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THE X-SHOOTER SPECTRAL LIBRARY AND CARBON STARS

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Abstract. Until recently, most empirical stellar spectral libraries were limited to a certain wavelength range or combined data from different stars, taken by different instruments of which some have low spectral resolution, limiting for instance our ability to analyze galaxies jointly in the ultraviolet, the optical and the near-infrared. The X-shooter Spectral Library, XSL, obtained using the X-shooter three-arm spectrograph on ESO's VLT, will help solving the current limitations. Here, we focus on spectra of carbon stars, which are part of this library. Carbon stars contribute significantly to the integrated spectra of galaxies containing young and intermediate-age populations, especially in the near-infrared, and therefore should be properly taken into account in stellar population synthesis models. A comparison with theoretical spectra is necessary to estimate the fundamental parameters of the observed stars, as well as to validate the spectral models across the broad ultraviolet to near-infrared wavelength range of X-shooter. We present preliminary results of such comparisons.

Keywords: spectroscopy, x-shooter, near-infrared, carbon stars

1 Carbon stars from the X-shooter Spectral Library

Stellar population models are powerful tools, widely used to determine galaxy ages, metallicities and abundances. The key ingredients for population synthesis are libraries of stellar spectra. However, up to now, no single empirical spectral library provides both a very broad wavelength range and a good spectral resolution. The X-shooter Spectral Library (XSL, Chen et al. 2011) is intended to meet this need.

XSL is being obtained using the X-shooter three-arm spectrograph on ESO's VLT (Vernet et al. 2011). What makes it unique is that it collects spectra over a broad wavelength range – ultraviolet (UVB), visible (VIS) and near–infrared (NIR) – simultaneously, as shown in the right panel of Fig. 1. This characteristic is particularly useful for observing variable stars, such as the cool asymptotic giant branch stars that contribute significantly to the light of galaxies.

Thanks to an ESO Large Programme, this stellar library will consist of about 600 stars, observed at moderate resolution (R $\sim$ 10 000), with complete coverage from 320 to 2480 nm, covering a large range of stellar parameters (L, Teff, [Fe/H]), as shown in the left panel of Fig. 1. The purpose is to sample the full range of relevant spectral types, in order to feed population synthesis models adequately.

Among the diversity of stars in XSL, we focus here on one spectral type: C-star. Carbon stars are among the brightest stellar objects in resolved galaxies containing young and intermediate age populations, mainly radiating in the near-infrared. In addition, they contribute significantly to the integrated spectra of such systems. Thus, it is important to take C stars into account properly in population synthesis.

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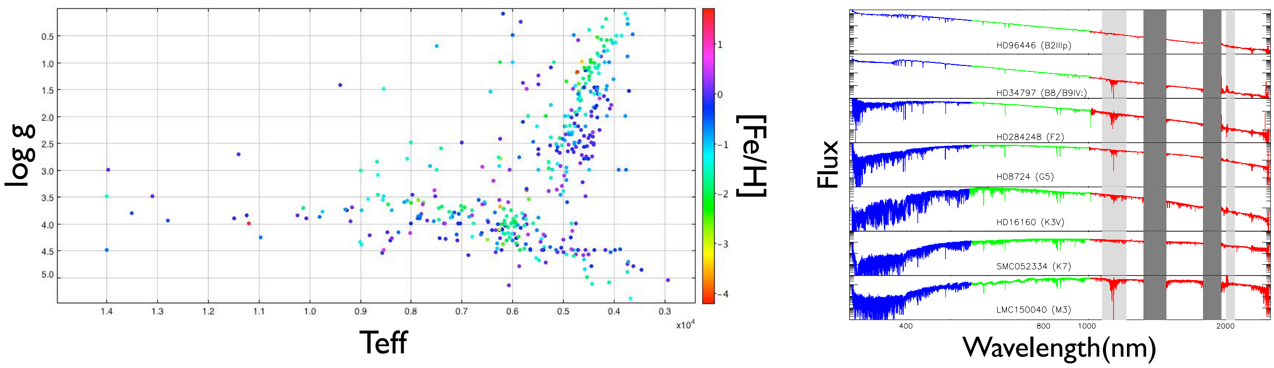

Fig. 1. Left: XSL sample (only 436 stars are represented here). **Right:** A sample of XSL stellar spectra sorted by temperature, taken from Chen et al. (2011). Grey bars cover areas of telluric absorption in the near-infrared.

Forty C-star spectra are currently found in XSL. We focus on a sub-sample of them for this preliminary study. Our goal is to answer this question: can the observed spectra across the whole wavelength range (visible to near-infrared) be reproduced with synthetic spectra based on a specific hydrostatic model atmosphere and artificially reddened according to a standard reddening law? In section 2, we will introduce the models used for this study. Then, in sections 3 and 4, we will present the results of our comparisons.

In this paper, we will not expand on the data reduction. We refer the readers to Chen et al. (2013) for the reduction of the two first semesters of data for the UVB and VIS arms. Details about the procedure adopted for the NIR arm of X-shooter will be provided in a forthcoming paper.

2 Hydrostatic model atmospheres for C-rich giants

The set of models used for this study are the model atmospheres of C-rich giants calculated by Aringer et al. (2009). These authors computed a grid of 746 spherically symmetric COMARCS atmospheres covering effective temperatures between 2400 and 4000 K, surface gravities from $\log(g[\mathrm{cm/s}^2])= 0.0$ to -1.0, metallicities ranging from the solar value down to one-tenth solar and C/O ratios in the interval between 1.05 and 5.0. Figure 2 shows examples of such models.

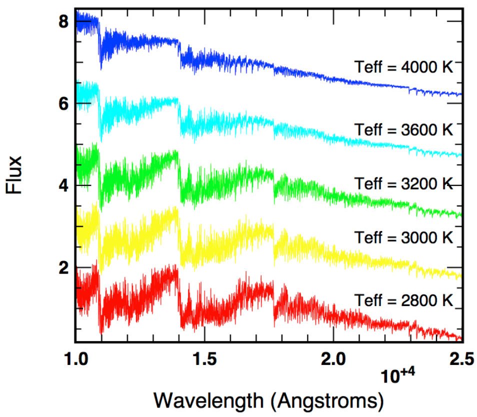

Fig. 2. Synthetic NIR spectra for C-rich giants of a fixed C/O=1.1, adapted from Aringer et al. (2009)

In their analysis, Aringer et al. show that the models reproduce the colours of the warmer carbon stars with weak pulsation. But to deal with cooler objects with intense variations, a proper treatment of the reddening caused by dusty envelope is needed. Thus, more sophisticated model atmospheres are needed to deal with more evolved red giants for which dynamic phenomena (pulsations of the stellar interiors and developments of dusty stellar winds) become significant, as demonstrated by Nowotny et al. (2011).

In our study, we use a subset of models with solar abundances and a variety of C/O ratios (1.05, 1.1, 1.4 and 2.0) and effective temperatures(2800, 3000, 3200, 3600, 4000 K). All the models are computed with log(g) = 0.0 and 1 $M_{\odot}$, at a constant spectral resolution R = 200 000.

These models focus on objects that can be described by hydrostatic models neglecting dynamical phenomena such as pulsation and mass loss. As a consequence, the reddening due to circumstellar dust is not included.

3 Best fit to NIR observations

In order to see if a single reddened hydrostatic model can reproduce the observed X-shooter C-star spectra, we perform a χ^2 minimization on a three-dimensional parameter space: Teff, C/O and A_V. We redden the dust-free models using a standard extinction law, following the prescription of Cardelli et al. (1989). We focus first on the near-infrared wavelength range, as carbon stars emit mostly in that spectral range.

Figure 3 provides an example of such a comparison. The black curve represents our XSL-NIR spectrum of a C-star with $(J-K) = 1.38$. The red curve is the best fit found. The grey bands mask the regions of strongest telluric absorption. We show the comparisons at two resolutions : a lower one with R $\sim$ 2 300 and a higher one with R $\sim$ 8 000. The models provide a good first order representation of the spectra in the near-infrared arm.

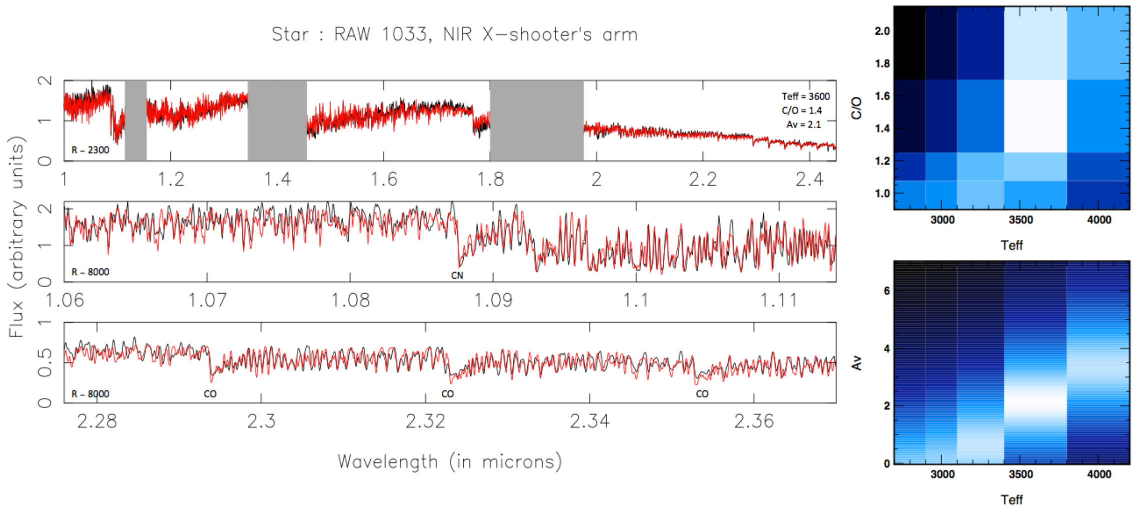

Fig. 3. Best fit (red) to the XSL-NIR spectrum (black) of a C-star (J-K = 1.38). The grey bands mask the regions of deepest telluric absorption. The upper plot shows the spectra smoothed to R $\sim$ 2 300, while the two other ones are for R $\sim$ 8 000. Right hand panels : χ^2 maps. Each map shows the χ^2 values for two dimensions of the grid, and the third is always minimized. White colors indicate the best fit.

4 Extension to the visible

Rare studies that attempt to analyze optical and near-infrared spectra jointly show that results obtained from different wavelength ranges do not agree very well (see Lançon et al. 2008, for an example based on star clusters in the starbust galaxy M82). Here, we make full use of X-shooter's ability to cover these two ranges simultaneously.

As shown in section 3, a good agreement seems to be found in the near-infrared. To see if an agreement is found over the whole visible /near-infrared wavelength range, we extend our best fit to the visible range.

As shown in Fig. 4, this preliminary study indicates that in the visible some deviations of the model spectrum from the observed one can be recognized. Tests performed with other C-stars indicate that bluer stars (for which the circumstellar reddening is less pronounced) are more easily reproduced. The full XSL sample needs to be used to confirm this trend.

To understand and resolve such discrepancies, C-star specific extinction laws and dynamical models now need to be considered. In the meantime, as mentioned by Nowotny et al. (2011), parameters for observed C-star derived from studies based on hydrostatic models should be regarded with caution.

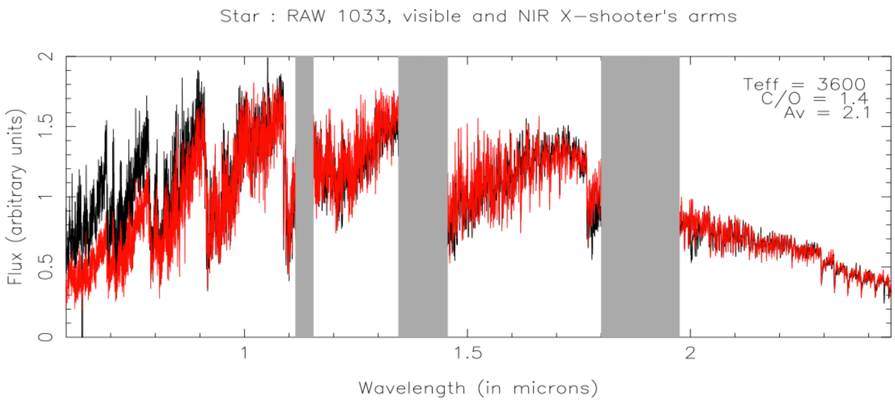

Fig. 4. Best fit (red) to the XSL-NIR spectrum, extended to the visible, and the merged empirical spectrum (black curve). Synthetic and observed spectra are rebinned to R $\sim$ 2300. The grey bands mask the regions of deepest telluric absorption.

5 Conclusions

XSL provides a large collection of stellar spectra, with moderate resolution, broad wavelength coverage and large range of stellar atmospheric parameters. The carbon stars from this collection are key elements for the stellar population synthesis applications. Thus, a proper determination of their fundamental parameters is crucial. Over a single X-shooter arm, good overall agreement is found between the data and theoretical models of static C-star, reddened with a standard extinction law. This is not longer the case over the full range of X-shooter. We are quantifying systematic discrepancies and exploring more complex models, aiming at improving the robustness of fundamental parameter estimates. Making use of X-shooter's spectral resolution, we will also assess detailed spectral features, which will reveal the chemistry and atmospheric structure of individual stars. For population synthesis applications, it is important to identify which ones are precisely understood.

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