The X-shooter Spectral Library (XSL) and its First Data Release

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Stellar spectral libraries play a pivotal role in astrophysics, helping us to understand the physics of stars and build models of stellar populations in order to study distant star clusters and galaxies. Aspects of current stellar spectral libraries that require improvement are: better calibrations, more stars, higher spectral resolution and broader wavelength coverage. The X-shooter spectrograph is well suited to the task, and we are building the X-shooter Spectral Library (XSL) of more than 700 stars covering the entire Hertzsprung–Russell diagram in the wavelength range 300–2480 nm at a mean resolving power of 10 000. Here we describe the sample, observations and reduction of the data, concentrating on the flux-calibrated, telluric-corrected near-ultraviolet and optical spectra of the first 237 unique stars observed in the first year of the survey. These spectra, the first data release, are now available at http://xsl.u-strasbg.fr/.

Based on measurements of the surface temperatures, compositions, masses, and rotation from the observed depths and widths of the stellar lines, stellar spectral libraries help us to understand the physics of stars and are necessary building block to construct models of stellar populations, without which we could study neither distant star clusters nor galaxies. Trager (2012) reviewed modern stellar spectral libraries designed for stellar population synthesis modelling and identified five desiderata for future libraries:
– Good calibrations — excellent flux and wavelength calibrations and accurate and high-precision stellar atmospheric parameters are required for the best stellar population models;
– Lots of stars — a comprehensive stellar population model requires all stellar evolutionary phases for all conceivable stellar compositions;
– Moderate-to-high spectral resolution — a stellar population model should be able to model both individual stellar clusters and massive galaxies;
– Broad wavelength coverage — no single stellar evolutionary phase contributes to all wavelengths of interest, and multiple evolutionary phases contribute to different wavelengths;
– Simultaneous observations at all wavelengths of interest — stellar spectral variability, particularly in cool stars, can cause serious problems with constructing stellar population models, especially if the number of stars is small.

All of these issues led us to begin the X-shooter Spectral Library (XSL) project in 2010. X-shooter has the required simultaneous wavelength coverage (300–2480 nm in one shot through three arms), resolution ~ 10 000, can be calibrated well in both wavelength and flux (described below), and can target faint stars in a variety of environments (from the nearby Galactic Disc to the Bulge and to the Magellanic Clouds) with a variety of chemical compositions, in order to provide a truly modern stellar spectral library.

Sample selection and observations

XSL's targets were selected to cover as much of the Hertzsprung–Russell diagram (HRD) as possible. In the early semesters (P84–P85) we concentrated on cool stars lacking from current libraries, especially red supergiants and asymptotic giant branch stars in the Milky Way and the Magellanic Clouds. We also included Galactic Bulge giants to cover metal-rich stars with abundances similar to those in giant elliptical galaxies. We show the HRD of these stars as a function of metallicity in Figure 1 and the sky distribution of these stars in Figure 2.

The survey was conducted in two phases: a two-semester pilot survey and a Large Programme. The pilot survey that resulted in XSL Data Release 1 (DR1; Chen et al., 2014) was undertaken in Periods 84 (programme 084.B-0869) and 85 (programme 085.B-0751). DR1 contains X-shooter UVB and VIS arm spectra of a total of 237 unique stars, with multiple observations of some stars, in particular variable cool giants (long-period variables and Mira-type stars) to probe their spectral variability. The XSL Large Programme (programme 189.B-0925) was carried out in Periods 89–92, resulting in spectra of a total of nearly 480 unique stars. Again, a handful of cool giants was observed at multiple epochs to probe spectral variability.

In all periods, the stars were observed with the X-shooter configuration described in Table 1. This X-shooter setup gave a typical resolution ~ 7000–11 000 over the wavelength range 300–2480 nm from

Mode	Arm	Slit	λ (nm)	R
Nod	UVB	0.5″ × 11″	300–600	9100
Nod	VIS	0.7″ × 11″	600–1020	11000
Nod	NIR	0.6″ × 11″	1000–2480	8100
Stare	UVB	5″ × 11″	300–600	
Stare	VIS	5″ × 11″	600–1020	
Stare	NIR	5″ × 11″	1000–2480	

Table 1. X-shooter observing modes for XSL. Note: Resolution $R = \lambda/\Delta\lambda$ is the nominal spectral resolution given by the X-shooter manual; the actual resolution in the UVB arm ranges from 7000–9500.

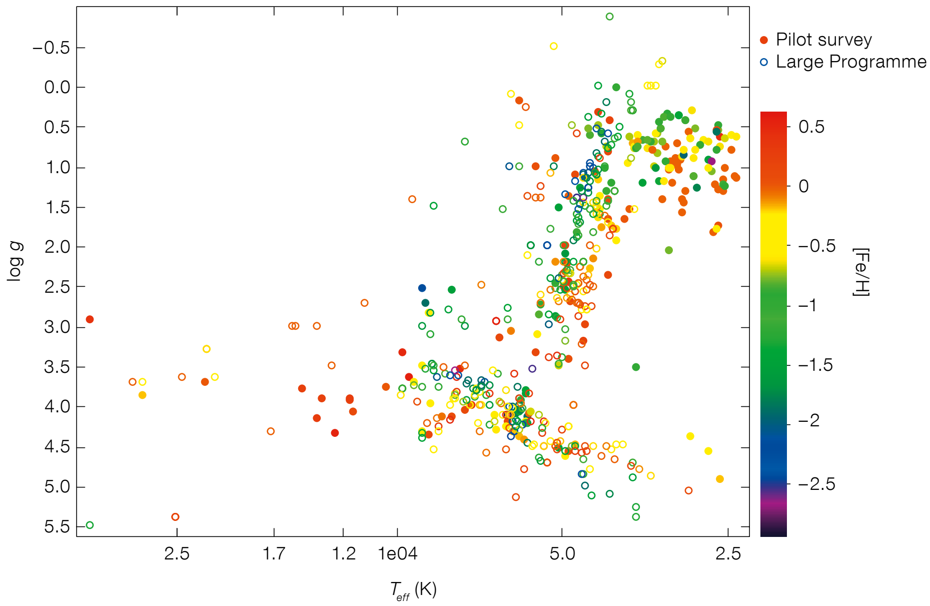
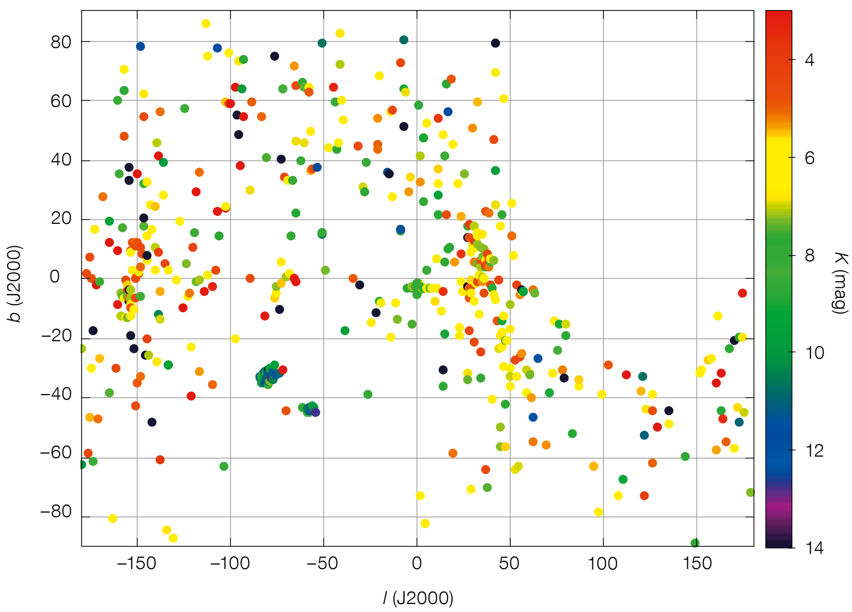


Figure 1. (Above) The Hertzsprung–Russell diagram of XSL stars (surface gravity log *g* as a function of effective temperature T_{eff}), colour-coded by metallicity [Fe/H]. The stars of the first data release (Chen et al., 2014) are indicated by filled circles. The remaining stars are indicated by open circles.

Figure 2. (Below)The sky distribution of XSL stars in Galactic coordinates. Points are coloured by their 2MASS *K*-band magnitudes.



the narrow-slit "nodding" observations and good flux calibration from the wide-slit "staring" observations. The programme was designed to fill any gaps in the observing queue, and therefore the observations were typically taken during poor seeing and thick cloud conditions; this however did not affect the relative flux calibration precision (see below).

Data reduction

The data reduction of the near-ultraviolet and optical spectra from the pilot survey 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 two-dimensional spectra, including bias and/or dark correction, flat-fielding, geometric correction, wavelength calibration and (when necessary) sky subtraction. 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; more details can be found in Chen et al. (2014).

Telluric correction

Ground-based observations are always subject to contamination from the Earth's atmosphere. In the visible and near-infrared portions of the spectrum, water vapour, molecular oxygen, carbon dioxide and methane generate strong absorption features that originate in the Earth's atmosphere and are referred to as telluric features. Corrections for telluric contamination therefore are important for the XSL spectra in the VIS and NIR arms.

We used "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 optical data. These stars are typically B2–A0 dwarfs, whose intrinsic spectra contain only H and He absorption lines on top of nearly pure blackbody spectra. We determined the telluric absorption spectrum at the time of observation of each of these stars by dividing the observed spectrum by a model of the star's intrinsic spectrum. We found that the telluric absorption lines changed strength on timescales shorter than the "long" exposure time (> 90 seconds) of faint XSL stars and the total overhead time of ~ 900 seconds, resulting in an imperfect telluric correction. In addition, small changes in spectral resolution and wavelength zero-point occurred even between successive observations. To optimise the telluric correction, we therefore built a library of telluric spectra, in which 152 telluric standard stars were carefully wavelength-calibrated and had their intrinsic spectra modelled and removed.

We developed a principal-component-analysis- (PCA) based method that can quickly and precisely perform telluric corrections for warm stars in XSL. Figure 3 shows the first six principal components from the bottom to top. We

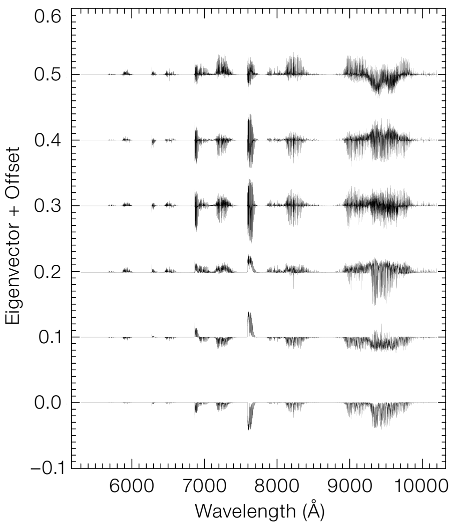


Figure 3. The first six principal components of the telluric library. The eigenvalues decrease from the bottom to the top of this figure (i.e., the first and largest eigenvector is the lowest). The eigenvectors have been offset for display purposes.

found that the first two primary components of our telluric library have a clear physical meaning: the first component presents the mean telluric spectrum of the library; the second component separates the contribution of most of the water vapour features from the O_2 features. We used the first 40 principal components to reconstruct the transmission of each star.

First the science spectrum was normalised, then the reconstructed transmission spectrum was built by projecting the mean-subtracted, normalised science spectrum onto the modified principal components and summing these projections. Telluric correction was finally performed by dividing the spectrum of the programme star by the reconstructed transmission. Figure 4 shows an example of the telluric correction of the K7IV star HD 79349. We found that telluric correction by PCA reconstruction does a good job for both early-type stars and some late-type stars, as this method works better for stars with simpler continua and high signal-to-noise ratios. Cool stars, such as carbon stars, have strong and sharp molecular bands. Tracing each absorption bandhead to apply the PCA method is therefore difficult for these stars, because some molecular bands occur exactly at the same wavelengths as the telluric absorption regions. Therefore we used the transmission spectrum taken from the telluric library closest in time to the programme star to correct the telluric absorption for all carbon stars, long period variable (LPV) stars and most of the M stars.

Flux and wavelength calibration

Knowledge of the spectral energy distribution of stars allows us to compute synthetic photometry, an important ingredient to compare with catalogues of stellar photometry and to combine stellar spectra together with the correct weights as a function of wavelength in stellar population models. Flux calibration is therefore critical for a spectral library in order to recover the overall spectral energy distribution of each star. Nearly all XSL stars, except the brightest ($K < 5$ mag), have both narrow-slit observations, to achieve high resolution, and a wide-slit observation, to preserve the total flux. The brightest stars would have saturated the detectors much too quickly in wide-slit mode and therefore were not observed in this mode.

We derived the atmospheric extinction curve of X-shooter in the pilot survey in the UVB and VIS arm using a number of flux-standard stars (BD+17 4708, GD 71, GD 153, EG 274, Feige 110, LTT 3218, and LTT 7987). Response curves for individual stars were generated from the chosen flux-standard star observed closest in time. A final flux calibration was carried out on the narrow-slit observations using the shape of wide-slit observations to avoid flux losses. We used

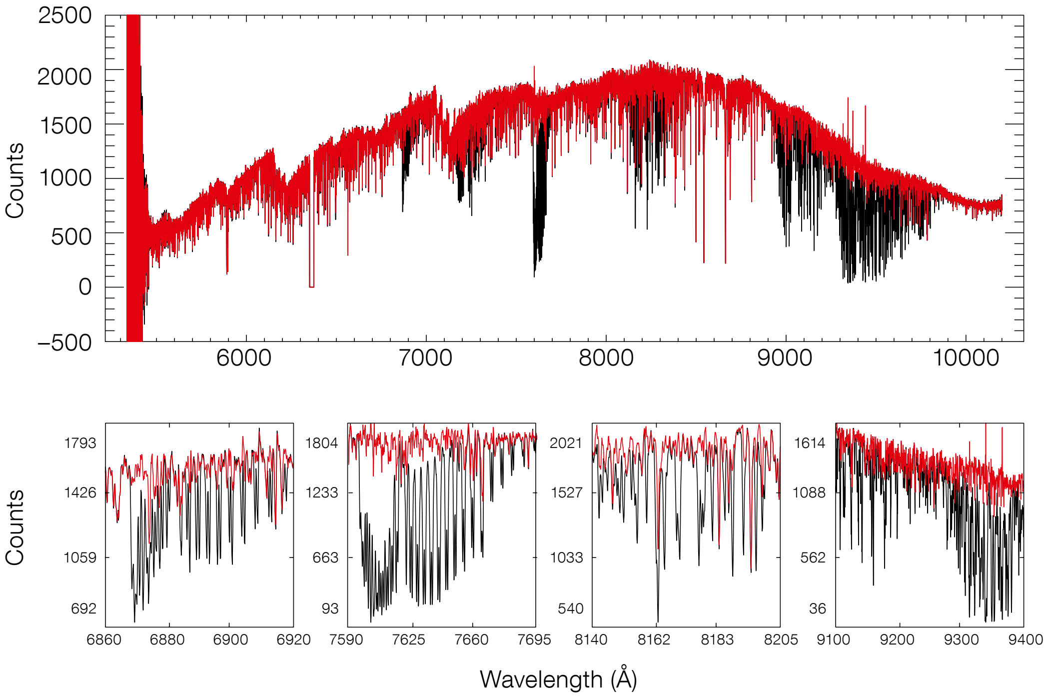


Figure 4. Spectrum of HD 79349 (K7IV) before (black) and after (red) telluric correction in the VIS arm, using the PCA reconstruction method described in the text. The lower panels show four zoomed-in regions to demonstrate the corrections in detail. The spikes around 935 nm are residuals after telluric correction.

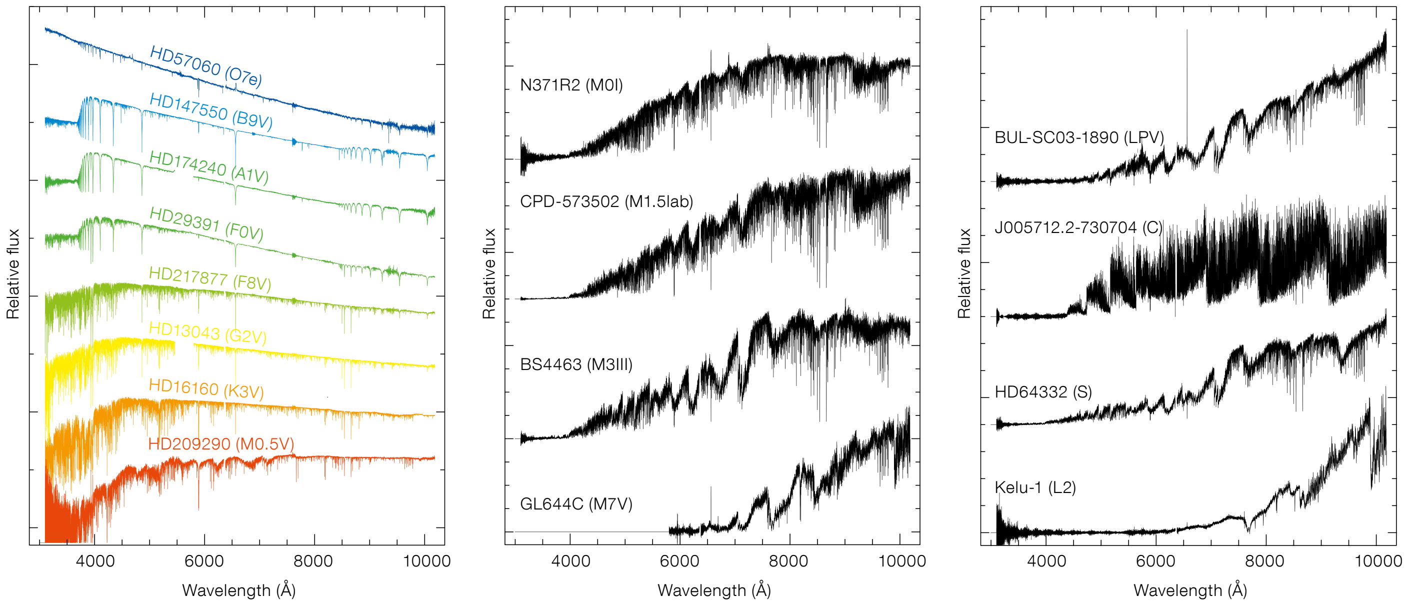


Figure 5. Left: The classic OBAFGKM temperature sequence as represented in XSL, shown in (relative) log F_λ flux units. Gaps around 570 nm indicate strong dichroic features between the X-shooter UVB and VIS arms. Middle: A sequence of M stars from XSL sorted by spectral type. The flat region in the star GL644C indicates a region with a very low signal-to-noise ratio. Right: A sample of LPV, C, S, and L stars in XSL.

the wide-slit exposure paired with each flux-calibrated, narrow-slit spectrum to achieve this. Typical flux-calibrated XSL spectra are shown in Figure 5.

We measured the spectral resolution and line shifts of our X-shooter spectra to check the wavelength calibration of our observations. We fitted 212 spectra of F, G, K stars with the synthetic library of Coelho et al. (2005) using the ULySS package[2] (Koleva et al., 2009) to determine the above properties. As shown in Figure 6, the instrumental (velocity) resolution in the UVB arm ranged from 13.3 to 18.1 km s^{-1} (velocity dispersion, σ), corresponding to a resolution of 9500–7000. We have corrected our XSL data in the UVB arm to the (air) restframes using the line-shift relation shown in Figure 6. In the VIS arm, the instrumental resolution was constant at 11.6 km s^{-1} (i.e., R = 10 986), very close to the resolution of 11 000 given by the X-shooter manuals.

Synthetic photometry comparison

We calculated synthetic colours on the Johnson–Cousins *UVBRI* and Sloan Digital Sky Survey (SDSS) photometric systems for the XSL stars and compared these colours with published values to check the reliability of our flux calibration. By comparing the calculated synthetic *B–V*, *U–B*, *R–I*, and *V–I* colours of the XSL-sample with the NGSL library[3] (Gregg et al., 2006) and observed colours from the Bright Star Catalogue (Hoffleit et al., 1983; Hoffleit & Jaschek, 1991) we found good agreement between XSL sample and literature stars, with offsets < 0.02 mag in all colours and scatters ranging from 0.07 mag in *U–B* to 0.02 mag in *R–I*. Since there are few literature stars that have the SDSS colours in common with our sample, we used the model colours computed by Lenz et al. (1998) as a rough check. In general, the agreement between the models and data was very good.

Comparison with literature spectra

As a further check, we made a direct comparison of the final XSL spectra with other libraries. The first year of XSL (DR1) had 77 stars in common with NGSL, 40 stars in common with the MILES (Sánchez-Blázquez et al., 2006) stellar spectral library[4], 34 stars in common with the ELODIE (Prugniel & Soubiran, 2001, 2004; Prugniel et al., 2007) spectral library[5], 26 stars in common with the IRTF (Rayner et al., 2009) spectral library[6] and 25 stars in common with the CaT (Cenarro et al., 2001) spectral library[7]. For each comparison, we convolved the comparison spectrum and XSL to the same intrinsic resolution, matched the continua, and measured the fractional difference between these spectra in telluric-free regions.

Comparing the XSL spectra with two higher-resolution spectral libraries, UVES POP (Bagnulo et al., 2003)[8] and ELODIE, we found that the typical residual between XSL and UVES POP is 2–4 % in relative flux after convolving the UVES POP spectra to the XSL resolution, and the typical residual between XSL and ELODIE is 2–6 % in relative flux after similarly convolving ELODIE to the XSL resolution. We found very good agreement in the line shapes and depths between XSL and the two higher-resolution libraries for both warm and cool stars. Comparison of XSL with the intermediate-resolution spectral library MIUSCAT (a combination of MILES, Indo–U.S.[9] and CaT; Vazdekis et al., 2012) showed a typical flux residual between XSL and MIUSCAT of 2 %. Comparison of XSL with the lower-resolution spectral library NGSL also showed good agreement: the typical relative flux residual between XSL and NGSL was 1 % over the common wavelength 320–1000 nm after removing the continuum shapes.

Applications of XSL

XSL is currently being applied to a number of studies, from the study of individual

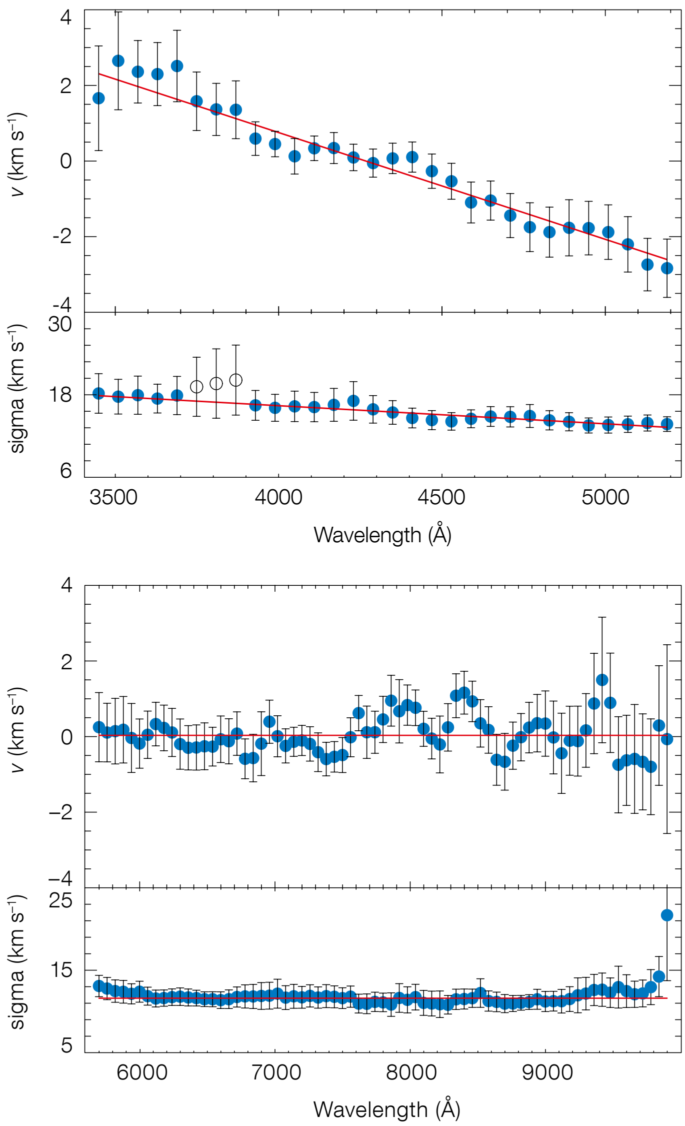


Figure 6. Average line-spread functions for the XSL DR1 FGK stars (212 spectra) in the X-shooter UVB (upper panel) and VIS (lower panel) arms. In each arm, the top panel shows the residual shift of the spectra (blue dots). The bottom panel shows the measured instrumental resolution (in velocity units). The error bars are the standard deviation in each wavelength bin. A simple first-order polynomial fit (red lines) of the line-spread function is given in each panel. The three open circles show the region where two different flat-field lamps are used simultaneously in the UVB arm, which may result in larger uncertainties.

stars (e.g., Davies et al., 2013), to use as spectral templates in determining the stellar velocity dispersions of intermediate-redshift early-type galaxy lenses for gravitational lensing studies (e.g., Spiniello et al., 2011) and to stellar population models. Chen (2013) made the first XSL stellar population models with the XSL DR1 spectra, which demonstrate a rich set of spectral features at a spectral resolution of 7000 over the spectra range 320–1000 nm. Gonneau et al. (2013) compared stellar atmosphere models of carbon stars to XSL VIS–NIR spectra to estimate effective temperatures, surface gravities, C/O ratios and extinctions of such stars.

Future perspectives

XSL will provide a benchmark library for stellar population studies in the near-ultraviolet, optical, and near-infrared in the era of James Webb Space Telescope and the Extremely Large Telescopes; for stellar atmosphere studies, especially for cool (super)giants; telluric corrections; and many other topics. XSL is, however, incomplete in a few critical areas, and these will be the topic of coming work by our team and others. In particular, XSL contains only a handful of M dwarf stars, critical for studies of the low-mass region of the initial mass function in integrated stellar populations. The X-shooter archive contains a reasonable number of M (and cooler) dwarfs, which our team will analyse after the XSL data reduction is complete. Furthermore, XSL is missing hot, very massive (young) stars, hotter than about B0 or O9. The lack of these stars compromises our ability to make stellar population models of very young populations. This lack will be addressed in the coming years, partly through our own efforts and partly through the efforts of others who specialise in observing such stars.

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Links

[1] X-shooter pipeline manual: http://www.eso.org/sci/software/pipelines/
[2] ULySS spectroscopic analysis package: http://ulyss.univ-lyon1.fr/
[3] Next Generation Stellar Library (NGSL): http://archive.stsci.edu/prepds/stisngsl/
[4] MILES stellar library: http://miles.iac.es/
[5] ELODIE spectral library: http://www.obs.u-bordeaux1.fr/m2a/soubiran/elodie_library.html
[6] IRTF spectral library: http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library/
[7] CaT stellar library: http://miles.iac.es/pages/stellar-libraries/cat-library.php
[8] UVES POP library: http://www.eso.org/sci/observing/tools/uvespop.html
[9] Indo–U.S. library: http://www.noao.edu/cflib/