Property	Value	Reference
RA(J2000)	$09^{\mathrm{h}}17^{\mathrm{m}}05^{\mathrm{s}}$	1	T_{eff}	7500 K	4
DEC(J2000)	$-59°16'31''$	1	$\log g$	2.40	4
Parallax	4.26 ± 0.10 mas	1	$v \sin i$	$10.0\,\mathrm{km\,s^{-1}}$	4
SpT	A7 Ib	2	M	$7.4\,M_{\odot}$	4
RV	$12 \pm 0.3\,\mathrm{km\,s^{-1}}$	3	$\log L/L_{\odot}$	3.69	4

References. (1) van Leeuwen (2007); (2) Gray & Garrison (1989);
(3) Gontcharov (2006); (4) Smiljanic et al. (2006)

and galactochemical evolution in a wide variety of environments (field galaxies, groups and clusters of galaxies). This facilitates investigations of the metallicity dependence of stellar winds and stellar evolution, of Galactic abundance gradients and the Galactic mass-metallicity relationship.

Important for realising the full potential of quantitative spectroscopy of A-SGs in the NIR will be that the analysis methodologies for the NIR spectral range will become comparable in accuracy and precision to those used in the optical currently. A major complication involves the amplification of non-LTE effects in the NIR of hot stars (see e.g. Przybilla & Butler, 2004; Przybilla, 2010).

Crucial for the development of the field is the availability of high-quality observational material for benchmarking the models and for exploring which line features are available for the atmospheric parameter determination and the abundance analysis. One would like to have available high-resolution and high-SNR spectral atlases of the NIR wavelength range of A-SGs comparable to those of the Sun (Delbouille et al., 1981) and of Arcturus (Hinkle et al., 1995).

2 CRIRES-POP

CRIRES-POP (Lebzelter et al., 2012) uses the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) on the ESO Very Large Telescope (VLT) to construct a high-quality (high-resolution and high-SNR) library with full wavelength coverage of the NIR spectra ($\sim 1\,\mu$m to $5\,\mu$m) of 26 representative stars throughout the Hertzsprung-Russell diagram, covering most of the important stellar evolutionary stages. The instrument provided wavelength coverage between 950 nm and 5300 nm with a measured 2-pixel resolving power of $R = \lambda/\Delta\lambda = 96\,000$ (at 2172 nm, Käufl et al., 2004). Despite its echelle configuration, CRIRES recorded in the available configuration only one spectral order, spread over four Aladdin III InSb arrays which introduced three small gaps into each exposure. About 200 instrumental settings (each providing four spectral pieces) were therefore required to obtain full wavelength coverage of the transparent atmospheric windows in the NIR. This corresponded to a total of ~8 hours of observing time to reach a $SNR > 200$ for a bright star like ι Car (A7 Ib, ~1.6 mag in J to K), which is the representative of the A-SGs within CRIRES-POS. The individual pipeline-reduced 1-D spectra for all target stars are already publicly available via the CRIRES-POP webpage `http://www.univie.ac.at/crirespop/`.

As CRIRES-POP was implemented as a filler program, the observations of ι Car were e.g. executed during eight nights spread over an entire year. For the construction of a spectral atlas such a time span becomes relevant if the target star is variable.

Table 2: Result of the Fourier analysis of ι Car. The frequency is given in d^{-1}, the amplitude A in mmag, the signal-to-noise ratio in terms of a confidence level σ. Multiples denote the harmonics of the orbital frequency of the BRITE satellites of $\sim 14.4\,\mathrm{d}^{-1}$.

f	A	SNR	Multiple	f	A	SNR	Multiple
0.028	0.735	5.88		43.027	0.425	9.30	$3f_{\mathrm{orb}}$
14.263	0.479	5.72	f_{orb}	43.046	0.425	11.00	$3f_{\mathrm{orb}}$
14.325	0.478	7.18	f_{orb}	57.345	0.420	7.05	$4f_{\mathrm{orb}}$
29.281	0.487	3.81	$2f_{\mathrm{orb}}$	100.376	0.353	7.86	$7f_{\mathrm{orb}}$
29.681	0.466	4.57	$2f_{\mathrm{orb}}$				

Literature data on the apparently single star ι Car are summarised in Table 1. Concerning variability of ι Car one can find two different viewpoints. Adelman et al. (2000) found that the star is among the photometrically least variable stars investigated by Hipparcos, while Ruban et al. (2006) support the presence of some kind of variability. We therefore reinvestigated the issue based on new observations.

3 Variability analysis

Stellar pulsations periodically change a star's magnitude, temperature, density and radius. These changes impact line strengths via modifications of the excitation and ionization state of the plasma. Periodic Doppler-shifts corresponding to expansion and contraction of various parts of the star occur. Depending on the pulsation profile of the star, the shape of spectral lines can also be distorted asymmetrically.

The spectroscopic observations of ι Car were obtained over a year; therefore pulsations and time-dependent changes of spectral lines are a potential issue to be considered for the construction of a spectral atlas. The BRIght Target Explorer (BRITE) Constellation provided suitable data for a pulsation analysis.

The five nanosatellites of the BRITE-Constellation provide precise photometric time-series measurements of bright stars on a Sun-synchronous 800-km high polar orbit. During one 100-minute orbit a target field is observed for about $15-35$ minutes and about $3-4$ times per minute. Each satellite is equipped with a 3-cm five or four-lens (Heweliusz only) telescope, a 4008×2672 pixel CCD detector and a filter.

ι Car was observed for about two months with the Austrian satellite BRITE-Austria (BAb) and the Canadian satellite BRITE-Toronto (BTr) using five and three different instrumental setups, respectively. The data reduction included removal of outliers, decorrelation of instrumental parameters and clipping. A Discrete Fourier Transform with pre-whitening was performed for the frequency analysis.

The frequency analysis was performed for each individual dataset and for all datasets combined, with the results listed in Table 2. The orbital period of the satellites of ~100 minutes leads to a fundamental orbital frequency of $\frac{24\cdot60\,\mathrm{min/d}}{100\,\mathrm{min}} = 14.4\,\mathrm{d}^{-1}$. Several multiples of this frequency (harmonics) were found in the analysis.

Only the lowest significant frequency with a period of $1/0.028 = 35.7\,\mathrm{d}$ was found not to be a harmonic of the fundamental orbital frequency. However, this low frequency only appears in one of the eight datasets, and it has to be noted that the total observing time spans less than the period of this frequency. Therefore, this frequency may relate to a non-linear offset and is discarded. We conclude that ι Car does not show any significant variability.

4 Telluric correction

CRIRES-POP employs a modelling approach to eliminate telluric absorption lines because of the large overheads required for the observation of telluric standards. Moreover, these rarely provide a perfect match to the telluric spectrum science target, effectively limiting the precision to which telluric features can be removed (Seifahrt et al., 2010). We adopted the software-tool *Molecfit* (Smette et al., 2015; Kausch et al., 2015), which uses the Line-By-Line Radiative Transfer Model code (Clough et al., 2014), the HIgh-resolution TRANsmission molecular absorption database (HITRAN, Rothman et al., 2009) and a layer model of Earth's atmosphere.

The stellar spectra in the Y, J and H bands and in the K, L and M bands were corrected by Kondrak (2014) and Ebenbichler (2015), respectively, by optimising parameters within *Molecfit*. The z-band data were corrected in the course of the present work.

5 Constructing the spectral atlas

Since the measured flux depends on the instrumental response function in each of the four detector chips of CRIRES, we normalised each of the over 750 single spectral pieces for the atlas preparation. Either a polynomial of second order or two different polynomials that were smoothly connected at a specific point on a chip were employed for this purpose. The broad absorption lines of hydrogen, which can cover several instrumental settings, required particular care in the normalisation process.

In the preparation of the merging of individual spectral pieces we noted that the wavelength calibration provided by the CRIRES pipeline faces problems in some wavelength ranges, resulting in non-linear wavelength shifts. Instead, a refined wavelength solution provided by *Molecfit* was used, based on the telluric line list. A heliocentric correction was applied to all spectra, as well as a Doppler correction for the constant radial velocity RV of ι Car with respect to the Sun in order to bring the spectra to the laboratory rest frame. The wavelength solution was finally transformed from vacuum to air wavelengths using the formula provided by Morton (1991) to facilitate a better comparison with existing line databases.

Low-quality data like spectra with low SNR or with apparently unreliable wavelength solution, or wavelength regions affected by an instrumental ghost were omitted in the co-addition and merging of spectral pieces. Such losses could be tolerated because most wavelength regimes are covered by several settings of CRIRES, providing a high degree of redundancy against potential problems in the spectral atlas construction and yielding typically a much higher SNR than the anticipated minimum value. An exception were spectral regions at the edges of the atmospheric windows with pronounced residuals from the telluric line removal (occurring for nearly-opaque lines) — they were discarded, as they they do not provide any viable information. Most of the detailed production steps were performed by Kondrak (2016), while the z-band was included within the present work.

The spectral line identification was initiated on the basis of the distinctive hydrogen lines and the numerous, typically strong and easily identifiable C I lines in this star. The Kurucz line list was employed using standard elemental abundances, energy level information and oscillator strengths to identify observed lines. Particular emphasis in the process was given to the verification of the presence of multiplet components in the correct line strength ratios.

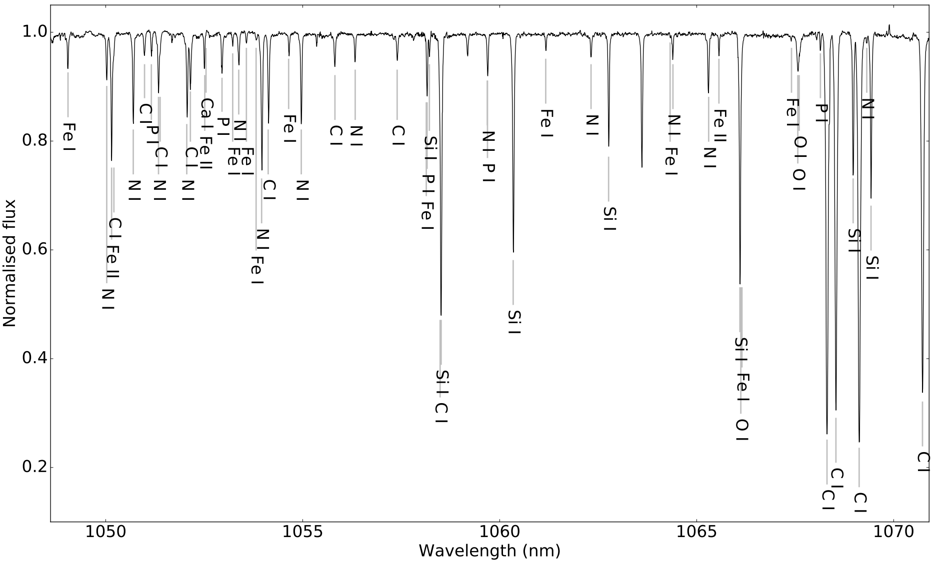

Fig. 1: Example of a small part of the spectral atlas of ι Car in the Y-band.

6 Summary and conclusions

We have given an overview on the pioneering work of the construction of a high-resolution ($R \approx 100\,000$) and high-SNR (> 200) spectral atlas in the NIR ($1\,\mu$m to $5\,\mu$m) for the A7 Ib supergiant ι Car, the first such atlas becoming available besides the work on the Sun and on a K-giant. Based on BRITE-Constellation photometry, ι Car was found to be invariable, which allowed the meaningful merging of about 200 spectra of small wavelength coverage obtained within the CRIRES-POP project over a year. Especially challenging was the sheer volume of data to be processed, in particular with regard to the telluric correction, and the necessary improvements to the pipeline-produced wavelength solutions, which were found to be flawed in some spectral ranges because of the scarcity of suitable lines in the wavelength calibration frames.

The atlas allows the completeness not only of the spectral line lists of relevance to the stellar spectrum to be investigated, but also the completeness and accuracy of the HITRAN database to be tested. While the latter will help to reduce remaining residuals in the telluric correction, the former may stimulate laboratory experiments to assign the unidentifiable lines. Currently, more than 1000 lines are identified in the NIR spectral atlas, with further efforts still ongoing.

A full quantitative analysis of the NIR spectrum and a comparison with results of the optical analysis is already initiated. Atmospheric and fundamental stellar parameters, as well as chemical abundances will be published together with the final spectral atlas of ι Car in the near future.

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