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XSL: The X-Shooter Spectral Library

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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 $R \sim 10000$. At the time of writing we have collected spectra for nearly 240 stars. An important feature of XSL is that we have already collected spectra of more than 100 Asymptotic Giant Branch stars in the Galaxy and the Magellanic Clouds.

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 (e.g. [1]). A spectral library gives the behavior of individual stellar spectra 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 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, bright giants contribute more light in the near-infrared than the faint giant and subgiant stars, while in the optical, the situation is reversed [2]. These Asymptotic Giant Branch (AGB) stars dominate the light of intermediate-aged and old stellar populations in the near-infrared but are unimportant in the optical (e.g., [3, 4]). 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 [5], [6], [7], [8], [9], and [10]. 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 [8]. 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

Table 1: Some previous stellar libraries

Library	Resolution $R=\lambda/\Delta\lambda$	Spectral range (nm)	Number of stars	Reference
STELIB	2000	320-930	249	[14]
ELODIE	10000	390-680	1300	[15, 16, 17]
INDO-US	5000	346-946	1237	[18]
MILES	2000	352-750	985	[19]
IRTF-SpeX	2000	800-2500	210	[20]
NGSL	1000	167-1025	374	[21]
UVES-POP	80000	307-1030	300	[22]
LW2000	1100	500-2500	100	[23]

elliptical galaxies [11, 12], because they are based on local stars with typical Milky Way disk abundance patterns.

In this proceeding we present the X-Shooter Stellar Library, XSL. XSL is being obtained using the new X-Shooter three-arm spectrograph on ESO's VLT [13]. XSL has the unique advantage of simultaneously acquiring spectra covering 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 objects in stars in the Galactic bulge and the Magellanic Clouds for the first time, along with stars in the Galactic disk and halo, at moderate spectral resolution ($R \sim 10000$).

1.1. Previous stellar libraries

We begin with a review of several previous empirical stellar libraries and their principal features, listed in Table 1. In the optical, we have (among others) Lick/IDS [24], MILES [19], ELODIE [15, 16, 17], STELIB [14], NGSL [21], and the Pickles library [25]. Libraries in the near-IR are a challenging task, but pioneering work has been done by Lançon and Wood [23] (LW2000), Rayner et al. [26] (IRTF-SpeX), and Mármol-Queraltó et al. [27]. However, extended-wavelength-coverage spectral libraries at moderate resolution are still largely missing.

STELIB [14] has been used to construct the widely used stellar population synthesis models of Bruzual & Charlot 2003 ([1], here after BC03). This library has a wide wavelength range, 3200–9300 Å, at modest resolution ($R \sim 2000$). The spectra of local galaxies have been reproduced by the models of BC03 through this library [28]. However, stars with low and high metallicites are sparse in this library, leading to problems in some regimes, like modeling old, metal-poor globular cluster spectra [29].

The ELODIE library [15, 16, 17] is a moderate-resolution spectral library with $R \sim 10000$. It has been applied in the PÉGASE-HR synthetic model [30]. The atmosphere parameter coverage of this library had been improved through its updated version, but the wavelength range is still limited in the optical region (4100–6800 Å).

The INDO-US library [18] includes a large number of stars (1273), covers a fair range in atmosphere parameters with moderate-resolution ($R \sim 5000$) . Atmospheric parameters of its stars are given in Wu et al. [31]. The data have been used for automated spectral classification of high-resolution spectra over a wide wavelength range [32]. The problem of this library is the lack of accurate spectrophotometry, making inclusion in stellar population models problematic.

The MILES library [19] is widely used in stellar population models. This library profits from its good physical parameter coverage, careful flux calibration, and a large number of stars (985), enabling stellar population models to predict metal-poor or metal-rich systems. The MILES library's wavelength range covers 3500–7500 Å at modest resolution ($R \sim 2000$) [33].

The Next General Spectral Library (NGSL[1], [21]) is a low resolution ($R \sim 1000$) stellar library obtained with STIS on HST. It contains ~ 400 stars having a wide range in metallicity and age. Since its spectra were observed in space, this library does not suffer from telluric absorption or seeing variations, and hence has excellent absolute spectrophotometry. Other features of NGSL are its broad wavelength coverage, from the space UV to 1 μm, and high signal-to-noise. There is also a high-resolution ($R \sim 40000$, covering 3600–11000 Å) extension of NGSL's southern stars taken with the UVES spectrograph of ESO's VLT (Hanuschik et al., in prep.).

The UVES Paranal Observatory Project (UVES-POP, [22]) is a library of spectra of ~ 300 nearby bright stars taken with UVES. The spectra cover the optical region at $R \sim 80000$ and have a typical S/N ratio is 300–500 in the V band. The library has been flux calibrated but has not been corrected for the severe telluric absorption in the red. For stellar population models the sample is incomplete, since it only contains bright stars around solar metallicity.

In the near-infrared range, the IRTF Spectral Library (IRTF-SpeX, [20]) contains 200 stars observed with the cross-dispersed infrared SpeX spectrograph on IRTF at a resolving power of $R \sim 2000$. The largest spectral library of very cool supergiants and giants over the wavelength range $\lambda = 0.5$–2.5 μm was published by Lançon & Wood (LW2000, [23]), which contains ~ 100 stars taken at a resolution of $R = 1100$, including observations over multiple phases. Unfortunately, cool giants are variable in optical and NIR, so simultaneous observations are required. Libraries with more limited spectral coverage in the near-infrared, like the 2.3 μm library of Marmól-Queraltó et al. [34], also exist, but are limited to a small number of spectral features (like the CO bandhead).

2. XSL

X-Shooter [13] 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 character is extremely useful for observing variable stars, especially very cool stars – like stars – whose spectra 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 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 [35] and SMC [36]. Red supergiant stars were taken from the lists of LW2000 and [37, 38]. To cover metal-rich stars with abundances similar to giant elliptical galaxies, we also included Galactic Bulge giants from the samples of [39, 40]. Our intention is that XSL will contain about 600 stars at the end of the survey.

2.2. Observations and data reduction

To date, 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 known stellar parameters in an HR diagram.

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[1] See `http://archive.stsci.edu/prepds/stisngsl/`

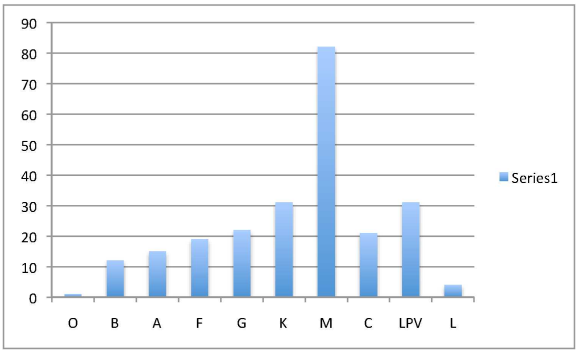


Figure 1: Distribution of spectral types of the main XSL samples (excluding telluric calibrators), retrieved from SIMBAD or based on educated guesses from the source library or atmospheric parameters.

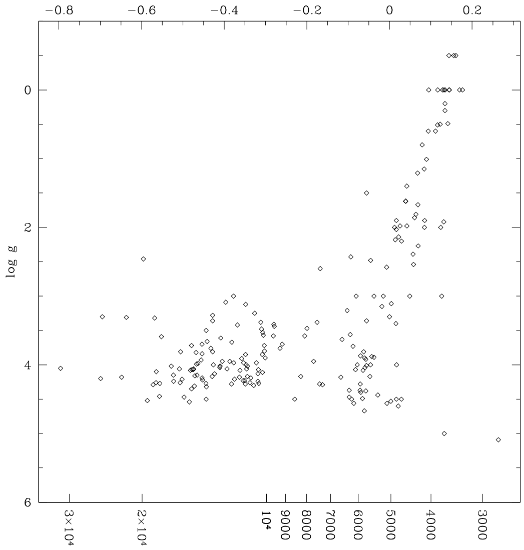


Figure 2: HR diagram of the 114 X-Shooter library stars with known $T_{\rm eff}$ and $\log g$. Bottom axis is $T_{\rm eff}$; top axis is log θ, where $\theta = 5040/T_{\rm eff}$.

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 excellent flux calibration (see, e.g., [19]).

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. We then used IRAF's `twodspec.apextract` routine 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. The UVB arm is shown in blue, the VIS arm in green and the NIR arm in red. Telluric corrections have been applied to the VIS and NIR arms. Grey bars 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 nearly complete telluric absorption.

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 telluric stellar spectrum library, 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 lines which must be corrected before the spectra can be used as telluric templates. We then

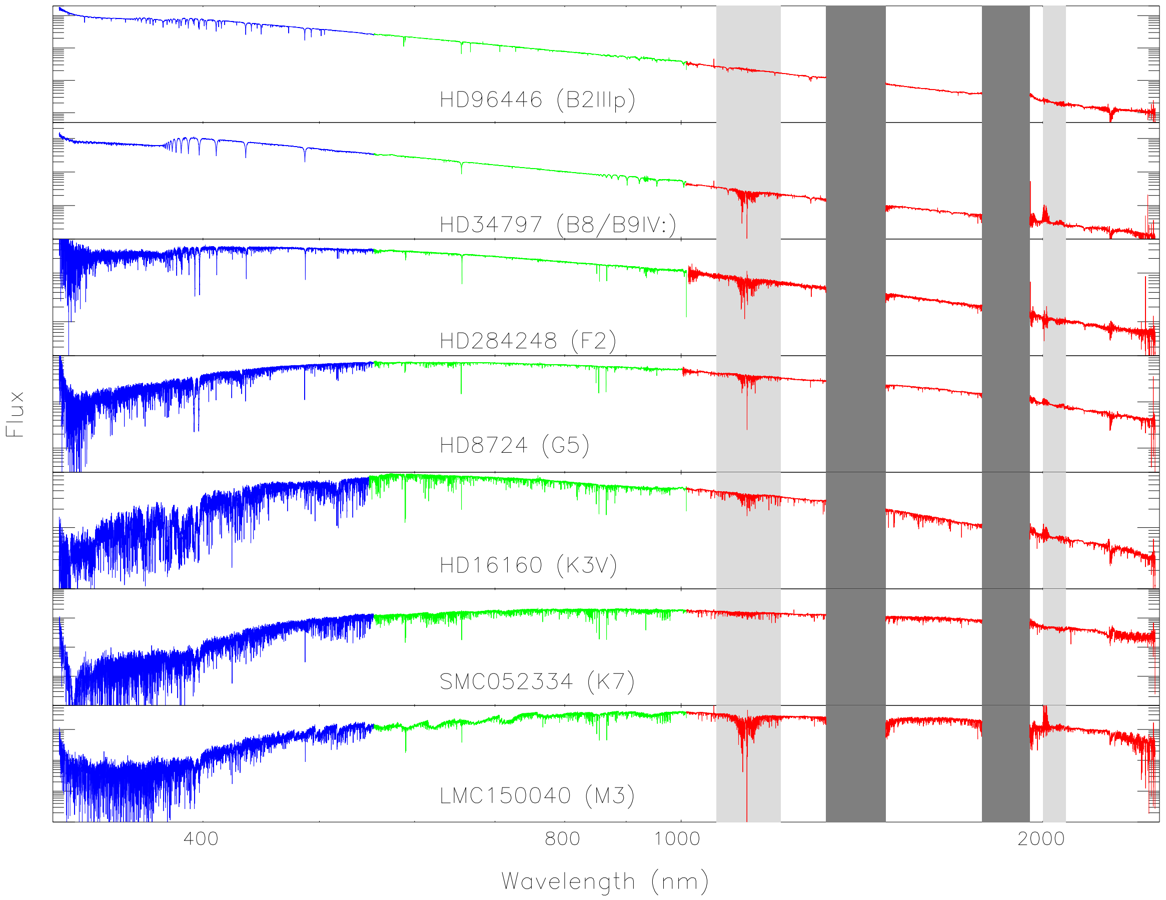
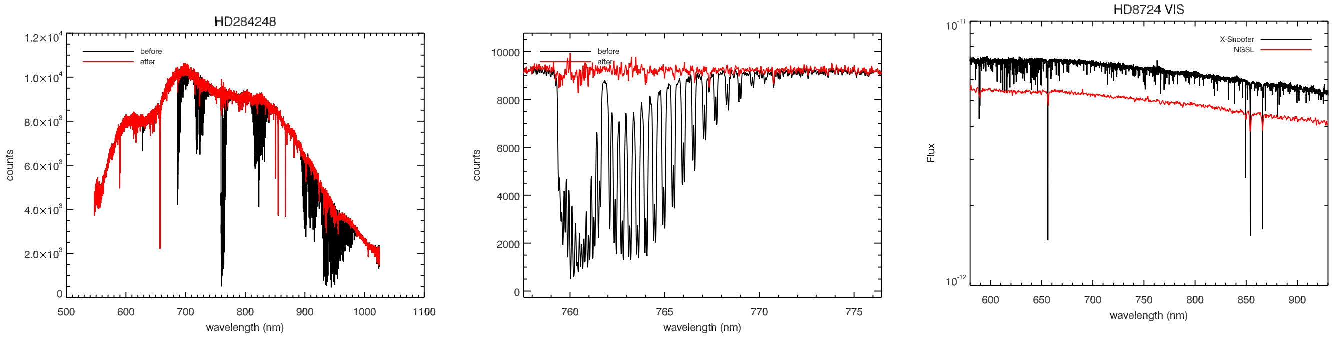


Figure 3: A sample of XSL stellar spectra sorted by temperature. Grey bars cover areas of severe (light grey) or nearly complete (dark grey) telluric absorption in the NIR arm.



(a) (b) (c)

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. (c): Flux-calibrated spectrum of HD 8724. The X-Shooter spectrum is shown in black and the NGSL spectrum is shown in red.

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 [41] 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 higher order 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 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 star 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 [42][2] and averaged to produce the response function. The Paranal extinction curve [43] was applied to perform the atmosphere extinction correction. Fig. 4c shows the flux-calibrated VIS arm spectrum of HD 8724 from X-Shooter (black line) and NGSL (red line). The UVB arm spectra are corrected in a similar matter. The NIR arm spectra will be telluric- and flux-calibrated simultaneously using the hot star telluric correction spectra in combination with the flux standards.

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 ($R \sim 10000$). 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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