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The X-Shooter spectral library

Y. P. Chen[1*], S. C. Trager[1], R. F. Peletier[1], A. Lançon[2], Ph. Prugniel[3] and M. Koleva[4,3]

[1]*Kapteyn Astronormical Institute, University of Groningen, Postbus 800, 9700 AV, Groningen, Netherlands*
[2]*Observatoire Astronomique, 11, rue de l'Université, F-67000 Strasbourg, France*
[3]*Université de Lyon, Université Lyon 1, 69622 Villeurbanne, France;*
CRAL, Observatoire de Lyon, CNRS UMR 5574, 69561 Saint-Genis Laval, France
[4]*Sterrenkundig Observatorium, Ghent University, Belgium*

Abstract. We are building a new spectral library with the X-Shooter instrument on ESO's VLT: XSL, the X-Shooter Spectral Library. We present our progress in building XSL, which covers the wavelength range from the near-UV to the near-IR with a resolution of $R \sim 10000$. As of now we have collected spectra for nearly 240 stars. Stellar atmospheric parameters for a large fraction of these stars have been determined using the full-spectrum fitting package ULySS together with the stellar spectral library ELODIE as templates.

Keywords : spectral library – instrument: X-Shooter – stars: fundamental parameters

1. Introduction

Stellar population models are powerful tools which are widely used to study galaxy evolution. Using these models, one can determine galaxy ages, metallicities and abundances. Spectral libraries are an integral component of stellar population models. A spectral library is a collection of stellar spectra sharing similar wavelength coverage and spectral resolution. The spectra in the stellar libraries change as function of effective temperature ($T_{\rm eff}$), gravity ($\log g$) and metallicity ([Fe/H]). A stellar population model integrates these spectra together with a set of stellar isochrones and an initial mass function to produce a model spectrum of an entire population. In order to

*Email: yanping@astro.rug.nl

Table 1. Some previous 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	800-2500	210	Rayner et al. (2009)
NGSL	1000	167-1025	374	Gregg et al. (2006)
UVES-POP	80000	307-1030	300	Bagnuolo et al. (2003)
LW2000	1100	500-2500	100	Lançon & Wood (2000)

reproduce galaxy spectra as precisely as possible, 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 in the near-infrared than the warmer faint giant stars, while in the optical, the situation is reversed (Frogel 1988). 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 1994; Maraston 1998). Detecting their presence requires *broad wavelength coverage* in both the target and model spectra.

Stellar spectral libraries can be classified into empirical and theoretical libraries, depending on how the library is obtained. Both theoretical and empirical libraries have improved in recent years. The most widely used theoretical libraries in stellar population models are those of Kurucz (1993), Munari et al. (2005), Gustafsson et al. (2008), Coelho et al. (2005, 2007), and Martins et al. (2005). Theoretical libraries have the advantage of (nearly) unlimited resolution and selectable abundance patterns – not only scaled-solar abundances but also non-solar patterns. Unfortunately, theoretical libraries suffer from systematic uncertainties, as they rely on model atmospheres and require a reliable list of atomic and molecular line opacities (Coelho et al. 2005). Empirical stellar libraries, on the other hand, 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 unable to reproduce the indices measured in giant elliptical galaxies (Peletier 1989; Worthey et al. 1992), because they are based on local stars with typical Milky Way disk abundance patterns. Table 1 lists several previous empirical stellar libraries and their principal features. In the optical, we have (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 library (Pickles 1985). Libraries in the near-IR are a challenging task, but pioneering work has been done by Lançon & Wood (2000); Lançon & Mouhcine (2002) (LW2000, LM2002), Rayner et al. (2009) (IRTF-SpeX), and Mármol-Queraltó et al. (2008). However, spectral libraries with extended wavelength coverage at moderate resolution are still largely missing.

In this contribution we present the X-Shooter Stellar Library, XSL. XSL is being obtained using the new X-Shooter three-arm spectrograph on ESO's VLT (Vernet et al. 2010). XSL has the unique advantage of simultaneously acquiring spectra covering the spectrum from the near-ultraviolet up to the near-infrared. Furthermore, the fact that X-Shooter is mounted on an 8.2-m telescope allows us to include faint stars from the Galactic bulge and the Magellanic Clouds for the first time, along with stars in the Galactic disk and halo, at moderate spectral resolution ($R \sim 10000$).

2. XSL

X-Shooter was built by a consortium of 11 institutes in Denmark, France, Italy and the Netherlands, together with ESO. It is currently mounted on UT2 on ESO's VLT. 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.

2.1 Sample selection

XSL targets were selected from many of the above libraries as well as supplementary literature sources. We took stars from Lick/IDS, MILES, and NGSL to cover $T_{\rm eff}$, $\log g$, and [Fe/H] as uniformly as possible. However, these libraries mostly lack the

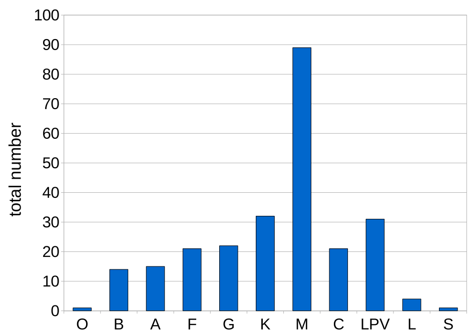

Figure 1. Distribution of spectral types of the main XSL samples (excluding telluric calibrators), retrieved from SIMBAD or based on educated guesses from the source library or atmospheric parameters.

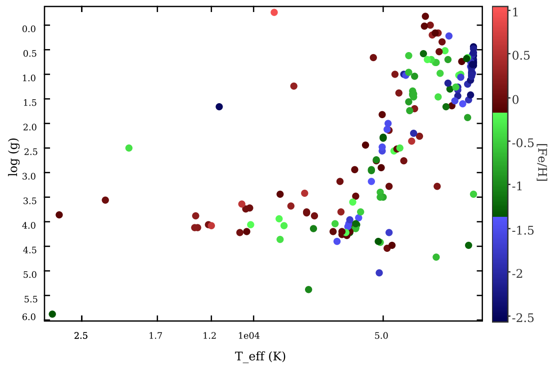

Figure 2. HR diagram of the 171 X-Shooter library stars with calculated $T_{\rm eff}$, $\log g$ and [Fe/H], where [Fe/H] is presented in different colors.

cool, bright stars so important in the near-infrared. For this purpose we selected AGB and LPV stars from LW2000 and IRTF-SpeX with declination $< 35^\circ$ marked M, C or S-stars. Long-period variable (LPV) stars were also collected from the LMC (Hughes & Wood 1990) and the SMC (Cioni et al. 2003). Red supergiant stars were taken from the lists of LW2000 and Levesque et al. (2005, 2007). To cover metal-rich stars with abundances similar to giant elliptical galaxies, we also included Galactic Bulge giants from the samples of Blanco et al. (1984) and Groenewegen & Blommaert (2005). Our intention is that XSL will contain about 600 stars at the end of the survey.

2.2 Observations and data reduction

At the end of 2011, 251 observations of 236 unique stars from the XSL input catalog have been made. Fig. 1 shows the distribution of our sample stars with different stellar types. We have collected a large sample of M, C, and LPV stars, interesting for many different cool star studies. In Fig. 2 we show those sample stars with calculated stellar parameters in an HR diagram. The targets were observed with X-Shooter with a $0.5'' \times 11''$ slit in the UVB arm (3000–6000 Å, R = 9100), a $0.7'' \times 11''$ slit in the VIS arm (6000–10200 Å, R = 11000), and a $0.6'' \times 11''$ slit in the NIR arm (1–2.5 μm, R = 8100). Stars were nodded along the slit to remove the sky background, a serious problem in the NIR arm even for very short exposures. In addition, for every star a wide ($5.0''$) slit spectrum was taken to allow for flux calibration.

The basic data reduction was performed with the public release of the X-Shooter pipeline version 1.1.0, following its standard steps up to the production of 2D spectra, including bias and/or dark correction, flat-fielding, wavelength calibration, sky subtraction, and optimal extraction. We then used IRAF's `twodspec.apextract` routine

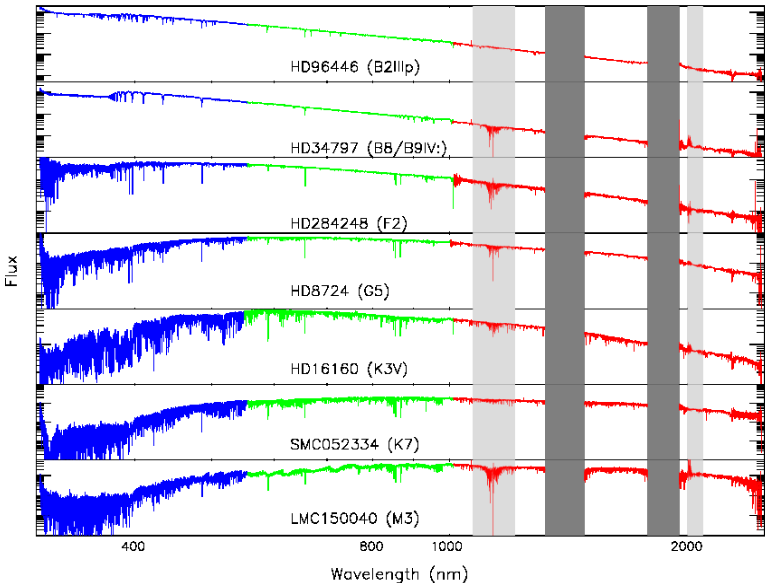

Figure 3. A sample of XSL stellar spectra sorted by temperature, spectral types are indicative only. Grey bars cover areas of severe (light grey) or nearly complete (dark grey) telluric absorption in the NIR arm.

to extract 1D spectra from the 2D spectra. We show typical X-Shooter library spectra in Fig. 3, which contains several spectral types from B2 to M3. In this figure flux calibration has been applied to all the three arms, where the UVB arm is marked in blue, VIS arm in green and the NIR arm in red. Telluric corrections have been applied to the VIS and NIR arms. Grey shaded areas demonstrate the telluric regions in the NIR arm, in which the light grey bars cover the areas of severe telluric absorption while the dark grey ones cover the areas where the telluric absorption is nearly complete.

2.3 Telluric correction

Since X-Shooter is a ground based instrument, correction for telluric absorption in the VIS and NIR arm spectra is very important. For this reason a hot star (typically a mid-B dwarf) was observed after every science object at a similar airmass. Unfortunately, the telluric absorption lines change strength on timescales shorter than the "long" exposure times ($\geq$ 90 seconds) of faint XSL stars and the total observational overhead time of $\sim$ 900 seconds, resulting in a noisy telluric correction. To optimize the telluric correction, we built a library of telluric spectra, in which the hot stars were carefully wavelength calibrated. First we masked out strong H and other lines from the telluric region, since we know that B and other hot stars usually have strong H

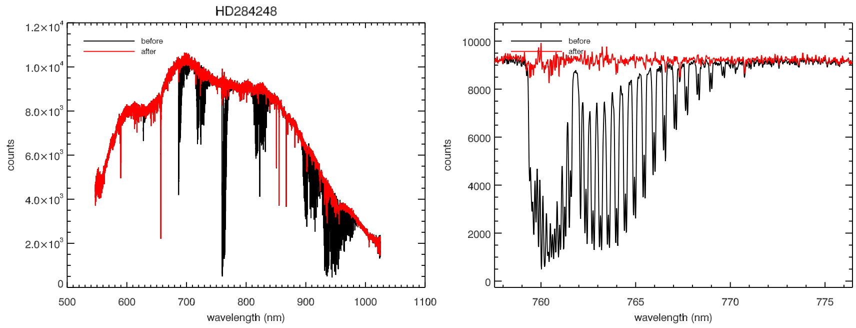

Figure 4. Telluric correction and flux calibration of XSL spectra. (a): Telluric corrected version (red) of HD 284248 together with the original spectrum with different telluric absorption bands (black). (b): Same as in Fig. 4a, zoomed in wavelength range $\lambda\lambda 758 - 776$nm.

lines which must be corrected before the spectra can be used as telluric templates. We then normalized the masked spectra to create our telluric standard library.

For each science object, we defined several telluric absorption regions and ran the spectral-fitting program pPXF (Cappellari & Emsellem 2004) to find a "best fit" telluric correction spectrum. We fitted the science spectrum with a linear combination of the spectra in the (normalized) telluric library, fitting at the same time the line-broadening of the science spectra, and multiplying the result with a polynomial. This step gave a "best fit" for the telluric absorption features to every science object. We then divided the science spectrum by this "best fit", resulting in a telluric-corrected science spectrum. Fig. 4a shows an example of HD 284248 in the VIS arm (without flux calibration), where the black line is the original reduced spectrum before telluric correction and the red line is after correction. To show the quality of the correction in more detail, we zoom into the telluric-corrected spectrum in the atmospheric "A" band between 758 and 776 nm in Fig. 4b.

2.4 Flux calibration

To perform a reliable flux calibration, we observed several spectrophotometric standards (BD+17 4708, GD71, LTT1020, GD153, EG274 and EG21) with a wide (5.0″) slit in "stare" mode at different airmasses. These flux standard stars were then reduced and extracted through the procedures mentioned above. The spectra were compared with the flux tables of the appropriate stars from the CALSPEC HST database (Bohlin 2007) [1] and averaged to produce the response function. The Paranal extinction curve (Patat et al. 2011) was applied to perform the atmosphere extinction correction. Several flux calibrated XSL stars are shown in Fig. 3.

[1] `http://www.stsci.edu/hst/observatory/cdbs/calspec.html`

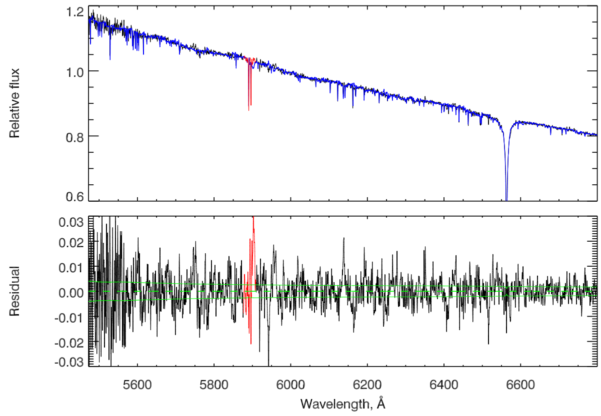

Figure 5. Fit of HD16031 (F0V) in VIS arm with ELODIE interpolator. Top panel: the XSL spectrum in black, and ULySS fitting in blue. Lower panel: residuals between the observation (XSL) and the best fit.

2.5 Atmospheric parameters

Accurate and homogeneous stellar atmospheric parameters are crucial to build trustable stellar population models. To determine the atmospheric parameters for 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). For these stars, a spectral model is built from an interpolator (Prugniel et al. 2007), a polynomial function of non-linear parameters λ, $T_{\rm eff}$, $\log g$, and [Fe/H] based on a library with known atmospheric parameters (e.g. ELODIE). As an example, Fig. 5 presents the fit for HD16031 (F0V) in the VIS arm. The top panel shows the XSL spectra in black and the fit from ULySS in blue. The red lines are bad pixels rejected from the fit. The residuals between the observation (XSL) and the best fit are shown in the lower panel, where the continuous green lines mark the residuals in 1σ deviation. The parameters determined are $T_{\rm eff} = 6181K$, $\log g = 4.13$, and [Fe/H] = -1.77. 171 out of original 244 XSL stars have their stellar parameters determined in this way, as shown in Fig. 2. The failures are very cool (long period variable) stars, we will improve parameter estimation of the long period variables by comparison with atmospheric models.

3. Summary

XSL, the X-Shooter Stellar Library, is intended to be the largest stellar library with complete wavelength coverage from 320–2480 nm and covering as large a range in stellar atmospheric parameters as possible. We will soon have a first version of XSL with spectra of ~ 240 stars. The final library will contain ~ 600 stars at moderate resolution (R ~ 10000). The completeness of the stellar parameter coverage will be enforced through carefully selected samples, so that not only stars with solar metallicities and abundances are included but also metal-poor or metal-rich stars from the Bulge and Magellanic Clouds. With X-Shooter's unique capability, the variable stars will be observed consistently, which will yield more reliable stellar population models.

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