The X-shooter Spectral Library and stellar population models

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XSL and associated stellar population models were created based on the knowledge gained from previous stellar libraries and stellar population models. More than 10 years since the XSL observations, this thesis provides DR3 of the stellar spectra and first XSL stellar population models across the full XSL wavelength range.

XSL DR3 is a version of the XSL which is population-synthesis-ready. In Chapter 2, we provided arm-merged 830 NUV-NIR spectra of 683 stars, the majority of which were corrected for Galactic dust extinction. In Chapter 3, we created the XSL SSP models. The models span the metallicity range $-2.2 < [\text{Fe/H}] < +0.2$ and ages above 50 Myr, and have unmatched spectral characteristics of the relatively high resolution ($R \sim 10,000$) and NUV–NIR wavelength coverage. In Chapter 4, we created SSP models with various IMF descriptions and investigated the interplay between the IMF and the AGB population in determining the SSP model colours and absorption line strengths. It has become clear that careful inclusion of cooler RGB and AGB (especially the TP-AGB) stars is important, as these stars dominate the NIR flux of the $\sim 1$ Gyr stellar populations. The aim of XSL-based SSP models is clear: to bridge the optical and NIR studies of intermediate-age and old stellar populations, these XSL stars should be well understood and appropriately included in the models.

5.1 Results chapter by chapter

In this section, I summarise the results of the scientific chapters.

Chapter 2: The X-shooter Spectral Library (XSL): Data Release 3

- We present the third data release of the X-shooter stellar library (XSL DR3), which consists of 830 spectra covering a wide range of stellar parameters. The DR3 dataset consists of the XSL DR2 data and spectra of 20 archival M-dwarf stars.
- The XSL DR3 spectra cover a wavelength range of 350–2480 nm and are corrected for the Galactic dust extinction.
- The spectra have a moderate-high spectral resolution of $\sigma = 13$, 11, 16 km s$^{-1}$ in the UVB, VIS, and NIR arms, respectively.
- We determined the scaling factors for UVB and NIR spectra relative to the VIS spectrum ($S_{\text{UVB}}$ and $S_{\text{NIR}}$), together with Galactic dust extinction (described by $A_V$), with the use of XSL spectral interpolator. Dust extinction is determined for 581 spectra via the interpolator. In addition, we use Lançon et al. (2021) values for 41 spectra (A. Lançon, priv. comm) and Joshi & Panchal (2019) values for 50 LMC and SMC stars. The UVB scaling factor is determined for 540 spectra through the interpolator and 270 by visual inspection (the majority of which are cool stars with noisy UVB
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The NIR scaling factor is determined for 554 spectra through the interpolator, and 249 by visual inspection.

- The overlap areas (545–590 nm and 994–1150 nm) of the X-shooter arms are affected by dichroic artefacts, which are not described by the error spectrum. The severity varies from spectrum to spectrum and is worse between UVB and VIS than between VIS and NIR. These areas in the spectrum should be used with extreme caution.

- We provide comparisons between XSL DR3 and Gaia EDR3, MILES, NGSL, CaT library, and (E-)IRTF. The normalised rms deviation is better than $D = 0.05$ or 5% for the majority of spectra in common between MILES (144 spectra of 180), NGSL (112/116), and (E-)IRTF (55/77) libraries. Comparing synthetic colours of those spectra reveals only negligible offsets and small rms scatter, such as the median offset(rms) $0.001 \pm 0.040$ mag in the (box1 – box2) colour of the UVB arm, $-0.004 \pm 0.028$ mag in (box3 – box4) of the VIS arm, and $-0.001 \pm 0.045$ mag in (box2 – box3) colour between the UVB and VIS arms, when comparing stars in common with MILES. We also find an excellent agreement between the Gaia published (BP – RP) colours and those measured from the XSL DR3 spectra, with a zero median offset and an rms scatter of 0.037 mag for 449 non-variable stars.

Chapter 3: Modelling simple stellar populations in the near-ultraviolet to near-infrared with the X-shooter Spectral Library (XSL)

- We present simple stellar population models based on the empirical X-shooter Spectral Library (XSL), with the metallicity span $-2.2 < [\text{Fe/H}] < +0.2$ and ages above 50 Myr.

- The XSL SSP models cover a wavelength range of 350–2480 nm and have a spectral resolution of $\sigma = 13, 11, 16$ km s$^{-1}$ in the UVB, VIS, and NIR arms, respectively.

- We construct sequences of the average spectra of static giants, variable O-rich giants, and C-rich giants to be included in the models separately. 44 oxygen-rich static giant stars were combined to a sequence of 10 average spectra, with each average spectrum consisting of stars with similar $(I-K)$ colour. 39 XSL spectra of O-rich TP-AGB stars were combined into a sequence of 9 average spectra in the same manner. Similarly, 26 XSL spectra of C-rich TP-AGB stars were combined into a sequence of 6 average spectra.

- XSL SSP models can reproduce the integrated optical colours of the Coma cluster galaxies at the same level as other semi-empirical models found in the literature. In the NIR, there are notable differences between the colours of the models and Coma cluster galaxies.

- The optical absorption-line index trends of different models are similar, but there are discrepancies between models for NIR indices. In some cases, the XSL models expand the range of predicted values of NIR indices, such as the MgII1.7 line, compared to other models based on empirical libraries. In other cases, there are offsets in predicted absorption line strengths. For example, there is a systematic offset between the E-MILES and XSL models in CN1.10 index values. The smaller XSL predictions are a direct consequence of separating C-rich TP-AGB stars and removing supergiant stars.

Chapter 4: Interplay between the stellar initial mass function and AGB stars in XSL simple stellar population models

- We present XSL simple stellar population models calculated with various unimodal and bimodal IMFs.
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- We describe the XSL SSP models in the context of IMF, but we give special attention to the possible role of asymptotic giant branch stars.
- The influence of TP-AGB stars on the XSL SSP model predictions for \( M_*/L_K \) peaks for populations with ages younger \( \log (\text{age yr}^{-1}) = 9.2 \), and shows some variation with age, depending on whether C-rich or O-rich TP-AGB stars dominate.
- The optical FeH Wing-Ford band, CN0.93, CaH2 and TiO1, and most of the NIR lines show abrupt index behaviour at SSP model ages associated with the culmination of the impact of TP-AGB stars on the light of the stellar population.
- The majority of XSL and IRTF stars follow the same \( H \)- and \( K \)-band CO-index strength behaviour. However, contrary to the IRTF stars labelled as AGBs, XSL TP-AGB stars do not have distinctively strong CO lines in the \( H \)- and \( K \)-bands, compared to static (e.g. RGB and early-AGB) stars.
- The availability of very cool RGB and TP-AGB spectra, and different methods of incorporating them into an SSP, influence the colours and absorption line indices of SSP models.

### 5.2 Future outlook

In this thesis, we have created, tested and made available XSL DR3 and SSP models but have also highlighted caveats and prospects. The ultimate aim is to provide XSL SSP models that give consistent results throughout the X-shooter wavelength range when applied to the spectra of observed stellar populations. First of all, XSL is the fundament of the XSL SSP models and needs to be technically correct.

#### Development of XSL

![Figure 5.1: A special case example of an attempt of model comparison of XSL CEMP star X0637. The closest models to the XSL UVB spectrum from the FERRE grid are shown with grey (with fixed N and O abundances) and black (a specifically tailored spectrum for N and O) from Else Starkenburg. Figure courtesy of A. Arentsen and E. Starkenburg (priv. comm.). This star has a UVB-VIS merging factor which is determined by crude visual inspection in DR3. However, model comparisons cannot be used to determine more accurate merging factors.](image)

- The scaling factors for UVB and NIR spectra relative to the VIS spectrum, and the Galactic dust extinction used to produce DR3 spectra, are dependent on Arentsen et al. (2019) stellar parameters through the XSL spectral interpolator. So are the XSL SSP models. Lançon et al. (2019) pointed out that when adopting these stellar parameters, the SEDs of the stellar atmosphere models are consistent with those of the data at temperatures above 5000 K. Below 5000 K, there are significant discrepancies in the SEDs, but when leaving the stellar parameters free to adjust, satisfactory representations of the SEDs are obtained down to about 4000 K.
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There is no perfect method for determining parameters of stellar spectra spanning across the HR diagram. Although Chapter 2 describes various quality assurance comparisons on the DR3 data, they concentrate on warmer stars. The immediate visual inspection of the individual results in Chapter 2, sometimes preferring visual inspection $S_{\text{UVB}}, S_{\text{NIR}}$ values, or literature $A_V$ values, as well as comparisons with various literature data, has generally ensured that such systematic trends are small, if present. With peculiar stars, such as the carbon enhanced metal-poor star (CEMP) X0637 illustrated in Fig. 5.1, it is very difficult to determine the merging of the UVB and VIS arms either by using a spectral interpolator, by crude visual inspection (as done in DR3 for this star), or even by model comparison.  

The library needs homogeneous and reliable determination of $T_{\text{eff}}, \log g$ and [Fe/H], but also [$\alpha$/Fe] and individual elemental abundances. Less than 15% of the metal-rich XSL stars ([Fe/H] $>$ −0.5), but about 75% of the metal-poor stars ([Fe/H] $<$ −1.5) prefer $\alpha$-enhanced models in Lançon et al. (2019). As a benefit, this would allow the generation of $\alpha$-enhanced SSP models. There is an ongoing project within the XSL team (I. Gorostieta, PhD thesis in prep.) looking at individual abundance determinations for the XSL stars.

Of course, Gaia DR3 (Andrae, R. et al. 2022; Gaia Collaboration et al. 2022a,b,c) provides a homogeneous catalogue of stellar parameters for the majority of XSL stars. Gaia collaboration has determined the effective temperature, surface gravity, metallicity, abundances of up to 13 chemical species, absolute MG magnitude, radius, distance, and extinction for single non-variable stars based on their astrometry, photometry, and low-resolution spectra. This wealth of data will surely improve XSL when implemented.

Only with a reliable determination of stellar parameters, can the merging of the X-shooter spectral arms and determining the Galactic dust extinction be done in a reliable way. Meanwhile, further testing of the SEDs of DR3 data is useful. We mention the efforts of Ivanov et al. (2019) (and an ongoing MUSE proposal) to verify the continuum shape of XSL spectra within the MUSE wavelength range (4800 − 9300, Å). As XSL UVB-VIS merging lies in this wavelength region, these comparisons are valuable. So far 35 high-quality MUSE spectra of stars in common with XSL have been published.

- **XSL giant stars with temperatures less than 4000 K need special attention, especially the TP-AGB stars.** Because luminous cool stars are particularly important contributors to the red and NIR light of stellar populations, XSL was designed to contain a large number of such objects. However, separating static from variable giant stars only based on NIR colour and one molecular feature is probably too rough. As is assigning a temperature to them with a general colour-temperature relation. It is difficult to separate the effects of temperature, gravity, metallicity, circumstellar extinction and variability in these stars. In the future, using distance-based luminosities, information on dust extinction and variability from the literature (star by star), is inevitable. Light curves for many of the TP-AGB stars in XSL are already available in various catalogues, such as in Gaia (Mowlavi et al. 2021; Lebzelter et al. 2022), or ASAS-SN catalogue of variable stars (Jayasinghe et al. 2018, 2019a,b), but needs compilation for XSL stars. Furthermore, we hope that future dynamical models of cool giants will help us relate spectral properties to those of the static and variable stars. With the publishing of the XSL DR2, DR3, the XSL team has made it possible for the astronomy community to come to aid with this problem.

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1The models from the FERRE grid (Allende Prieto et al. 2006) used in Fig. 5.1 are available at http://github.com/callendeprieto/ferre
Coelho et al. (2020) showed that predicted stellar population colours are more affected by the coverage of the spectral library than the choice of a synthetic versus empirical library. Derived galaxy ages can be underestimated when stellar population synthesis models with limited parameter coverage are used. There are ongoing projects to expand XSL on two fronts:

- Successful ESO X-shooter proposal ‘Missing stars in XSL: stellar light at the metallicities of globular clusters and dwarf galaxies’ (ESO program 105.20EJ.002, PI: A. Lançon) led to observations of 20 low-metallicity dwarf stars that will be included in XSL. The metal-poor objects in XSL are studied by V. Branco Silva (PhD thesis in prep.), to model metal-poor stellar populations such as globular clusters.

- 222 B-type stars from the X-shooter archive are being prepared to be included in XSL (C. Larkin in prep.) with the aim of better constraining 50-200 Myr stellar population models.

As discussed throughout Chapters 3 and 4, stellar population modelling is difficult in practice. Even with a strong fundament, SSP modelling entails careful consideration of specific methodologies.

Testing and development of XSL SSP models

- XSL SSP models need to be used to retrieve stellar population parameters of known simpler stellar populations from the optical and the NIR and the full X-shooter wavelength range. For example, the sample of X-shooter observations of nuclear star clusters in six nearby galaxies of Kacharov et al. (2018) would be an ideal test bench for XSL SSP models. These tests would highlight if the modelling of cool giants in XSL SSP models gives realistic results, and what kind of improvements are needed.

- In Chapter 3 we incorporated the spectra of 44 oxygen-rich (quasi-)static stars cooler than 4000 K, 39 oxygen-rich TP-AGB stars, and 26 spectra of carbon-rich TP-AGB stars into our new stellar population models. We used empirical colour–temperature relations to bypass the stellar parameter estimation of these cooler than 4000 K stars. However, sometimes we needed a template spectrum at the tip of the RGB which is redder than the reddest spectrum on the constructed static sequence. This might be the reason why the super-solar-metallicity XSL SSP models resulted in having bluer NIR colours compared to the E-MILES models. Furthermore, the used colour-temperature relation can change the NIR SED of the resulting SSP model.

Our empirical separation into static and O-rich TP-AGB stars based on \((I-K)\) colour and \(H^\prime/H_2O\) feature might exclude from our static sequence a few spectra of very cool stars that would be acceptable representations of the coolest RGB stars. The separation of RGB or E-AGB stars and TP-AGB stars in NIR stellar population models is important. As mentioned before, separating static from variable giant stars only based on molecular features is probably too rough, and should be done using distance-based luminosities, information on dust extinction and variability from the literature.

So far, the average spectra of variable giant stars remain a convenient practical choice to represent these stars in SSP models. However, better understanding the stellar parameters and variability would mean we could use the full potential of the 44 oxygen-rich (quasi-)static cool giant stars, 39 oxygen-rich TP-AGB stars, and 26 spectra of carbon-rich TP-AGB stars. The XSL team has already taken some first steps towards a better understanding of the cool giants. C-rich TP-AGB stars in the X-Shooter Spectral Library were studied by Gonneau et al. (2016, 2017) and O-rich TP-AGB stars by Lançon et al. (2019). Additionally, Gaia DR3 data can come to assist: Gaia Collaboration et al. (2022a) has roughly identified 15 740 carbon stars in their dataset. An accurate determination of the chemical properties and luminosity function of these stars with Gaia data is
important for testing the reliability of theoretical models, which later can be used to understand XSL carbon stars better.

- **XSL SSP models** described in Chapters 3 and 4 use a mix of interpolation methods. The cool dwarf stars are generated by the local interpolator below 4000 K, as are stars hotter than 8000 K. Spectra of stars with effective temperatures between 4500 K and 7000 K are generated by the global interpolator. In the future, **machine-learning-based stellar spectral interpolators**, such as presented in Sharma et al. (2020), could be used. These interpolators require less fine-tuning than the local or global interpolators.

- **Creating $\alpha$-enhanced stellar population models, and models with variable elemental abundances.** This is necessary to be able to study stellar populations that have $\alpha$-enhanced abundances, such as massive elliptical galaxies. As emphasised in Chapter 4, many IMF-sensitive spectral line indices are sensitive to individual elemental abundances, such as the NaI2.2 index to sodium abundance, which cannot be studied with current XSL models.

- **XSL can be combined with either theoretical or other empirical stellar libraries, to cover the gaps in or extend the XSL HR diagram.** For example, theoretical spectra of stars can be used to support the spectral interpolator at the edges of the parameter space of the stellar library, where only rare stars are present (e.g. as in Prugniel et al. 2011).

The development of stellar population models is a continuous work. With NIRSpec (Jakobsen et al. 2022, Ferruit et al. 2022, Böker et al. 2022) on JWST launched, and HARMONI on the ELT (Thatte et al. 2016) and NISP on Euclid (Laureijs et al. 2012) on the horizon, NIR SSP modelling will see an accelerated development in the nearby future to keep up with the data flow. For example, the model-to-observations CO mismatch problem seen in ETGs can be solved with XSL SSP modelling. This would require further testing of the interplay between the methods of RGB and AGB modelling, IMF and [C/Fe] enhancement in XSL SSP models. Furthermore, IMF studies benefit from the vast amount of giant or dwarf-sensitive spectral line indices in the NIR SSP models, but before using XSL SSP models in this way, elemental abundance patterns need to be included in the models, and the role of TP-AGB stars should be better understood. XSL is aimed at becoming a benchmark stellar library in the optical and NIR. The combination of a relatively high resolution, the large number of stars, and the extended wavelength coverage of the XSL will help us to join optical and NIR studies of intermediate and old stellar populations.