Empirical calibrations of optical absorption-line indices based on the stellar library MILES

Jonas Johansson, Daniel Thomas and Claudia Maraston
Institute of Cosmology and Gravitation, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX

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ABSTRACT
Stellar population models of absorption-line indices are an important tool for the analysis of stellar population spectra. They are most accurately modelled through empirical calibrations of absorption-line indices with the stellar parameters such as effective temperature, metallicity and surface gravity, which are the so-called fitting functions. Here we present new empirical fitting functions for the 25 optical Lick absorption-line indices based on the new stellar library Medium resolution INT Library of Empirical Spectra (MILES). The major improvements with respect to the Lick/IDS library are the better sampling of stellar parameter space, a generally higher signal-to-noise ratio and a careful flux calibration. In fact, we find that errors on individual index measurements in MILES are considerably smaller than in Lick/IDS. Instead, we find the rms of the residuals between the final fitting functions and the data to be dominated by errors in the stellar parameters. We provide fitting functions for both Lick/IDS and MILES spectral resolutions and compare our results with other fitting functions in the literature. A FORTRAN 90 code is available online in order to simplify the implementation in stellar population models. We further calculate the offsets in index measurements between the Lick/IDS system and a flux-calibrated system. For this purpose, we use the three libraries MILES, ELODIE and STELIB. We find that offsets are negligible in some cases, most notably for the widely used indices Hβ, Mgβ, Fe5270 and Fe5335. In a number of cases, however, the difference between the flux-calibrated library and Lick/IDS is significant with the offsets depending on index strengths. Interestingly, there is no general agreement between the three libraries for a large number of indices, which hampers the derivation of a universal offset between the Lick/IDS and flux-calibrated systems.

Key words: line: profiles – stars: abundances – stars: fundamental parameters.

1 INTRODUCTION
Stellar population models of absorption-line indices are a key tool for the analysis of star cluster and galaxy absorption spectra. They are used to derive the fundamental stellar population properties such as age, metallicity and element abundance ratios. In particular, optical absorption-line diagnostics in the spectra of evolved stellar populations have been successfully adopted in the past in studies on galaxy evolution (e.g. Worthey, Faber & Gonzalez 1992; Davies, Sadler & Peletier 1993; Vazdekis et al. 1997; Kuntschner & Davies 1998; Trager et al. 1998, 2000; Worthey 1998; Henry & Worthey 1999; Kuntschner 2000; Thomas et al. 2005) and globular cluster formation (e.g. Kissler-Patig 1998; Forbes et al. 2001; Kuntschner 2002; Brodie et al. 2005; Puzia et al. 2005). The Lick/IDS system (Burstein et al. 1984; Faber et al. 1985; Gorgas et al. 1993; Worthey et al. 1994; Worthey & Ottaviani 1997; Trager et al. 1998) is the standard set of absorption-line indices that has been used extensively during the last two decades for studying absorption features of stellar populations. This system consists of index definitions for 25 prominent absorption features between 4000 and 6500 Å present in the spectra of evolved stellar populations.

For studies of galaxy and star cluster evolution, absorption lines need to be modelled for stellar populations (e.g. Rose et al. 1994; Worthey et al. 1994; Worthey & Ottaviani 1997; Maraston 1998, 2005; Leitherer et al. 1999; Vazdekis 1999; Trager et al. 2000; Bruzual & Charlot 2003; Thomas, Maraston & Bender 2003; Thomas, Maraston & Korn 2004). A convenient way goes through the use of empirical calibrations. This is motivated by the fact that theoretical model atmospheres are known to suffer from incomplete line lists and continuum uncertainties. (e.g. Korn, Maraston & Thomas 2005; Rodríguez-Merino et al. 2005; Coelho et al. 2007; Lee, Worthey & Dotter 2009; Walcher et al. 2009). Empirical calibrations, on the other hand, have the disadvantage to be hardwired...
to the chemical abundance pattern of the Milky Way, which can be overcome in a semi-empirical approach as in the models by Trager et al. (2000), Thomas et al. (2003, 2004) and Schiavon (2007).

Empirical calibrations can be inserted in the models in two ways. In the first and most widely used approach, absorption-line indices enter stellar population modelling through calibrations of the empirical relationship between the indices and the stellar atmospheric parameters \( T_{\text{eff}}, \log g \) and \([\text{Fe/H}]\) as provided by stellar libraries. As these calibrations are usually obtained through polynomial fitting procedures, they are commonly referred to as ‘fitting functions’. The quality of the final stellar population model critically depends on the accuracy with which these relationships can be inferred from stellar libraries, i.e. the coverage of stellar parameter space and the reliability of the index measurements. The computational procedure with which the fitting functions are determined is a further crucial step in producing accurate models. A number of studies in the literature are devoted to such empirical calibrations for various stellar libraries, for either the Lick indices, parts of the Lick indices or other prominent absorption features (Buzzoni, Garibaldi & Mantegazza 1992; Buzzoni, Mantegazza & Garibaldi 1994; Worthey et al. 1994; Borges et al. 1995; Gorgas et al. 1999; Cenarro et al. 2002; Schiavon 2007; Maraston et al. 2009).

Alternatively to the use of fitting functions, absorption-line indices can be measured directly on the synthetic spectral energy distribution (SED) from stellar population models that are based on empirical stellar libraries. The benefit of this method is that the full SED can be compared pixel by pixel to observations (e.g. Panter et al. 2007; Tojeiro et al. 2007).

The major strength of fitting functions, instead, lies in the fact that they allow for interpolation between well-populated regions of stellar parameter space which increases the accuracy of the model in stellar parameter space that is only sparsely sampled by empirical stellar libraries. Moreover, each absorption index or spectral feature is represented by an individual fitting function, which is optimized to best reproduce its behaviour in stellar parameter space. Fitting functions are also easier to implement in a stellar population synthesis code, and models based on fitting functions are better comparable.

The widely used fitting functions of Worthey et al. (1994) and Worthey & Ottaviani (1997) are based on the Lick/IDS stellar library (Burstein et al. 1984; Faber et al. 1985). They are adopted in most stellar population models (Worthey 1994; Vazdekis et al. 1996; Trager et al. 2000; Thomas et al. 2003, 2004, 2005; Annibali et al. 2007) in the literature. Other fitting functions based on the same stellar library exist (Buzzoni et al. 1992, 1994; Borges et al. 1995) and lead to overall consistent results in the final stellar population model (Maraston et al. 2003). Major progress has been made with the advent of a new generation of stellar libraries (Jones 1999; Prugniel & Soubran 2001; Le Borgne et al. 2003; Sánchez-Blázquez et al. 2006) that have led to considerable improvements regarding coverage of stellar parameter space, spectral resolution, signal-to-noise ratio (S/N) and flux calibration.

In particular, the latter is a critical step forward. As the Lick/IDS system is not flux calibrated, observations have to be re-calibrated on to the Lick/IDS system through comparison with Lick standard stars. This requirement hampers the analysis of data samples for which spectra of such calibration stars are either not available at sufficient quality or do not cover the appropriate rest-frame wavelength range. This problem is most imminent in high redshift observations and in galaxy redshift surveys such as the Sloan Digital Sky Survey (York et al. 2000). The new flux-calibrated libraries allow the analysis of flux-calibrated spectra at any redshift without spectroscopic standard stars.

Flux-calibrated stellar libraries in the literature that are suitable for stellar population modelling include the MILES (Sánchez-Blázquez et al. 2006) library. The MILES library is particularly well suited for stellar population modelling of absorption-line indices owing to its favourable combination of spectral resolution, wavelength range, stellar parameter coverage and quality of flux calibration. In this paper, we present new Lick index fitting functions based on the MILES stellar library. To take advantage of the full spectral resolution of the MILES library, we have produced fitting functions for both the lower Lick/IDS resolution [8–11 Å full width at half-maximum (FWHM)] and the higher resolution of the MILES library (2.3 Å FWHM). A new version of the Thomas et al. (2003) stellar population model of absorption-line indices based on these new fitting functions will be presented in a subsequent paper.

This paper is organized as follows. In Section 2, we present the Lick indices measured on the MILES library and a quality evaluation of the index measurements. We discuss offsets between the flux-calibrated MILES and the Lick/IDS systems. The empirical fitting method is presented in Section 3 along with the resulting fitting functions. In Section 4, we compare the fitting functions of this work with fitting functions from the literature. We summarize in Section 5.

2 THE MILES STELLAR LIBRARY

The MILES library (Sánchez-Blázquez et al. 2006) consists of 985 stars with spectra in a wavelength range of 3525–7500 Å, well covering the Lick indices, and with a spectral resolution of 2.3 Å (see Sánchez-Blázquez et al. 2006 for further details). Important for the aim of this work is the careful flux calibration of the MILES spectra. Also, Sánchez-Blázquez et al. (2006) selected the sample of stars to fill the gaps in stellar parameter space covered by previous stellar libraries. This makes the MILES library particularly suitable for modelling absorption-line indices of stellar populations.

Stellar parameter estimates in the literature show a scatter due to varying methods applied, as discussed in Maraston et al. (2003) for \([\text{Fe/H}]\). The stellar parameters \((T_{\text{eff}}, \log g, [\text{Fe/H}])\) for the stars in the MILES library are presented in Cenarro et al. (2007), where estimates from the literature have been used and put on a homogeneous scale. Three of 985 stars have no available estimates for none of the stellar parameters \(T_{\text{eff}}, \log g, [\text{Fe/H}]\). 35 stars lack estimates only for \([\text{Fe/H}]\) and are located in sparsely populated regions at the ends of the \(T_{\text{eff}}\) range. The stars have therefore been assigned a solar metallicity to increase the number of data points.

2.1 Empirical stellar Lick indices

Our aim was to produce fitting functions for both the resolution of the MILES library (2.3 Å) and the resolution of the Lick/IDS library (8–11 Å). We have therefore measured the 25 Lick indices directly on the original stellar spectra and on the spectra downgraded to the Lick/IDS resolution described by the curve presented in Worthey & Ottaviani (1997). We have used the index definitions from Trager et al. (1998) and also from Worthey & Ottaviani (1997) for the higher order Balmer lines (H\(_\delta_A\), H\(_\delta_F\), H\(_\gamma_A\) and H\(_\gamma_F\)). Observational errors and offsets to the Lick/IDS library are described in the following sections.
2.1.1 Observational index errors

We have derived typical observational index errors in order to evaluate the quality of our index measurements. To this end, we have used pixel 1σ observational errors (Sánchez-Blázquez private communication) to perturb each stellar spectrum, at both MILES resolution and Lick/IDS resolution, through 600 Monte Carlo realizations. We have then measured the 25 Lick indices for each perturbed spectrum and determined 1σ errors for each index by using the spread in index measurements from the realizations. The index errors of the individual stellar spectra are used for weighting the least-squares fit when deriving both the offsets to the Lick system (Section 2.1.2) and the fitting functions (Section 3).

Trends between the index errors and the atmospheric parameters or line-strength indices can in principle bias the fits, but we have found such trends not to affect the results. Only for the Balmer indices do we find weak trends of increasing errors with decreasing temperature and decreasing index strength. No trends withlogg and Fe/H are found for the Balmer indices. These weak trends can probably be explained with a higher S/N for bright hot stars where the Balmer indices increase significantly in strength. Since we compute the fitting functions in bins of temperature, these trends have no significant effects on the final fitting functions.

The final 1σ typical index errors were determined by taking the median error of the whole stellar library for each index. The typical index errors are presented in Table 1 for both MILES and Lick/IDS resolution. Compared to the typical index errors for the Lick/IDS stellar library (Trager et al. 1998), also included in Table 1, we find the errors of the MILES library to have improved significantly. The stars of the Lick/IDS library were observed about 30 yr before the MILES library. Considering the technical development in 30 yr time, an improvement in the measured indices ought to be expected.

2.1.2 Lick index offsets

We have computed Lick index offsets between the MILES library and the Lick/IDS library using the stars in common between the two libraries. These offsets can be used for comparisons between models based on this work with models based on the Worthey et al. (1994) and Worthey & Ottaviani (1997) fitting functions. The offsets are also used in Section 4 to compare the fitting functions of this work with the fitting functions of Worthey et al. (1994) and Worthey & Ottaviani (1997).

Fig. 1 shows index-by-index comparisons for the residuals between the index measurements of the two libraries as a function of index strength. Worthey & Ottaviani (1997), Kuntschner (2001) and Schiavon (2007) computed zero-point offsets to the Lick/IDS library, while Puzia et al. (2002) computed their offsets as second-order least-squares fits. For most indices, we find index-strength-dependent residuals between the two libraries (Fig. 1). We have therefore computed the offsets using a σ-clipping linear least-squares fitting routine, weighted with the individual index errors derived in Section 2.1.1. The slope and intercept of these fits are presented in Table 1 and also included in Fig. 1 (black solid lines). σ-clipped data points are indicated with red crosses in Fig. 1 and the error bars are the 1σ index errors presented in Section 2.1.1. The error bars along the x-axis are represented by the index errors derived for the MILES library, while the error bars along the y-axis are represented by the combined errors of the MILES and Lick/IDS libraries in quadrature.

Table 1. Typical Lick index errors and offsets to the Lick/IDS library. M-σ and L-σ correspond to index errors at the resolution of the MILES and Lick/IDS libraries, respectively. T98-σ are the index errors presented in Trager et al. (1998) for the Lick/IDS library. $I_{lib}$ are indices measured on the libraries (MILES, ELODIE and STELIB) for which offsets to the Lick/IDS library are presented. $I_{Lick}$ are indices measured on the Lick/IDS library.

| Index | Error | M-σ | L-σ | T98-σ | Offset $I_{lib}$ = a $I_{Lick}$ + b | STELIB |
|-------|-------|-----|-----|-------|---------------------------------|--------|
|                   |       | 1   | 2   | 3     | a                               | b       | a   | b     |
| 1     | Hα   | 0.164 | 0.125 | 0.64 | 0.960 | −0.054 | 0.955 | 0.721 | 0.940 | 0.823 |
| 2     | Hγ   | 0.093 | 0.075 | 0.40 | 0.965 | 0.049 | 0.936 | 0.397 | 0.956 | 0.242 |
| 3     | CN1  | 0.0042 | 0.0038 | 0.018 | 0.912 | 0.008 | 0.897 | −0.012 | 0.986 | −0.010 |
| 4     | CN2  | 0.0050 | 0.0042 | 0.019 | 0.907 | 0.006 | 0.900 | −0.008 | 0.985 | −0.013 |
| 5     | Ca227 | 0.063 | 0.047 | 0.25 | 0.904 | 0.074 | 0.771 | 0.163 | 0.918 | −0.057 |
| 6     | Ca4300 | 0.112 | 0.093 | 0.33 | 0.858 | 0.625 | 0.870 | 0.646 | 0.924 | 0.565 |
| 7     | Hβ   | 0.142 | 0.107 | 0.48 | 0.976 | −0.148 | 0.967 | −0.057 | 1.022 | −0.735 |
| 8     | Hγ   | 0.069 | 0.059 | 0.33 | 0.963 | −0.038 | 0.962 | 0.016 | 0.999 | −0.238 |
| 9     | Fe4383 | 0.155 | 0.127 | 0.46 | 0.932 | −0.220 | 0.929 | −0.184 | 0.915 | 0.796 |
| 10    | Ca4455 | 0.073 | 0.056 | 0.22 | 0.747 | −0.067 | 0.785 | −0.105 | 0.891 | −0.228 |
| 11    | Fe4553 | 0.122 | 0.096 | 0.37 | 0.857 | 0.290 | 0.838 | 0.390 | 0.877 | −0.002 |
| 12    | Ca4668 | 0.179 | 0.156 | 0.57 | 0.903 | 0.484 | 0.913 | 0.295 | 0.992 | 0.512 |
| 13    | Hδ   | 0.063 | 0.051 | 0.19 | 0.981 | 0.126 | 0.996 | 0.015 | 1.004 | 0.032 |
| 14    | Fe5015 | 0.139 | 0.115 | 0.41 | 0.902 | 0.084 | 0.926 | 0.178 | 0.899 | 0.168 |
| 15    | Mg1  | 0.0017 | 0.0013 | 0.006 | 0.911 | 0.0004 | 0.923 | 0.005 | 0.903 | −0.009 |
| 16    | Mg2  | 0.0023 | 0.0014 | 0.007 | 0.918 | −0.003 | 0.940 | 0.0006 | 0.960 | −0.013 |
| 17    | Mg3  | 0.053 | 0.045 | 0.20 | 0.964 | 0.108 | 0.935 | 0.247 | 1.003 | −0.026 |
| 18    | Fe5270 | 0.058 | 0.047 | 0.24 | 0.923 | 0.101 | 0.919 | 0.180 | 0.932 | 0.173 |
| 19    | Fe5335 | 0.063 | 0.044 | 0.22 | 0.960 | 0.135 | 0.963 | 0.032 | 0.946 | 0.110 |
| 20    | Fe5406 | 0.044 | 0.031 | 0.18 | 0.874 | 0.269 | 0.913 | 0.165 | 0.853 | 0.264 |
| 21    | Fe5709 | 0.060 | 0.050 | 0.16 | 0.979 | −0.026 | 0.907 | 0.015 | 1.019 | −0.046 |
| 22    | Fe5782 | 0.057 | 0.043 | 0.19 | 0.920 | 0.037 | 0.879 | −0.004 | 0.906 | 0.088 |
| 23    | NaD   | 0.082 | 0.064 | 0.21 | 0.990 | −0.162 | 0.979 | −0.069 | 0.993 | −0.071 |
| 24    | TiO1  | 0.0021 | 0.0017 | 0.006 | 0.918 | −0.005 | 0.895 | −0.006 | 0.918 | 0.0003 |
| 25    | TiO2  | 0.0022 | 0.0016 | 0.006 | 0.904 | 0.0007 | 0.912 | 0.005 | 0.940 | 0.009 |

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Extreme outliers, i.e. data points that clearly showed strong deviating values compared to the bulk of data points, were removed prior to running the fitting routine, in order to avoid stars with anomalous index strengths to affect the final fits. For three indices ($C_2$4668, Fe5015 and Mg$b$), we found offsets at particularly high index strengths that deviated from the offset trends for the majority of data points. The low number of data points at these index strengths and the absence of data points at intermediate index strengths induced a bias in the derived offsets. The data points at particularly high index strengths were therefore discarded when determining the final offsets.

Offsets between the MILES and the Lick/IDS library derived in Sánchez-Blázquez et al. (2009) are also included in Fig. 1 (dotted lines). These offsets and the offsets derived in this work for the MILES library, except that no individual index errors were used as weights in the least-squares fitting. For STELIB the lack of information did not allow for a computation of index errors, while the derived index errors for ELODIE were found to be unreliable as they showed unrealistically small values. Since we only found small deviations in the offsets derived for the MILES library when not weighting as compared to weighting the least-squares fits, we compare the offsets derived for all three libraries.

In accordance with the MILES library, we found index-strength-dependent offsets also for the ELODIE and STELIB libraries. We have also determined offsets to the Lick/IDS library for two other flux-calibrated stellar libraries, namely ELODIE (Prugniel & Soubiran 2001) and STELIB (Le Borgne et al. 2003). These offsets were determined using the same procedure as described above for the MILES library, except that no individual index errors were used as weights in the least-squares fitting. For STELIB the lack of information did not allow for a computation of index errors, while the derived index errors for ELODIE were found to be unreliable as they showed unrealistically small values. Since we only found small deviations in the offsets derived for the MILES library when not weighting as compared to weighting the least-squares fits, we compare the offsets derived for all three libraries.

In accordance with the MILES library, we found index-strength-dependent offsets also for the ELODIE and STELIB libraries. We found deviating offset trends at high index values for the same indices as for the MILES library ($C_2$4668, Fe5015 and Mg$b$).

The offsets derived for the ELODIE and STELIB libraries are also presented in Table 1 and Fig. 1 (magenta and green lines, respectively). Clearly, deviations in the offsets are found between the libraries, especially for the STELIB library compared to the other two libraries. However, the STELIB library is also the library having the least number of stars in common with the Lick/IDS library, giving a higher statistical uncertainty in the derived offsets. The STELIB library only has 44 stars in common with the Lick/IDS library.
library, while ELODIE has 112 stars and the MILES library has 237 stars in common with the Lick/IDS library. Ca4227 showed particularly strange behaviour with index strength, and the accuracy of the final offsets for this index could be questionable.

In Fig. 1 we find agreements within the $1\sigma$ index errors between the offsets derived for all three libraries for H$\beta$, Mg$b$, Fe5270, Fe5335, Fe5406, Fe5709, Fe5782 and NaD. This implies a better agreement between all libraries at wavelengths redder than $\sim$4800 Å, with the exception for the broader molecular indices Mg$_1$, Mg$_2$, TiO$_1$ and TiO$_2$ that show differences greater than the $1\sigma$ index errors, which is also found for Fe5015. Agreements between offsets derived for MILES and ELODIE only, well within the $1\sigma$ index errors, are found for G4300, H$\gamma$A, H$\gamma$F, Fe4383, Ca4455, Fe4531 and C$_2$4668. This instead implies a worse agreement between MILES and ELODIE at wavelengths bluer than $\sim$4250 Å (H$\delta$A, H$\delta$F, CN1, CN2 and Ca4227), where we in general find inconsistencies between all three libraries. The significant deviation in offset between the libraries for several indices hampers the derivation of a universal offset between the Lick/IDS and flux-calibrated systems as described by these libraries.

This conclusion gets further support from the study of Sánchez-Blázquez et al. (2006) who show that offsets exist between the three flux-calibrated libraries MILES, STELIB and ELODIE. These offsets are generally in good agreement with the individual Lick offsets found in this work.

### 3 Fitting Functions

In order to produce empirical fitting functions for the MILES library, we combine our measured Lick indices with the corresponding stellar atmospheric parameters (see Section 2). It is a complex task to find the best relationship between indices and stellar atmospheric parameters, with several methods available in the literature. The
method adopted in this work is presented in this section along with
the derived fitting functions.
A user-friendly FORTRAN 90 code is available online at
www.icg.port.ac.uk/~johannsj to make the implementation of our
fitting functions easier.

3.1 Fitting method

The relationship between Lick index strengths and stellar param-
eters shows a complex behaviour, making it difficult to find one
reliable empirical fitting function for the whole parameter space.
To solve this problem, the parameter space must be divided into
subregions where local fitting functions can be computed. How-
ever, it is desirable to find the simplest set of fitting functions
and achieve a final representation of the data that is as accu-
rate as possible. Hence, the limits of the subregions have to be
carefully chosen. It has also to be assured that adjacent subre-
gions overlap, making smooth transitions possible. For these trans-
itions, we have adopted cosine-weighted interpolations following
Cenarro et al. (2002). The choice of subregions is discussed in
Section 3.2.

Following the extensive number of published fitting functions
in the literature (Worthey et al. 1994; Gorgas et al. 1999; Cenarro
et al. 2002; Schiavon 2007; Maraston et al. 2009), we use a linear
least-squares fitting routine to determine the local relationships
as polynomials in the following way:

$$I(\theta, [\text{Fe/H}], \log g) = \sum_i \beta_i \theta^i [\text{Fe/H}]^j \log g^l,$$

where $j, k, l \geq 0$ and the atmospheric effective temperature is
represented by $\theta = 5040/T_{\text{eff}}$. The representation of $T_{\text{eff}}$ using $\theta$ is
chosen due to the wide range of spectral types in the stellar library.
The number of terms in equation (1) can be made arbitrarily high.
However, the goal is to find the best compromise between simplicity
and accuracy by discarding terms with higher order polynomials
that are negligible or induce unphysical behaviours. To this end,
several methods have been developed in the literature. Worthey
et al. (1994) presented a method to find the converging rms scatter
by successively including terms and test if the rms scatter was
significantly reduced by means of an $F$-test. Gorgas et al. (1999)
and Cenarro et al. (2002) instead test if each term significantly differed
from zero through a $T$-test. Schiavon (2007) point out that both
methods mentioned above are sensitive to the coverage of parameter
space. Therefore, Schiavon (2007) combines the two methods by
first successively removing statistically insignificant terms and then
interactively testing the remaining terms for unphysical behaviours
and their effect on the rms scatter.

In this work, we adopt a mix of the above-mentioned methods.
We choose successive inclusion over successive removal of terms.
The main reason for this choice is that the normal equations of the
linear least-squares routine run a high risk of becoming degenerate
when terms that respond similarly to the data are combined. By
including terms, we can better control the degeneracy of the nor-
mal equations. If degenerate normal equations were reached after
the inclusion of a new term, this new term was discarded since a possible
lower order term already responded to the data in a similar fashion.

Finally, we determined the local fitting functions through an error-
weighted linear least-squares routine (for individual index errors,
see Section 2.1.1). Terms were successively included following the
procedure described in Gorgas et al. (1999), by starting with the
constant $(j, k, l = 0$ in equation 1) and then increasing the sum of
powers $j + k + l$ up to a maximum of $j + k + l = 3$, including
all possible cross-terms. However, since the effective temperature
is the parameter showing the most complex behaviour we included
polynomials of $\theta$ up to $j = 5$. If the variance was not reduced
at the inclusion of a new term, the term was discarded. When a
reduced variance was found, the new term and all the previously
included terms were tested by means of a $T$-test to determine if the
coefficients $\beta_i$ were statistically different from zero [by using
the coefficient errors following Gorgas et al. (1999); Cenarro et al.
(2002)]. Terms with coefficients having a significance level $\alpha \leq 0.1$
were kept. We then interactively studied the fitting functions and
removed terms inducing unphysical behaviours or not affecting the
rms scatter significantly. At the end of each run the sample was
$\sigma$-clipped, by removing data points deviating more than $3\sigma$,
and the fitting redone on the new sample.

Extreme outliers that clearly deviated from the bulk of data points
were discarded prior to running the fitting routine, hence to avoid
stars with anomalous index strengths affecting the fitting functions.

3.2 Definition of subregions in parameter space

Thanks to the good coverage of stellar parameters, the MILES
library shows a complex behaviour of the relationship between the
Lick indices and the stellar parameters. We have therefore divided
parameter space into several subregions.

The relationship between the Lick indices and the stellar param-
eters shows a bimodality between high and low gravity stars (i.e.
giants and dwarfs). The first major subregions that we have chos-
en are therefore in high and low values of $\log g$ space (from now
referred to as the dwarf and giant subregions, respectively), in
accordance with Gorgas et al. (1999), Cenarro et al. (2002) and
Schiavon (2007). The same $\log g$ subregion limits have been used
for all indices. The lower limit for the dwarf subregion was set
to $\log g = 3.6$, while the upper limit for the giant subregion was
set to $\log g = 4.0$, giving an overlap region of $\Delta \log g = 0.4$.
In Fig. 2 the subregions are shown together with their analogues
in the stellar population models of Maraston (2005), for $\log g$ as
a function of $\theta$. The different evolutionary phases for the mod-
els are indicated in Fig. 2. This shows that the choice of lim-
its for the dwarf and giant subregions coincides very well with
the division into the main sequence and the post-main sequence,
as the $\log g$ overlap region mainly covers the sub-giant branch
(SGB).

To fully recover the detailed behaviour within the $\log g$ sub-
regions, we divided the full $\theta/T_{\text{eff}}$ range into four subregions. The
choice of the limits for $\theta/T_{\text{eff}}$ subregions follows the behaviour
of the models and the distribution of stars as a function of $\theta/T_{\text{eff}}$.
This can be seen in Fig. 2 where the limits of the $\theta/T_{\text{eff}}$ subregions
are represented by the mid-points in the overlap regions, averaged over
all indices. The $\theta/T_{\text{eff}}$ subregions are discussed in the following, by
referring to the $\theta/T_{\text{eff}}$ subregions with the names D1–4 and G1–4
given in Fig. 2.

First for the giant subregion.

(i) Only the tip of the red-giant branch (RGB) for high metallicitys
falls within G1 (Fig. 2). The lower limit (in $\theta$) for this subregion
coincides with the strong drop-off in the distribution of data points
(Fig. 2). With the weak dependency on metallicity for this sub-
region and the low number of data points, we fit this subregion
independently of metallicity.

(ii) G2 and G3 clearly separate out the RGB to be fitted mainly
in G2 (Fig. 2).
(iii) Most indices show a distinct change in the behaviour of the index strengths as a function of the stellar parameters for hot A-type stars, around $\theta = 0.5$–0.6 (see Figs 3 and A1–A24). The overlap regions between G3 and G4 are therefore located around this range in $\theta$.

Then for the dwarf subregion.

(i) The lowest part of the main sequence falls within D1 (Fig. 2). As for the giant subregion, the lower limit (in $\theta$) for this subregion coincides with the strong drop-off in the distribution of data points.

(ii) The division of $\theta/T_{\text{eff}}$ space into D2 and D3 was found to improve the fits in terms of a significantly reduced rms scatter.

(iii) As for the giant subregion, most indices show a distinct change in the behaviour of the index strengths as a function of the stellar parameters for hot A-type stars, around $\theta = 0.5$–0.6 (see Figs 3 and A1–A24). The overlap regions between D3 and D4 are therefore located around this range in $\theta$.

The number of the $\theta/T_{\text{eff}}$ subregions is the same for all indices. With the exceptions for TiO$_1$ and TiO$_2$ that show a much simpler behaviour, we have therefore used less $\theta/T_{\text{eff}}$ subregions (see Figs A23 and A24, Tables A23, A24, B24 and B25). Since the different indices show a varying dependence on the stellar parameters, the limits for the subregions have been adjusted for each index individually to reduce the rms scatter.

The choice of subregions in log $g$ and $\theta/T_{\text{eff}}$ space makes up the base for our fitting functions. On top of these, metallicity space had to be divided into two subregions for 10 indices (CN$_1$, CN$_2$, Ca4227, G4300, Fe4383, Fe5015, Mg$_1$, Mg$_2$, Mg$b$ and NaD) in order to fully reproduce the metal-poor end, but only in the low gravity subregion and in the specific temperature range around
Figure 3. The fitting functions for Fe5335 (Lick resolution) are shown in the upper panels for various metallicities and overplotted on data in corresponding metallicity bins. The error bars on the data are observational index errors (see Section 2.1.1). The colours correspond to [Fe/H] = −2.0 (green), [Fe/H] = −1.35 (blue), [Fe/H] = −1.35 (red) and [Fe/H] = 0.35 (cyan) for the fitting functions and [Fe/H] < −1.8 (green), −1.8 < [Fe/H] < −1.0 (blue), −1.0 < [Fe/H] < 0.2 (red) and [Fe/H] > 0.2 (cyan) for the data. The left-hand and right-hand upper panels show giants (log $g$ < 3.6) and dwarfs (log $g$ > 3.6), respectively, for the average log $g$ of the data in bins of $\Delta \theta = 0.1$ at steps of $\theta = 0.01$. Fixed log $g$ values are used at the ends of the $\theta/T_{\text{eff}}$ range, with log $g$ = 1.0, 2.0 (cold, warm end) and log $g$ = 4.6, 4.0 (cold, warm end) for giants and dwarfs, respectively. Data points with black crosses have been $\sigma$-clipped by the least-squares fitting routine. The lower left-hand panel shows the residuals between the data and the fitting functions as a function of $\theta$ and the dashed lines represent the overall rms value for the fitting functions. The lower right-hand panel shows the distribution of the residuals for three $\theta/T_{\text{eff}}$ bins, indicated by different colours where blue have $\theta < 0.841$, black $0.841 \geq \theta < 1.045$ and red $\theta \geq 1.045$.

1.0 < $\theta$ < 1.4 (5040 < $T_{\text{eff}}$ < 3600). We have therefore independently fitted metal-rich and metal-poor stars, divided at [Fe/H] $\sim$ −1.0 for the affected temperatures in the low gravity sub-region for the 10 indices.

Even though the MILES library covers an extensive range of stellar parameter space, the very ends are obviously still sparsely populated. Therefore, the fitting functions are not valid beyond $\theta > 1.8$ ($T_{\text{eff}} < 2800$) and $\theta < 0.2$ ($T_{\text{eff}} > 25200$). The dwarf main sequence that extends to very low temperatures is well covered within these limits (Fig. 2). Very hot young stars with temperatures greater than 25200 K do not have strong indices in the visual parts of their spectra.

3.3 [\alpha/Fe] trends

Globular cluster stars are significantly [$\alpha$/Fe] enhanced with respect to solar values ($\sim$0.3; Carney 1996). The [$\alpha$/Fe] trend of field stars in the solar neighbourhood instead shows increasing [$\alpha$/Fe] enhancements with decreasing metallicity down to [Fe/H] $\sim$ −1.0 (Edvardsson et al. 1993; Fuhrmann 1998; Milone, Sansom & Sánchez-Blázquez 2009). It is first at this metallicity that the field stars reach globular cluster [$\alpha$/Fe] values. Having globular cluster stars for [Fe/H] $>$ −1.0 can therefore induce [$\alpha$/Fe] trends biased towards globular cluster values in stellar libraries dominated by field stars. The globular cluster M71 has a metallicity of [Fe/H] = −0.84
and is represented by a significant number of 28 stars in the MILES library, which could possibly induce such a bias. The stars from this globular cluster were therefore discarded when computing the final fitting functions, since the MILES library is reasonably well populated with field stars around the metallicity of M71.

The \([\alpha/Fe]\) bias of the solar neighbourhood must be taken into account when deriving stellar population models based on empirical stellar libraries, as discussed in Maraston et al. (2003). Model adjustments are therefore needed when adopting the fitting functions of this work. Such adjustments are described in Tripicco & Bell (1995), Thomas et al. (2003, 2004, 2005) and Korn et al. (2005).

### 3.4 Spectral resolution

We have computed fitting functions for both the MILES and Lick/IDS resolutions (see Section 2.1). The same final set of terms was used for both resolutions. Coefficients and coefficient errors for the fitting functions are presented in Appendix A for Lick resolution and Appendix B for MILES resolution – see Supporting Information. The \(\sigma\)-clipped number of data points \((N)\) for the local fitting functions is also included in the coefficient tables (Tables 2, A1–A24, B1–B25), along with the rms of the residuals between the data and the final fitting functions, both local and overall. The visual behaviours, residuals and distribution of residuals of the fitting functions are shown for Lick resolution in Appendix A. An example is presented for Fe5335 and Lick resolution in Tables 2 and 3 for coefficients and coefficient errors, respectively. The visual behaviours of the fitting functions for Fe5335 are shown in Fig. 3, where they are presented for the dwarf and giant subregions separately and for varying metallicities. In Appendix A, the visual behaviour of fitting functions for several \(\log g\) values at fixed \(\theta\) is also presented for indices showing strong \(\log g\) dependencies within the \(\log g\) subregions.

#### 3.5 Errors

In this section, we briefly discuss possible error sources affecting the final fitting functions. Such error sources include the index measurements of the MILES spectra, but these show very high quality, in terms of typical observational index errors, as discussed in Section 2.1.1. However, the overall rms of the final fitting functions (see Section 3.4) are considerably larger than the typical observational index errors (see Section 2.1.1). Possible error sources for this scatter are instead uncertainties in the stellar parameter estimates and intrinsic scatter in the index strengths.

The residuals between the final fitting functions and the data, presented in the lower left panels of Figs 3 and A1–A24 as a function of \(\theta\), show a typically larger scatter for cooler temperatures where

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**Table 2.** Fe5335 fitting function coefficients for Lick/IDS resolution.

| Term | \(\leq 0.58\) | \(0.50 - 1.1\) | \(0.95 - 1.5\) | \(\geq 1.2\) | \(\leq 0.58\) | \(0.50 - 1.0\) | \(0.85 - 1.4\) | \(\geq 1.2\) |
|------|-------------|-------------|-------------|-----------|-------------|-------------|-------------|-----------|
| Const. | -0.056 82 | -1.257 | 125.1 | -279.0 | -0.8217 | -43.41 | 56.65 | 10.18 |
| \(\log g\) | 0.4726 | 1.861 | -343.3 | 591.9 | 9.547 | 217.8 | -190.9 | -4.614 |
| \(\theta^2\) | -0.6719 | - | - | - | - | 1.336 | -14.42 | 0.6270 |
| \([Fe/H]\) | - | - | 1.797 | 314.1 | -406.0 | -30.62 | -397.3 | 205.6 |
| \(\theta^3\) | - | - | - | - | - | - | 0.9821 | - |
| \([Fe/H]^2\) | - | - | 1.808 | 1.048 | - | - | -4.202 | 31.08 |
| \(\theta^2[Fe/H]\) | - | - | - | - | - | - | 0.3445 | - |
| \(\theta^2[Fe/H]^2\) | - | - | - | - | - | - | - | - |
| rms | 0.1111 | 0.2352 | 0.3446 | 0.7921 | 0.08168 | 0.1348 | 0.1879 | 0.7221 |
| \(N\) | 81 | 358 | 365 | 113 | 51 | 349 | 207 | 17 |

**Table 3.** Fe5335 fitting function coefficient errors for Lick/IDS resolution.

| Term | \(\leq 0.58\) | \(0.50 - 1.1\) | \(0.95 - 1.5\) | \(\geq 1.2\) | \(\leq 0.58\) | \(0.50 - 1.0\) | \(0.85 - 1.4\) | \(\geq 1.2\) |
|------|-------------|-------------|-------------|-----------|-------------|-------------|-------------|-----------|
| Const. | 0.01305 | 0.04702 | 1.237 | 2.860 | 0.1784 | 2.914 | 2.000 | 0.06966 |
| \(\log g\) | 0.03082 | 0.1169 | 3.120 | 5.928 | 1.544 | 15.82 | 5.800 | 0.04788 |
| \(\theta^2\) | -0.01732 | - | - | - | - | 0.1617 | 0.3727 | 0.01636 |
| \([Fe/H]\) | - | - | 0.07110 | 2.603 | 4.059 | 4.200 | 31.77 | 5.571 |
| \(\theta^3\) | - | - | - | - | - | - | 0.01056 | - |
| \([Fe/H]^2\) | - | - | - | - | - | - | 0.08236 | - |
| \(\theta[Fe/H]\) | - | - | 0.01959 | 0.008170 | - | - | 0.4293 | 0.7186 |
| \(\theta^2[Fe/H]\) | - | - | - | - | - | - | - | - |
| \(\theta^2[Fe/H]^2\) | - | - | 0.01251 | 0.003640 | - | - | 0.2782 | 0.3495 |
| \(\theta^4\) | - | - | - | - | - | - | 0.005307 | 0.08761 |

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index values exhibit strong sensitivities to $T_{\text{eff}}$. The source of this correlation is probably, at least partly, uncertainties in the stellar parameters, since these will have a larger effect when the index strengths show strong dependencies on the stellar parameters, i.e. $\theta/T_{\text{eff}}$ uncertainties will have less effect when the index strengths show weaker dependencies on $\theta/T_{\text{eff}}$.

### 4 COMPARISONS WITH THE LITERATURE

In this section, we compare the fitting functions derived in this work with the fitting functions in the literature derived for stellar libraries other than MILES. We search for differences in various parameter regimes. Comparisons are made with the classical and extensively adopted fitting functions of Worthey et al. (1994) and Worthey & Ottaviani (1997) (from now on WFF), shifted with the offsets derived in Section 2.1.2, and with the more recent fitting functions of Schiavon (2007) (from now on SFF, which were based on the Jones library (Jones 1999).

We have performed the comparisons in different regions of parameter space to find the regimes where major differences roam. The comparisons have been divided into three $\theta/T_{\text{eff}}$ bins, referred to as cold, intermediate and warm temperatures, with $\theta/T_{\text{eff}}$ limits presented in Table 4. Each of these bins has been further divided into two $\log g$ bins with $\log g = 2.0$ (referred to as giants) and $\log g = 4.5$ (referred to as dwarfs) to make up a total of six bins. The average residuals between the fitting functions were computed in each bin at [Fe/H] steps of 0.5 in the range $-2 \leq [\text{Fe/H}] \leq 0.5$ and presented in Figs 4 and 5 as a function of metallicity for the comparisons with WFF and SFF, respectively.

The comparisons have only been made within the parameter limits for which the fitting functions are applicable, described in Worthey et al. (1994) (WFF), Schiavon (2007) (SFF) and Section 3.2, resulting in the limits of the $\theta/T_{\text{eff}}$ bins presented in Table 4. Due to the limitations of the SFF we cannot make comparisons for the warm giant regime, while the intermediate giant regime has a varying lower $\theta$ limit (see Schiavon 2007 for individual index limits).

The overall rms of the final fitting functions (see Section 3.4) are shown in Figs 4 and 5 as grey shaded areas (1 rms dark grey and 2 rms light grey). This gives a reference to the differences found between the libraries.

Overall, there is good agreement between the fitting functions within the rms. We find the biggest residuals to occur at the ends of parameter space, i.e. at the metallicity and temperature extremes (see Figs 4 and 5). This was expected since the number of data points decrease towards the ends of parameter space, resulting in larger uncertainties of the fitting functions. In the rest of this section, we discuss the comparisons for individual indices in terms of stellar parameter regions that show differences beyond the 1 and 2 rms levels.

#### 4.1 H$\delta_{A}$

**WFF comparison (Fig. 4).** Warm giants extend well beyond the 2 rms level where this work shows much weaker indices. We find both warm and cold dwarfs to show stronger indices for this work, even extending beyond the 2 rms level for the metal-poor and metal-rich ends, respectively. Otherwise, this work shows slightly weaker indices extending to the 1 rms level.

**SFF comparison (Fig. 5).** Cold dwarfs show weaker indices for this work, beyond the 1 rms level. Warm and intermediate temperature dwarfs show stronger indices for this work out to the 2 rms level in the metal-poor regime. Intermediate temperature giants show stronger indices out to the 2 rms level at the ends of the metallicity scale. Otherwise, differences within the 1 rms level are mainly found.

#### 4.2 H$\gamma$

**WFF comparison (Fig. 4).** The most obvious difference is found for warm giants where this work shows much weaker indices, extending well beyond the 2 rms level. Otherwise, differences are mainly found within the 1 rms level, except for the metal-rich end of cold and warm dwarfs that show stronger indices for this work beyond the 2 rms level.

**SFF comparison (Fig. 5).** This work shows in general stronger indices in the metal-poor regime, beyond the 1 rms level for intermediate temperature and warm dwarfs and beyond the 2 rms level for intermediate temperature giants. In the metal-rich regime we instead find weaker indices for this work, out to the 2 rms level for intermediate temperature and cold giants.

#### 4.3 CN$_{1}$

**WFF comparison (Fig. 4).** The warm end for giants shows significantly stronger indices for this work, extending well beyond the 2 rms level. Otherwise, this work shows in general stronger indices at the metal-poor end and weaker indices at the metal-rich end, out to the 2 rms level in both cases.

**SFF comparison (Fig. 5).** Intermediate temperature giants and dwarfs show weaker and stronger indices for this work, respectively, at the metal-rich end. Otherwise, agreements within the 1 rms level are mainly found.

#### 4.4 CN$_{2}$

**WFF comparison (Fig. 4).** Warm dwarfs show weaker indices for the entire metallicity scale for this work, out to the 2 rms level. Otherwise, differences similar to the previous index are found.

**SFF comparison (Fig. 5).** Due to problems with implementing the SFFs, we cannot make a reliable comparison.

#### 4.5 Ca4227

**WFF comparison (Fig. 4).** Cold dwarfs show stronger indices for this work, extending out to the 2 rms level in the metal-poor regime, while cold giants instead show weaker indices for this work out to the 2 rms level at the metal-poor end. Warm giants show stronger indices for this work beyond the 1 rms level at the metal-poor end. Cold dwarfs show stronger indices for this work, even extending beyond the 2 rms level at the metal-poor end.

**SFF comparison (Fig. 5).** The most prominent difference is found for cold giants in the metal-poor regime, extending well beyond the
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Figure 4. Comparisons between the fitting functions of this work (referred to as J09) and Worthey et al. (1994) (W94), and with Worthey & Ottaviani (1997) (W97) for $H_δ_A$, $H_δ_F$, $H_γ_A$ and $H_γ_F$. The panels show the difference J09-W94/W97 as a function of metallicity for each Lick index. The comparisons are made for giants (log $g = 2.0$, solid lines) and dwarfs (log $g = 4.5$, dashed lines). The different colours correspond to the different bins of $θ/T_{eff}$ space, with limits stated in Table 4, where the average difference has been computed, blue for the warm, black for the intermediate and red for the cold temperature bin. Fitting function residuals in terms of 1 rms (dark grey shaded areas) and 2 rms levels (light grey shaded areas) are indicated. The errors are represented by the combined errors of the MILES and Lick/IDS libraries in quadrature (for more on the errors, see Section 2.1.1).

2 rms level. Cold dwarfs show stronger indices for this work at the metal-rich end, beyond the 1 rms level. Otherwise, differences within the 1 rms level are found.

4.6 G4300

WFF comparison (Fig. 4). Warm giants extend well beyond the 2 rms level with stronger indices for this work. Metal-poor cold giants show stronger indices for this work, extending to the 2 rms level. Cold metal-poor dwarfs extend beyond the 1 rms level, showing weaker indices for this work. Cold and warm metal-rich dwarfs show stronger and weaker indices for this work, respectively, beyond the 1 rms level.

SFF comparison (Fig. 5). Differences beyond the 1 and 2 rms levels are found in several regimes, strongest at the ends of the metallicity scale.

4.7 $H_γ_A$

WFF comparison (Fig. 4). Warm giants show significantly weaker indices for this work, well beyond the 2 rms level. Warm dwarfs and cold giants show stronger indices for this work out to the
2 rms level. Otherwise, differences within the 1 rms level are mainly found.

SFF comparison (Fig. 5). The most significant difference is found for intermediate temperature dwarfs, showing weaker indices for this work in the metal-poor regime well beyond the 2 rms level. Otherwise, differences are mainly found around the 1 rms level.

4.8 $H_{\alpha}$

**WFF comparison (Fig. 4).** Weaker indices are found for this work for warm giants and cold dwarfs beyond the 2 and 1 rms levels, respectively. Otherwise, differences within the 1 rms level are mainly found.
**Figure 5.** Same as Fig. 4, but for the comparison between this work (J09) and Schiavon (2007) (S07). The errors are represented by index errors of the MILES library (see Section 2.1.1).

**SFF comparison (Fig. 5).** Due to problems with implementing the SFFs, we cannot make a reliable comparison.

### 4.9 Fe4383

**WFF comparison (Fig. 4).** Warm giants and warm dwarfs show stronger indices out to the 2 rms level at the metal-poor end. Cold giants show weaker indices, out to the 2 rms level at the metal-poor and metal-rich ends. Otherwise, differences within the 1 rms level are mainly found.

**SFF comparison (Fig. 5).** Cold dwarfs show significantly stronger indices for this work, well beyond the 2 rms level. Warm dwarfs instead show weaker indices, out to the 2 rms level. Otherwise, differences within the 1 rms are mainly found.
4.10 Ca4455

\emph{WFF comparison (Fig. 4).} Cold giants show stronger indices for this work, extending well beyond the 2 rms level in the metal-rich regime. Cold dwarfs show weaker indices for this work, extending well beyond the 2 rms level. The warm regime shows stronger indices for this work, extending beyond the 1 rms level in the metal-poor regime.

4.11 Fe4531

\emph{WFF comparison (Fig. 4).} Cold dwarfs show stronger indices for this work at the 1 rms level for the metal-poor end and increasing well beyond the 2 rms level at the metal-rich end. Intermediate temperature giants show stronger indices for this work, out to the 2 rms level at the metal-rich end.

4.12 C4468

\emph{WFF comparison (Fig. 4).} The metal-rich end shows weaker indices for this work, mainly down to the 1 rms level. The metal-poor end shows weaker and stronger indices for this work extending beyond the 1 rms level for the warm bins and cold dwarfs, respectively.

\emph{SFF comparison (Fig. 5).} Cold giants show weaker indices for this work beyond the 1 rms level in the metal-rich regime. Intermediate temperature dwarfs show stronger indices for this work at the metal-rich end out to the 2 rms level.

4.13 Hβ

\emph{WFF comparison (Fig. 4).} We find this work to show weaker indices for warm giants well beyond the 2 rms level. Cold dwarfs show stronger indices for this work beyond the 2 rms level. Cold giants show weaker indices for this work beyond the 1 rms level.

\emph{SFF comparison (Fig. 5).} Cold dwarfs show the biggest differences right beyond the 1 rms level. Otherwise, differences within the 1 rms level are found.

4.14 Fe5015

\emph{WFF comparison (Fig. 4).} Cold giants show weaker indices for this work, beyond the 2 rms level in the metal-poor regime. Intermediate temperature giants show stronger indices for this work beyond the 2 rms level in the metal-rich regime.

\emph{SFF comparison (Fig. 5).} Cold giants show significantly weaker indices for this work, well beyond the 2 rms level. This work shows weaker indices for cold dwarfs beyond the 1 rms level in the metal-poor regime. Otherwise, differences within the 1 rms are mainly found.

4.15 Mg1

\emph{WFF comparison (Fig. 4).} Cold dwarfs show stronger indices for this work, out to the 2 rms level in the metal-poor regime. Cold giants show stronger indices for this work at intermediate metallicities. No differences are found beyond the 2 rms level.

4.16 Mg2

\emph{WFF comparison (Fig. 4).} Cold dwarfs show stronger indices for this work beyond the 1 rms level in the metal-poor regime. Cold giants show stronger indices for this work beyond the 1 rms level for intermediate metallicities. Otherwise, differences within the 1 rms level are mainly found.

\emph{SFF comparison (Fig. 5).} The cold end shows weaker indices for this work in the metal-poor regime, beyond the 2 rms level. Cold dwarfs instead show stronger indices for this work beyond the 2 rms level at the metal-rich end.

4.17 Mgb

\emph{WFF comparison (Fig. 4).} Cold and intermediate temperature giants show weaker indices for this work, extending beyond the 2 rms level. Intermediate temperature and cold dwarfs show weaker and stronger indices, respectively, for this work in the metal-poor regime, beyond the 1 rms level.

\emph{SFF comparison (Fig. 5).} Due to problems with implementing the SFFs, we cannot make a reliable comparison.

4.18 Fe5270

\emph{WFF comparison (Fig. 4).} The warm end shows stronger indices beyond the 2 rms level in the metal-poor regime. Cold giants show weaker indices for this work beyond the 2 rms level. The metal-rich end shows stronger indices for this work beyond the 1 rms level for intermediate temperature cold dwarfs.

\emph{SFF comparison (Fig. 5).} We find weaker indices for this work beyond the 1 rms level for cold giants. Stronger indices for this work beyond the 2 rms level are found for cold dwarfs in the intermediate metallicity regime. Otherwise, differences well within the 1 rms level are found.

4.19 Fe5335

\emph{WFF comparison (Fig. 4).} Cold giants show weaker indices for this work well beyond the 2 rms level. The warm end shows stronger indices out to the 1 rms level at intermediate metallicities. Cold dwarfs show weaker and stronger indices out to the 1 rms level at the metal-poor and metal-rich ends, respectively.

\emph{SFF comparison (Fig. 5).} Cold dwarfs show stronger indices beyond the 2 rms level at intermediate metallicities and weaker indices beyond the 2 rms level at the metal-rich end. Cold giants show weaker indices for this work beyond the 1 rms level. Intermediate temperature dwarfs instead show stronger indices for this work, beyond the 1 rms level in the metal-rich regime.

4.20 Fe5406

\emph{WFF comparison (Fig. 4).} The cold end shows stronger indices for this work beyond the 1 rms level in the metal-rich regime. Intermediate temperature giants show weaker indices for this work beyond the 1 rms level. No differences are found beyond the 2 rms level.

4.21 Fe5709

\emph{WFF comparison (Fig. 4).} Cold dwarfs show stronger indices for this work, extending beyond the 2 rms level at the metal-rich end. Otherwise, no significant differences beyond the 1 rms level are found.

4.22 Fe5782

\emph{WFF comparison (Fig. 4).} Warm giants show stronger indices for this work in the metal-poor regime, extending beyond the 2 rms level
at the metal-poor end. *Cold giants* show stronger indices for this work regime, beyond the 1 rms level. *Warm dwarfs* show stronger indices for this work beyond the 1 rms level at the metal-poor end.

**4.23 NaD**

WFF comparison (Fig. 4). The cold end shows stronger indices for this work extending well beyond the 2 rms level, especially in the metal-poor regime. *Intermediate temperature giants* show stronger indices for this work, extending beyond the 2 rms level in the metal-rich regime.

**4.24 TiO_2**

WFF comparison (Fig. 4). Cold dwarfs show weaker indices for this work, extending well beyond the 1 rms level at the metal-rich end. Otherwise, no differences are found beyond the 1 rms level.

**4.25 TiO_2**

WFF comparison (Fig. 4). We find significantly weaker indices for this work for *cold dwarfs*, extending very far beyond the 2 rms level. Otherwise, no significant differences are found beyond the 1 rms level.

**5 SUMMARY**

We have derived new empirical fitting functions for the relationship between Lick absorption indices and stellar atmospheric parameters ($T_{eff}$, [Fe/H] and log g) described by the MILES library of stellar spectra, for both the resolution of the MILES library and the resolution of the Lick/IDS library. The MILES library consists of 985 stars selected to produce a sample with extensive stellar parameter coverage. The MILES library was also chosen because it has been carefully flux-calibrated, making standard star-derived offsets unnecessary. This becomes important when comparing stellar population models to high redshift data where no resolved individual stars are available.

We find the index measurements of the MILES spectra to have very high quality in terms of observational index errors. These errors are also found to be significantly smaller than for the Lick/IDS library. This was expected since the MILES library was observed nearly 30 yr after the Lick/IDS library. Given the high quality of the index measurements, index errors should not be the major error sources for the final fitting functions. We instead find indications that the stellar parameter estimates are significant error sources.

Lick index offsets between the MILES library and the classic Lick/IDS library are derived in order to be able to compare stellar population models based on this work with models in the literature. We find these offsets to be dependent on index strength and have therefore derived least-squares fits for the residual between the two libraries. Offset to the Lick/IDS library are also derived for the flux-calibrated ELODIE and STELIB libraries. We find clear offset deviations between the libraries. The largest deviations are found for the STELIB library compared to the other two libraries, which is also the library having least stars in common with the Lick/IDS library. The deviations in offsets found between the three libraries undermine the derivation of universal offsets between the Lick/IDS and these flux-calibrated systems.

We compare the fitting functions of this work to the fitting functions in the literature, namely the fitting functions of Worthey et al. (1994), Worthey & Ottaviani (1997) and Schiavon (2007). Generally, we find good agreement within the rms of the residuals between the data and the fitting functions of this work. The differences found in the comparisons vary significantly from index to index and especially from one stellar parameter region to another for individual indices. However, the major differences are found in the outskirts of stellar parameter space, i.e. at the temperature and metallicity ends. This is probably due to a low number of data points in these regimes for the stellar libraries, inducing uncertainties which result in the major differences found.

In a forthcoming paper (Thomas et al. in preparation), the fitting functions of this work will be implemented in stellar population models following the techniques of Maraston (2005) and Thomas et al. (2003).

A user-friendly FORTRAN 90 code is available online at www.icg.port.ac.uk/~johanmsj to smooth the implementation of our fitting functions in population synthesis codes.

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**REFERENCES**

Annibali F., Bressan A., Rampazzo R., Zeilinger W. W., Danese L., 2007, A&A, 463, 455
Borges A. C., Idiart T. P., de freitas Pacheco J. A., Thévenin F., 1995, AJ, 110, 2408
Brodie J. P., Strader J., Denicoló G., Beasley M. A., Cenarro A. J., Larsen S. S., Kuntschner H., Forbes D. A., 2005, AJ, 129, 2643
Bruzual G., Charlot S., 2001, MNRAS, 344, 1000
Burstein D., Faber S. M., Gaskell C. M., Krumm N., 1984, ApJ, 287, 586
Buzzoni A., Garibaldi G., Mantegazza L., 1992, AJ, 103, 1814
Buzzoni A., Mantegazza L., Garibaldi G., 1994, AJ, 107, 513
Carney B. W., 1996, PASP, 108, 900
Cenarro A. J., Gorgas J., Cardiel N., Vazdekis A., Peletier R. F., 2002, MNRAS, 329, 863
Cenarro A. J. et al., 2007, MNRAS, 374, 664
Coelho P., Bruzual G., Charlot S., Weiss A., Barbuy B., Ferguson J. W., 2007, MNRAS, 382, 498
Davies R. L., Sadler E. M., Peletier R. F., 1993, MNRAS, 262, 659
Edvardsson B., Andersen J., Gustafsson B., Lambert D. L., Nissen P. E., Tomkin J., 1993, A&A, 275, 101
Faber S. M., Friel E. D., Burstein D., Gaskell C. M., 1985, ApJS, 57, 711
Forbes D. A., Beasley M. A., Brodie J. P., Kissler-Patig M., 2001, ApJ, 563, 143
Fuhrmann K., 1998, A&A, 338, 161
Gorgas J., Faber S. M., Burstein D., Gonzalez J. J., Courteau S., Prosser C., 1993, ApJS, 86, 153
Gorgas J., Cardiel N., Pedraz S., Gonzalez J. J., 1999 A&AS, 139, 29
Henry R. B. C., Worthey G., 1999, PASP, 111, 919
Jones L. A., 1999, Univ. North Carolina
Kissler-Patig M., Brodie J. P., Schroder L. L., Forbes D. A., Grillmair C. J., Huchra J. P., 1998, AJ, 115, 105
Korn A. J., Maraston C., Thomas D., 2005, A&A, 438, 685
Kuntschner H., 2000, MNRAS, 315, 184
Kuntschner H., 2001, Ap&SS, 276, 885
Kuntschner H., Davies R. L., 1998, MNRAS, 295, 29

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