DOI: 10.18727/0722-6691/5165

MUSE Spectral Library

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Empirical stellar spectral libraries have applications in both extragalactic and stellar studies. We have assembled the MUSE Spectral Library (MSL), consisting of 35 high-quality spectra of stars covering the Hertzsprung–Russell diagram, and verified the continuum shape of our spectra with synthetic broadband colours. We also report indices from the Lick system, derived from the new observations. Our data demonstrate that integral field units (IFUs) are excellent tools for building spectral libraries with reliable continuum shapes that can be used as templates for extragalactic studies.

Introduction and sample

Empirical stellar spectral libraries are a universal tool in modern astronomy, with applications in both extragalactic and galactic stellar studies. They can have multiple uses: to match and remove continua to reveal weak emission lines; as templates to measure stellar kinematics in galaxies; and to measure stellar parameters such as effective temperatures and surface gravities. Theoretical stellar models can have significant weaknesses; for example, Sansom et al. (2013) found discrepancies in Balmer lines and the incomplete treatment of molecules (also shown by Castelli, Gratton & Kurucz, 1997). This occasionally leads to poorly predicted broad-band colours. At the same time, the typical empirical libraries suffer from low resolution and/or sparse coverage of the parameter space (Pickles, 1998; Le Borgne et al., 2003; Yan et al., 2018).

Spectral datasets that are available include the Elodie library (Soubiran et al., 1998; Prugniel & Soubiran, 2001; Le Borgne et al., 2004) and the X-shooter Spectral Library (XSL; Chen et al., 2014). The latter showcases the problems that increasing resolution and multi-order cross-dispersed spectrographs bring; synthetic broadband optical (UBV) colours show poor agreement with observed colours from the Bright Star Catalogue (on average at ~ 7%; see Table 5 and Figure 26 in Chen et al., 2014). The differences are likely related to pulsating variable stars observed at different phases. Slit losses are another issue; for many stars these are caused by the attenuation of flux, or other losses inherent to slit-based spectrographs.

We embarked on a project to build an empirical spectral library without slit losses using the MUSE (Multi-Unit Spectroscopic Explorer; Bacon et al., 2010) IFU, with the goal of spanning all of the major sequences on the Hertzsprung–Russell diagram and serving as a benchmark for the shapes of other theoretical and empirical spectra. Our final products are spectra suitable for galactic modelling, stellar classification and other applications. Here we report on our first sample of 35 MSL spectra.

Our initial sample numbered 33 XSL stars[1]. In addition, HD 193256 and HD 193281B serendipitously fell inside the MUSE field of view. The full sample is described in Table 1 of Ivanov et al. (2019).

Observations and data reduction

The spectra were obtained with MUSE at the European Southern Observatory (ESO) Very Large Telescope, Unit Telescope 4 (Yepun), on Cerro Paranal, Chile. Table A.1 in Ivanov et al. (2019) gives the observing log. We obtained six exposures for each target, except for HD 204155 which was observed 12 times. We placed the science targets at the same spaxels as the spectrophotometric standards to minimise any residual systematics from the instrument.

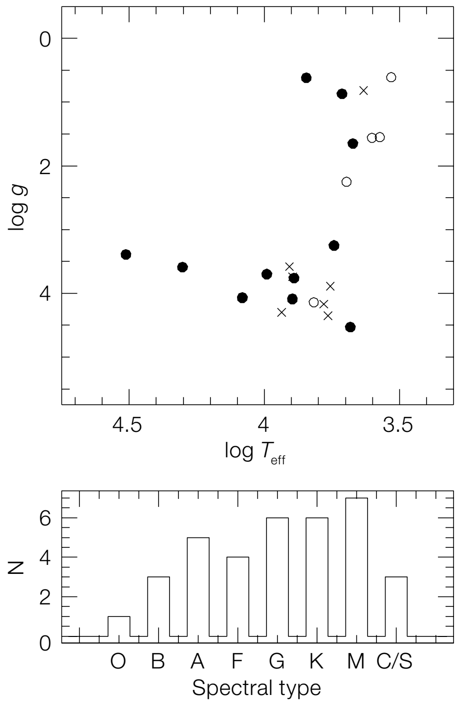

Figure 1. Properties of the MSL stars. Top: surface gravity log g vs. effective temperature T_{eff} for stars with [Fe/H] ≤ −0.5 dex (crosses), −0.5 < [Fe/H] < 0.0 dex (open circles), and [Fe/H] ≥ 0.0 dex (filled circles). Bottom: distribution of the stars by spectral type.

Data reduction was performed with the ESO MUSE pipeline (v. 2.6) within the ESOReflex 3 environment (Freudling et al., 2013). The 1D spectra were extracted using a circular aperture with a radius of 6 arcseconds. This number was selected after experiments with different aperture sizes, to guarantee that "aperture" losses led to less than a 1% change in the overall slope of the spectra from the blue to the red.

Three stars were treated differently, without major loss of continuum fidelity. For the asymptotic giant branch star [B86] 133 we reduced the extraction aperture radius to 4 arcseconds to avoid contamination from nearby sources. For HD 193256 the aperture had a radius of 4.6 arcseconds, and the sky annulus had an inner radius of 4.6 arcseconds and a width of 2 arcseconds because the star was close to the edge of the MUSE field of view. HD 193281 is a binary with a separation of ~ 3.8 arcseconds. We disentangled the two spectra as described in Ivanov et al. (2019).

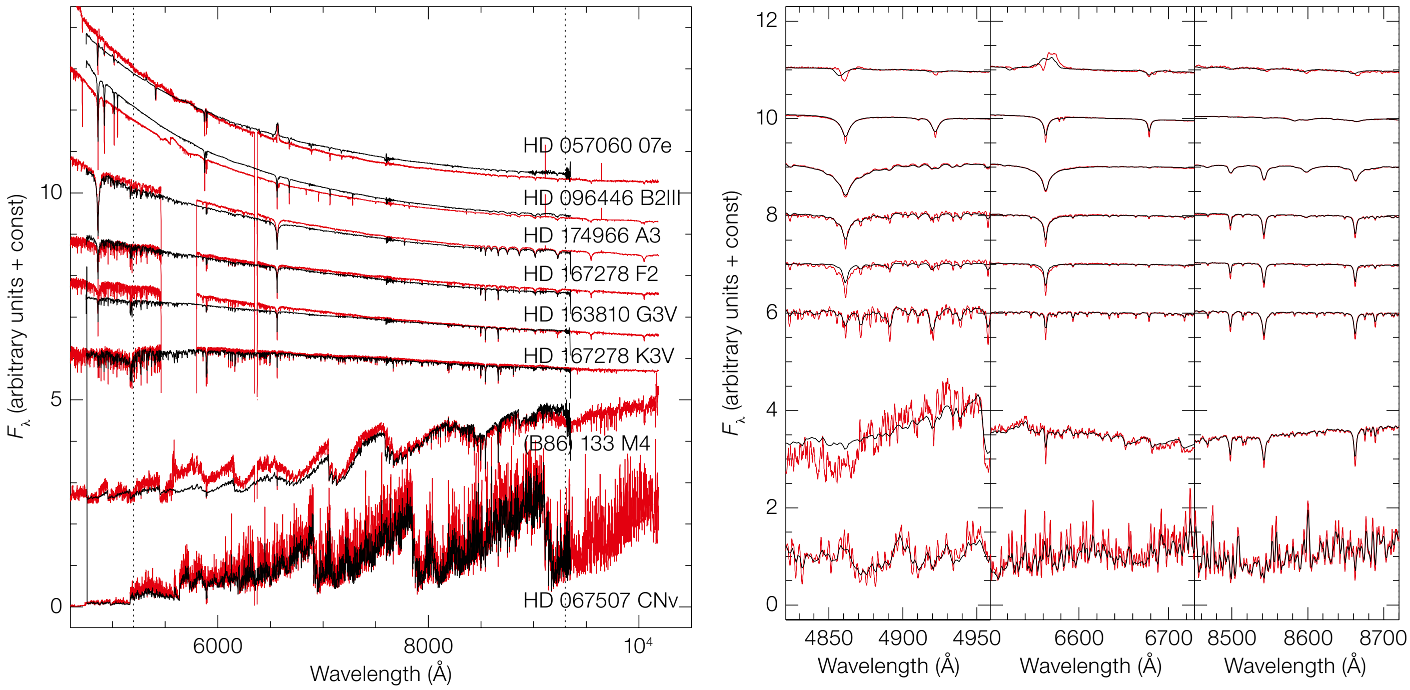

Figure 2. Comparison of a subset of our MSL spectra (black) with the XSL spectra (red; boxcar smoothed over 8 pixels). The spectra are normalised to unity between the two vertical dotted lines shown on the left, and shifted vertically for display purposes. Left: entire MUSE spectral range; right: zoom around the Hβ, Hα, and Ca triplet features (left to right). No radial velocity correction is applied.

The final MSL spectra have signal-to-noise ratios S/N > 70–200 and are available via the ESO MUSE webpage[2] or via CDS/VizieR[3]. The Lick indices (Worthey et al., 1994) that fall within the wavelength range covered by MUSE were measured in the new MSL spectra (Table C.1 in Ivanov et al., 2019).

Analysis and discussion

We demonstrate excellent agreement between the 6 (or 12 in the case of HD 204155) individual observations (Figures 2 and A.1 in Ivanov et al., 2019). A direct comparison of the MSL and XSL spectra for eight randomly selected stars across the spectral type sequence is shown in select wavelength ranges in Figure 2. In most cases, the agreement on a scale of a few hundred pixels — in other words, within the same X-shooter spectral order — is excellent. However, on a larger scale we find deviations between the XSL and MSL spectra. We fitted second-order polynomials to the ratios and extrapolated them over the full wavelength range covered by the XSL library to demonstrate that, if these trends hold, the overall peak-to-peak flux differences can easily reach ~ 20%, meaning that the overall continua of the cross-dispersed spectra is somewhat ill-defined.

Finally, we calculated synthetic Sloan Digital Sky Survey (SDSS) colours from both MSL and XSL spectra (Figure 5 in Ivanov et al., 2019). The MUSE sequences are slightly tighter than the XSL ones, confirming that the IFU MUSE spectra have more reliable shapes. This is expected in light of the slit losses and the imperfect order stitching of the XSL spectra. Furthermore, X-shooter has three arms and is in effect three different instruments; some of the colours can mix fluxes from the different arms, which may contribute to the larger scatter.

Acknowledgements

This paper is based on observations made with the ESO VLT at the La Silla Paranal Observatory (Programme ID 099.D-0623). We have made extensive use of SIMBAD at the Centre de Données astronomiques Strasbourg (CDS) and of the VizieR tool and CDS, Strasbourg, France. Enrico M. Corsini, Elena Dalla Bontà, Lorenzo Morelli, and Alessandro Pizzella acknowledge financial support from Padua University through grants DOR1715817/17, DOR1885254/18, DOR1935272/19, and BIRD164402/16.

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Links

[1] The XSL library: http://xsl.u-strasbg.fr/
[2] The MUSE spectral library at the ESO MUSE webpage: https://www.eso.org/sci/facilities/paranal/sciops/tools/MUSE_Spectral_Library.html
[3] The MUSE spectral library at VizieR/CDS: http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/629/A100