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The X-Shooter Spectral Library (XSL) in the optical – First year of the survey

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Abstract. We present the first release of XSL, the X-Shooter Spectral Library. This release contains 239 stars spanning the wavelength 3000–10200 Å observed at a resolving power $R \equiv \lambda/\Delta\lambda \sim 10000$. The spectra were obtained at ESO's 8-m Very Large Telescope (VLT). The sample contains O – M, long-period variable (LPV), C and S stars. The spectra are flux-calibrated and telluric-corrected. We describe a new technique for the telluric correction. The wavelength coverage, spectral resolution and spectral type coverage of this library make it well suited to stellar population synthesis of galaxies and clusters, kinematic investigation of stellar systems and studying the physics of cool stars.

Keywords : stars: atmospheres – galaxy: stellar content – stars: fundamental parameters – catalogues

1. Introduction

Spectral libraries play an important role in different fields of astrophysics. In particular they serve as references for the classification and automatic analysis of large stellar spectroscopic surveys and are fundamental ingredients of the models of stellar populations used to study the evolution of galaxies.

A spectral library is a collection of stellar spectra sharing similar wavelength coverage and spectral resolution. The spectra change as a function of effective temperature ($T_{\rm eff}$), gravity ($\log g$) and metallicity ([Fe/H]). In order to reproduce galaxy

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Table 1. A selection of previous empirical stellar libraries.

Library	Resolution R=$\lambda/\Delta\lambda$	Spectral range (nm)	Number of stars	Reference
STELIB	2000	320-930	249	Le Borgne et al. (2003)
ELODIE	10000	390-680	1388	Prugniel & Soubiran (2001, 2004) Prugniel et al. (2007)
INDO-US	5000	346-946	1237	Valdes et al. (2004)
MILES	2000	352-750	985	Sánchez-Blázquez et al. (2006)
IRTF-SpeX	2000	800-5000	210	Rayner, Cushing & Vacca (2009)
NGSL	1000	167-1025	374	Gregg et al. (2006)
UVES-POP	80000	307-1030	300	Bagnulo et al. (2003)
LW2000	1100	500-2500	100	Lançon & Wood (2000)

spectra as precisely as possible in stellar population models, one requires a comprehensive stellar spectral library that covers the entire desired parameter space of $T_{\rm eff}$, $\log g$, and [Fe/H]. Moreover, extended wavelength coverage is strongly desirable, because different stellar phases contribute their light in different bands. For instance, cool giants contribute more light than warmer faint giant stars in the near-infrared, while in the optical, the situation is reversed (Frogel 1988; Maraston 2005). Asymptotic giant branch (AGB) stars dominate the light of intermediate-aged stellar populations in the near-infrared but are unimportant in the optical (Charlot & Bruzual 1991; Worthey et al. 1994; Maraston 1998). Detecting their presence requires *broad wavelength coverage* in both the target and model spectra.

Empirical stellar libraries have the advantage of being drawn from real, observed stars and therefore do not suffer this limitation; however they frequently have relatively low resolution (with a few exceptions; see below) and are typically unable to reproduce the indices measured in giant elliptical galaxies (Peletier 1989; Worthey, Faber & González 1992), because they are based on local stars with Milky Way disk abundance patterns. Table 1 lists several previous empirical stellar libraries and their principal features. In the optical, there are the (among others) Lick/IDS (Worthey & Ottaviani 1997), MILES (Sánchez-Blázquez et al. 2006), ELODIE (Prugniel & Soubiran 2001, 2004; Prugniel et al. 2007), STELIB (Le Borgne et al. 2003), NGSL (Gregg et al. 2006), and the Pickles (1998) libraries. Building stellar libraries in the near-IR is a challenging task, but pioneering work has been done by Lançon & Rocca-Volmerange (1992); Lançon & Wood (2000); Lançon & Mouhcine (2002) (LW2000, LM2002), Mármol-Queraltó et al. (2008), and Rayner et al. (2009, IRTF-SpeX). However, spectral libraries with extended wavelength coverage at moderate resolution are still largely missing.

With the ability of the high efficiency, broad wavelength coverage, and high/moderate resolution of the X-Shooter spectrograph at ESO's VLT (Vernet et al. 2011), we can now have high-resolution empirical stellar libraries. We have been developing the

X-Shooter Spectral Library (XSL, PI: Trager), a survey of $\gtrsim$ 700 stars covering the entire Hertzsprung–Russell (HR) diagram, including both cool (M dwarfs, M giants, C stars, long-period variables, etc.) and hot stars (up to late O stars), with wavelength coverage from 300–2480 nm – i.e., the entire near-ultraviolet (NUV) to near-infrared (NIR) range – at $R \sim 8000$–11000.

Here we present the first two of six periods of XSL data (from ESO Periods 84 and 85). We concentrate in this paper on the NUV–optical data (3000–10200 Å) from the UVB and VIS arms of X-Shooter.

2. XSL and sample

A unique capability of X-Shooter is that it collects spectra in the wavelength range from the near-ultraviolet to the near-infrared – 300–2500 nm – through its three arms *simultaneously*. This property is extremely useful for observing variable stars, especially very cool stars – like AGB stars – whose spectra may vary substantially during their pulsation cycles.

XSL targets are selected from several empirical stellar libraries as well as supplementary literature sources as described by Trager et al. (this volume). The observed modes used, slit widths, and CCD readout modes are detailed in Table 2 (see Chen 2013; Chen et al. 2013, for details).

Table 2. X-Shooter observing modes for XSL in Periods 84 and 85.

Mode	Arm	Slit	λ (nm)	R	Readout (bright)	Readout (faint)
Nod	UVB	$0\farcs5 \times 11''$	300–600	9100	400k/1pt/hg	100k/1pt/hg
Nod	VIS	$0\farcs7 \times 11''$	600–1020	11000	400k/1pt/hg	100k/1pt/hg/2×2
Nod	NIR	$0\farcs6 \times 11''$	1000–2480	8100		
Stare (P84)	UVB	$5'' \times 11''$	300–600		100k/1pt/hg/2×2	100k/1pt/hg/2×2
Stare (P85)	UVB				400k/1pt/hg	100k/1pt/hg
Stare (P84)	VIS	$5'' \times 11''$	600–1020		100k/1pt/hg/2×2	100k/1pt/hg/2×2
Stare (P85)	VIS				400k/1pt/hg	100k/1pt/hg
Stare	NIR	$5'' \times 11''$	1000–2480			

3. Data reduction

Basic data reduction was performed with the public release of the X-Shooter pipeline version 1.5.0, following the standard steps described in the X-Shooter pipeline manual[1] up to the production of 2D spectra, including bias and/or dark correction, flat-fielding, geometric correction, wavelength calibration and sometimes sky subtraction.

[1] See `http://www.eso.org/sci/software/pipelines/`

A number of issues were discovered during the pipeline reduction process which required further processing steps. We give details about two of the most significant of these steps here.

3.1 Telluric Correction

Ground-based spectroscopy is always subject to contamination from the Earth's atmosphere. Absorption features that originate in the Earth's atmosphere are referred to as telluric features. Correction for telluric contamination, therefore, is important for the XSL spectra in the VIS and NIR arms. We use telluric standard star observations taken as part of the standard X-Shooter calibration plan directly after each of our science observations as a basis for telluric correction of our data. We find that the telluric absorption lines change strength on timescales shorter than the "long" exposure time ($\geq$ 90 seconds) of faint XSL stars and the total overhead time of $\sim$ 900 seconds, resulting in an imperfect telluric correction. In addition, small changes in spectral resolution and wavelength zero-point occur even between successive observations. To optimize the telluric correction, we built a library of telluric spectra, in which 152 hot stars were carefully wavelength calibrated.

We have developed a principal component analysis (PCA)-based method that can quickly and precisely perform the telluric corrections on the XSL data for the warm stars. We find that the first two primary components of our telluric library have clear physical meaning: the first component presents the mean spectrum of the telluric library; the second component tends to separate the transmission contribution of most of the water vapour features from O_2 features. We use the first 40 principal components to reconstruct the transmission of each star. Telluric correction can then be performed by dividing the reconstructed transmission. Figure 1 shows an example of HD 79349 (K7IV), with its original 1D spectrum and telluric-corrected version.

3.2 Flux Calibration

Flux calibration is important to a spectral library. In XSL, most stars have both narrow-slit observations to achieve high resolution and a wide-slit observation to preserve the total flux. We derive the extinction curve of X-Shooter in Periods 84 and 85 in the UVB and VIS arm, respectively, using a number of flux-standard stars. We show typical XSL spectra in the OBAFGKM sequence in Fig. 2.

4. Quality checks

We determine the line-spread function (LSF) of our X-Shooter spectra to accurately measure the spectral resolution and confirm the wavelength calibration of our obser-

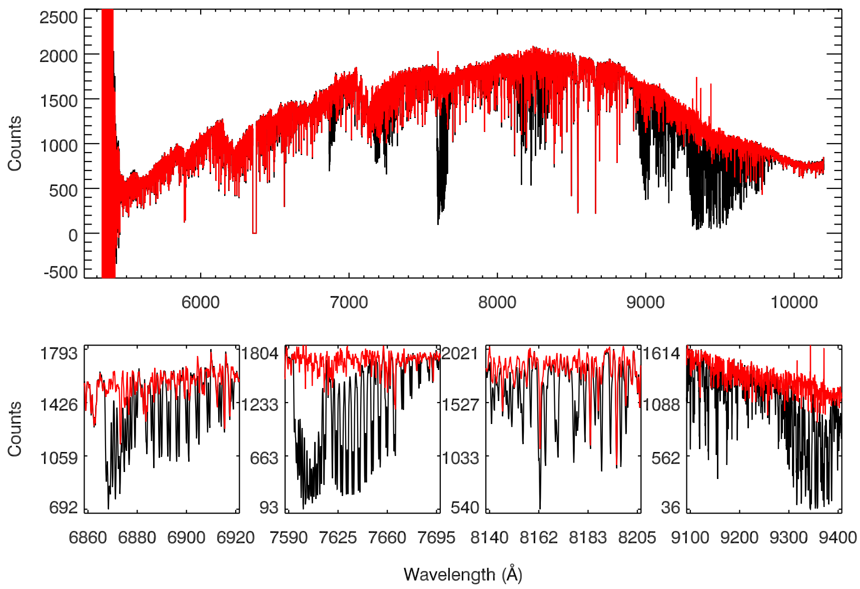

Figure 1. Spectrum of HD 79349 (K7IV) before (black) and after (red) telluric correction in the VIS arm, using the PCA reconstruction method described in the text. The lower panel shows four zoomed-in regions to show the corrections in detail. Artificial spikes around 9350 Å are the residuals after telluric correction.

vations. 212 spectra of F, G, K stars are fitted with synthetic library of Coelho et al. (2005) using the function `ULY_LSF` from ULySS package. The instrumental velocity dispersion in the UVB arm ranges from 13.3 to 18.1 km s^{-1}, corresponding to a resolution $R = 9584 - 7033$. In the VIS arm, the instrumental variation is constant at $\sigma_{\rm VIS} = 11.62$ km s^{-1}(i.e. $R = 10986$), very close to the stated resolution $R = 11000$.

As a further check on the quality of XSL, we compare our spectra with two higher-resolution spectral libraries: UVES POP (Bagnulo et al. 2003) and ELODIE[2] (Prugniel & Soubiran 2001, 2004; Prugniel et al. 2007). To make this comparison we first smooth the UVES POP and ELODIE spectra to the resolution of the XSL spectra and then use pPXF to match the continua and velocity zero points, masking bad pixels when necessary. The typical residual between XSL and UVES POP is 2 – 4%; the typical residual between XSL and ELODIE is 2 – 6%. We find very good agreement in the line shapes and depths between XSL and the two higher-resolution libraries, for both warm and cool stars. This gives us confidence that the XSL spectra will

[2]Note that we use the high-resolution version of the ELODIE library with $R \sim 42000$ for this comparison.

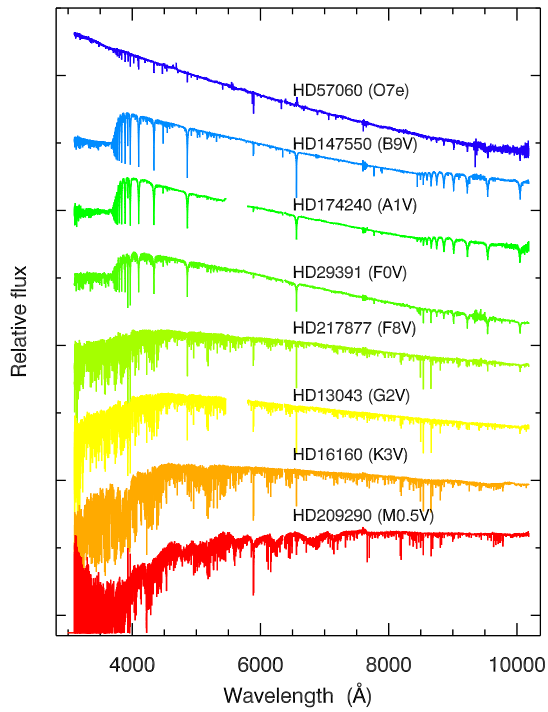

Figure 2. OBAFGKM sequence of the XSL sample in $\log(F_\lambda)$. Gaps around 5700 Å indicate strong dichroic features between the UVB and VIS arms.

be a useful basis for moderate-resolution studies of both stars and composite stellar populations.

5. Atmospheric parameters

Accurate and homogeneous stellar atmospheric parameters are crucial to build trustable stellar population models. To determine the atmospheric parameters of warm stars in the XSL, we used the ULySS package, which minimizes the difference between the observed spectra and a parametric model by full-spectrum fitting (Koleva et al. 2008, 2009) using the MILES interpolator (Prugniel, Vauglin & Koleva 2011). We estimate parameters of the cool stars using the full-spectrum-fitting package pPXF (Cappellari & Emsellem 2004) plus an interpolated theoretical grid of BT-SETTL[3](Allard, Homeier & Freytag 2011) models due to the limited cool star sample in the MILES

[3]`http://phoenix.ens-lyon.fr/Grids/BT-Settl/`

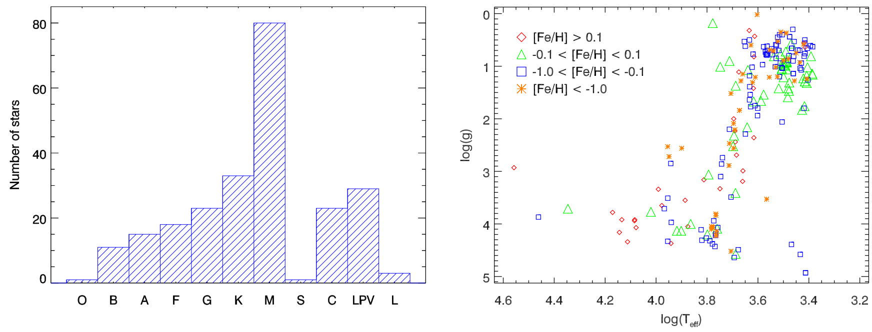

Figure 3. Left: Distribution of spectral types in XSL observed in Periods 84 and 85 (excluding telluric calibrators). Spectral types were retrieved from SIMBAD or based on educated guesses from the source libraries or atmospheric parameters. Right: HR diagram of the 219 XSL stars (O – M, LPV, S) with calculated $T_{\rm eff}$, $\log g$ and [Fe/H], where [Fe/H] is presented in different colours.

interpolator. Spectra of cool stars in the VIS arm are used to perform the fit due to their lower signal-to-noise ratios in the UVB arm.

We carefully estimate the averaged literature parameters for each star, without using those of Prugniel & Soubiran (2001) and Koleva & Vazdekis (2012), since they were determined using the same ULySS method and might have the same biases in the parameters. We find reasonable agreement between our calculation and the averaged literature parameters. The standard deviations are 4.0% in $T_{\rm eff}$, 0.4 and 0.32 dex for $\log g$ and [Fe/H], respectively. Most of the outliers come from variable stars and sometimes cool stars.

We summarize the sample in DR1 and the adopted atmospheric parameters in Fig. 3.

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