To use or not to use synthetic stellar spectra in population synthesis models?

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ABSTRACT
Stellar population synthesis (SPS) models are invaluable to study star clusters and galaxies. They provide means to extract stellar masses, stellar ages, star formation histories, chemical enrichment and dust content of galaxies from their integrated spectral energy distributions, colours or spectra. As most models, they contain uncertainties which can hamper our ability to model and interpret observed spectra. This work aims at studying a specific source of model uncertainty: the choice of an empirical vs. a synthetic stellar spectral library. Empirical libraries suffer from limited coverage of parameter space, while synthetic libraries suffer from modelling inaccuracies. Given our current inability to have both ideal stellar-parameter coverage with ideal stellar spectra, what should one favour: better coverage of the parameters (synthetic library) or better spectra on a star-by-star basis (empirical library)? To study this question, we build a synthetic stellar library mimicking the coverage of an empirical library, and SPS models with different choices of stellar library tailored to these investigations. Through the comparison of model predictions and the spectral fitting of a sample of nearby galaxies, we learned that: predicted colours are more affected by the coverage effect than the choice of a synthetic vs. empirical library; the effects on predicted spectral indices are multiple and defy simple conclusions; derived galaxy ages are virtually unaffected by the choice of the library, but are underestimated when SPS models with limited parameter coverage are used; metallicities are robust against limited HRD coverage, but are underestimated when using synthetic libraries.

Key words: galaxies: stellar content – stars: atmospheres

1 INTRODUCTION
Stellar population synthesis (SPS) models are among the most powerful tools developed over the last few decades in astrophysics. Originally based on the seminal work by Tinsley & Gunn (1976, see also Tinsley 1978), they are today the means through which we are able to model (and thus, interpret) the integrated properties of galaxies and unresolved star clusters. In the current era of large spectroscopic galaxy surveys, SPS models play a key role in inferring massive amounts of information about the origin and evolution of galaxies (see, e.g., Kauffmann et al. 2003; Tremonti et al. 2004; Gallazzi et al. 2005; da Cunha et al. 2008; Cid Fernandes et al. 2009; Conroy & Gunn 2010; Sodré et al. 2013; Chevallard & Charlot 2016, for examples of the use of SPS models in the interpretation of large samples of galaxies).

SPS models can be built in a variety of ways, but the so-called Evolutionary Stellar Population Synthesis models are among the ones with more predictive and interpretative power, and have been used very frequently in the literature (e.g. Bruzual A. 1983; Arimoto & Yoshii 1986; Guiderdoni & Rocca-Volmerange 1987; Charlot & Bruzual 1991; Bruzual & Charlot 1993, 2003; Bressan et al. 1994; Fritze-v. Alvensleben & Gerhard 1994; Worthey 1994; Vazdekis et al. 1996, 2013; Fioc & Rocca-Volmerange 1997, 2019; Kodama & Arimoto 1997; Maraston 1998, 2005; Coelho et al. 2007; Leitherer et al. 1999; Conroy & Gunn 2010; Conroy & van Dokkum 2012). Such models are built upon a set of key ingredients, namely: (i) stellar evolutionary tracks or isochrones; (ii) stellar flux libraries; (iii) initial mass functions; and (iv) star formation histories (see e.g. the review by Conroy 2013).

A model can only be as good as its ingredients, and there are published studies devoted to the investigation of the uncertainties affecting SPS models (e.g. Charlot et al. 1996; Conroy et al. 2009; Percival & Salaris 2009). These
studies have shown that limitations of SPS models can arise from uncertainties in both stellar evolution theory and stellar spectral libraries.

In this work, we take a new look at quantifying the uncertainties affecting SPS models by studying a particular source of error: the impact of choosing between an empirical (i.e. observational) or a theoretical library of individual stellar spectra to describe stellar fluxes. By ‘stellar spectral library’, we mean a compilation of homogeneous spectra (either observed or modelled), of which a plethora is available in the literature.1 For stellar population studies, a library should ideally provide complete coverage of the Hertzsprung–Russell diagram (HRD hereafter), accurate and precise atmospheric parameters (effective temperature, $T_{\text{eff}}$, surface gravity, log g, abundances, [Fe/H] and [Mg/Fe], rotation, micro- and macro-turbulent velocities, etc.), as well as a good compromise between wavelength coverage, spectral resolution and signal-to-noise ratio (SNR). Both empirical and theoretical spectral libraries have been largely used in the literature, each presenting advantages and disadvantages.

In a theoretical library (e.g., in recent years, Leitherer et al. 2010; Palacios et al. 2010; Sordo et al. 2010; Kirby 2011; de Laverny et al. 2012; Husser et al. 2013; Coelho 2014), a stellar spectrum has well-defined atmospheric parameters, does not suffer from low SNR or flux calibration problems, and covers a larger wavelength range at a higher spectral resolution than any empirical library. The drawback is that current limitations in our knowledge of the physics of stellar atmospheres and in the databases of atomic and molecular opacities make theoretical spectra suffer from limited ability to reproduce observations accurately (e.g. Bessell et al. 1998; Küçüksas et al. 2005; Kurucz 2006; Martins & Coelho 2007; Bertone et al. 2008; Coelho 2009; Plez 2011; Lebzelter et al. 2012b; Sansom et al. 2013; Coelho 2014; Knowles et al. 2019).

In an empirical library, in contrast, all spectral features are accurate (modulo any observational and data reduction problems). Several such libraries have been proposed with different coverages in wavelength, resolution and stellar parameters (e.g., in recent years, Ayres 2010; Blanco-Cuaresma et al. 2014; Chen et al. 2014; De Pascale et al. 2014; Lebzelter et al. 2012a; Liu et al. 2015; Villaume et al. 2017; Worley et al. 2012, 2016; Lira et al. 2017; Worley et al. 2012, 2016; Luo et al. 2015; Yan et al. 2018). The strongest limitation of an empirical library is that it is virtually impossible to fully sample the parameter space – in terms of atmospheric parameters, including abundance ratios – needed to probe the full range of galaxy evolution studies: stellar populations exist in other galaxies, which are not represented by the stars we harbour in our Galaxy, such as young metal-poor stars expected to dominate the spectra of high-redshift galaxies (e.g., Stark 2016) and chemical mixtures different from those tracing the specific history of the solar neighbourhood. A classical example of the latter is the over-abundance of α-process over iron-peak elements in high-metallicity populations found in elliptical galaxies (e.g. Worthey et al. 1992; Thomas et al. 2005). Moreover, even to date, assigning atmospheric parameters to observed spectra remains challenging, to the point that different groups often derive different parameters for the same stars. This is a concern for the community, which triggered the creation of an IAU Working Group on Stellar Spectral Libraries.2 Meanwhile, impressive work is being achieved towards deriving accurate and precise parameters for stars, while exploring and understanding the sources of deviant parameter estimates (e.g. Gilmore et al. 2012; Smiljanic et al. 2014; Jofré et al. 2014, 2015, 2017, and references therein).

SPS models incorporating stellar spectral libraries can be roughly classified into 4 types:

(i) models relying purely on empirical stellar libraries, which we refer to as semi-empirical SPS models3 (e.g., Maraston et al. 2009; Vazdekis et al. 2010, 2016);
(ii) models relying purely on theoretical stellar libraries, which we refer to as fully-theoretical SPS models (e.g., Leitherer et al. 1999; Delgado et al. 2005; Maraston 2005; Coelho et al. 2007; Percival et al. 2009; Buzzoni et al. 2009; Lee et al. 2009; Leitherer et al. 2014);
(iii) models combining empirical and theoretical libraries to sample the parameter space and widen the wavelength coverage (e.g. Bruzual & Charlot 2003; Maraston & Strömbäck 2011);
(iv) models using an empirical library as a base (typically for solar abundances), from which predictions are computed differentially (often via theoretical spectra), which we refer to as differential SPS models (Prugniel et al. 2007; Walcher et al. 2009; Conroy & van Dokkum 2012; Vazdekis et al. 2015).

Traditionally, the trend has been to prefer empirical libraries to study stellar absorption features in the spectra of old stellar populations (e.g. Vazdekis et al. 2016), while models for young and UV-bright stellar populations heavily rely on theoretical libraries (e.g. Leitherer et al. 2014). The recent work by Martins et al. (2019) probed different spectral libraries to reproduce the integrated spectra of Galactic star clusters, concluding that modern theoretical libraries are competitive also for modelling old populations.

Our focus in the present work is on the comparison between semi-empirical and fully-theoretical SPS models. In particular, we aim at investigating how the strengths and caveats of empirical versus theoretical libraries of stellar spectra impact the integrated properties of Simple Stellar Populations (SSPs). The questions we seek to answer are:

(i) How do the uncertainties identified in theoretical stellar libraries affect integrated colours and spectral indices of model stellar populations?
(ii) How does the non-ideal coverage of the HR diagram by empirical libraries affect the predictions of integrated properties of stellar populations?
(iii) How do random errors in the stellar atmospheric parameters translate into the models?

1 A comprehensive list has been maintained over the years by David Montes, see https://webs.ucm.es/info/Astrof/invest/actividad/spectra.html

2 https://www.iau.org/science/scientific_bodies/working_groups/306/

3 Semi-empirical models are still based on theoretical prescriptions for stellar evolution.
(iv) To what extent does the choice of an empirical or a theoretical library affect age and metallicity estimates from integrated light of galaxies?

To address these questions, we compute SPS models for different choices of empirical and theoretical stellar libraries, isolating the effects introduced by the use of synthetic versus empirical spectra from those due to the HRD coverage. These SPS models are tailored to the specific tests performed in this paper and are not expected to be useful for the general user.

The structure of the paper is as follows: we start by detailing a new synthetic stellar library in Section 2; in Section 3 we describe the SPS models built to address the questions outlined above; Section 4 shows results from the model comparison. The discussion and conclusions follow in Sections 5 and 6. We provide ancillary information in an online appendix. All models computed for this work are available at http://specmodels.iag.usp.br.

2 SynCoMiL: A SYNTHETIC COUNTERPART TO THE MILES LIBRARY

For the present work we built a Synthetic Counterpart to the MILES Library (SynCoMiL), a theoretical spectral grid which mimics the MILES stellar library in terms of its wavelength and HRD coverage, and spectral resolution. MILES (Sánchez-Blázquez et al. 2006; Cenarro et al. 2007) is a carefully flux-calibrated empirical spectral library widely used in stellar population modelling (e.g. Vazdekis et al. 2010, 2012, 2015, 2016; Martín-Hernández et al. 2010; Maraston & Strömbäck 2011; Röck et al. 2016). It contains spectra for close to 1000 stars covering 3540 – 7410 Å at FWHM ~ 2.5 Å spectral resolution (Falcón-Barroso et al. 2011). Atmospheric parameters for the stars in MILES were first compiled from the literature by Cenarro et al. (2007). Prugniel et al. (2011) and Sharma et al. (2016) re-derived these parameters, providing error estimates for the majority of the MILES stars, MILES was designed to have an optimal coverage of the HRD in terms of the effective temperature $T_{\text{eff}}$, surface gravity log $g$, and metallicity [Fe/H] of the stars in the library. The [Fe/H] vs. [α/Fe] relation for the MILES stars, characterised by Milone et al. (2011), made the library particularly suitable for comparison with stellar spectral models, where both the abundance pattern and the global metallicity need to be defined.

It is well known that atomic and molecular opacities play an essential role in stellar atmosphere models and corresponding synthetic spectra. An analysis of libraries from the literature shows different predictions for spectral indices, depending on the exact combination of opacities and grid (e.g. Martins & Coelho 2007). The authors illustrate a trend with $T_{\text{eff}}$ (hot stars are better reproduced on average than cool ones) and wavelength (redder spectral indices being on average better reproduced than bluer ones). The recent work by Knowles et al. (2019, see their fig. 16) shows that modern grids still show evidence for a light trend with wavelength, and their differential predictions also differ. Nonetheless, and even though improving the opacities is a slow and time-consuming process, considerable progress has been achieved over time (e.g. Peterson & Kurucz 2015; Kurucz 2017; Franchini et al. 2018). The recent work by Martins et al. (2019) compared the ability of different grids (both empirical and synthetic) in reproducing the integrated spectra of globular clusters. They show that current synthetic grids are competitive, despite still showing discrepancies when compared to observations. Martins & Coelho (2017) discuss current needs regarding synthetic libraries, in particular for applications to stellar population studies.

The computation of SynCoMiL is largely based on the work by Coelho (2014) (C14 hereafter). Comparisons with MILES library stars discussed in C14 (see her table 6 and fig. 10) show trends with $T_{\text{eff}}$ and wavelength similar to the ones mentioned above. The ingredients for these models are summarised below, and we refer the reader to C14 for technical details.

(i) Opacity distribution functions (ODFs) were adopted from C14 for iron abundances [Fe/H] = –1.3, –1.0, –0.8, –0.5, and from Castelli & Kurucz (2003) for [Fe/H] = –3.0, –2.5, –2.0, –1.5, –1.0, –0.3, –0.2, –0.1, +0.0, +0.2, +0.3, +0.4, +0.5, +1.0. A new set of ODFs was computed with [Fe/H] = –0.5 and [α/Fe] = +0.2.

(ii) Model atmospheres were computed with ATLAS9 (Kurucz 1970; Sbordone et al. 2004) for stars with $T_{\text{eff}} \geq 3500$ K and the ODFs described above, adopting the atmospheric parameters of the MILES stars and the convergence criteria as in Mészáros et al. (2012). For stars with $T_{\text{eff}} < 3500$ K we used existing MARCS atmosphere models (Gustafsson et al. 2008) to compute a small grid of cool stars. In all MARCS models we adopted the standard chemical composition class, with spherical model geometry for log $g \leq$ 1.5, and plane-parallel for log $g \geq$ 4.5.

(iii) Synthetic stellar spectra were computed with the SYNTHE code (Kurucz & Avrett 1981; Sbordone et al. 2004), based on the ATLAS9 and MARCS models. The opacities are as in C14 with one update, the inclusion of the molecular transition C$_2$ D-A from Brooke et al. (2013) to correct for the problem identified by Knowles et al. (2019). For stars with $T_{\text{eff}} \geq 3500$ K the synthetic spectrum was computed based on the ATLAS9 models. Cooler star spectra were computed from the MARCS model grids, then interpolated to achieve the atmospheric parameters of SynCoMiL stars. Interpolation was performed linearly in $\theta = 5040/T_{\text{eff}}$, log $g$ and [Fe/H], with the flux in logarithmic scale. We adopted this scheme after different tests comparing synthetic spectra with the interpolated ones.

(iv) The synthetic spectra were then corrected for the effect of predicted lines, interpolating linearly the coefficients listed in Table B1 of C14 to the exact atmospheric parameters of the SynCoMiL stars.

(v) The spectra were convolved, rebinned and trimmed to match the resolution, dispersion and wavelength range of MILES (Falcón-Barroso et al. 2011).

We adopt the MILES atmospheric stellar parameters

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4 As made available by F. Castelli; downloaded on April 29 2016 from http://wwwuser.oats.inaf.it/castelli/odfnew.html
5 Available at http://marcs.astro.uu.se
6 As made available by R. Kurucz; downloaded on Dec 2016 from http://kurucz.harvard.edu/molecules.html
mainly from Prugniel et al. (2011), with the revision for cool stars provided by Sharma et al. (2016). For 26 stars we use the parameters from Cenarro et al. (2007), either because Prugniel et al. (2011) do not provide an independent determination, or because we concluded by visual comparison that the Cenarro et al. (2007) parameters permit a closer match between observed and model spectra. For stars HD001326B and HD199478 we modified slightly the reported parameters, as we could not obtain converged models for the nominal parameters. The changes in $T_{\text{eff}}$ and $\log g$ are nevertheless small — the smallest needed to achieve convergence — and are within the reported errors. We list in Table 1 the atmospheric parameters adopted for each star in MILES and SynCoMiL, along with their respective sources. To mimic the abundance pattern of the MILES library, we follow table 7 of C14, based on the work by Milone et al. (2011).

![Figure 1](image)

**Figure 1.** *Top panels:* The $\chi^2$ and $\Delta$ metrics as a function of $T_{\text{eff}}$ for the SynCoMiL stars. Red crosses indicate stars which have not been used in the SPS models (see text in Section 2). The smooth line corresponds to a LOESS (locally estimated scatter plot smoothing) regression to the points, plotted to aid the eye. *Bottom panels:* Distribution of $\chi^2$ and $\Delta$ values for the SynCoMiL library.

SynCoMiL spectra were compared with the empirical ones from MILES both visually and quantitatively. Quantitative differences between model and observations were obtained via a $\chi^2$ metric:

$$\chi^2 = \sum_{\lambda} \left( \frac{f_{\lambda}^{\text{syn}} - f_{\lambda}^{\text{obs}}}{\sigma_{\lambda}^2} \right)^2,$$

and a median deviation $\Delta$ defined as

$$\Delta = \text{median}\left( \frac{|f_{\lambda}^{\text{syn}} - f_{\lambda}^{\text{obs}}|}{f_{\lambda}^{\text{obs}}} \right).$$

Table 1. Atmospheric parameters used as input values in the computation of SynCoMiL (abridged; the full table is available as supplementary online material; see Table A1). Unlisted MILES stars are not used in the SPS models in this work and are reported separately in Table 2 (see Section 2).

| MILES ID | Star   | $T_{\text{eff}}$ | $\log g$ | [Fe/H] | Notes |
|----------|--------|------------------|----------|--------|-------|
| 001      | HD224930 | 5411             | 4.19     | -0.78  | b     |
| 002      | HD225212 | 4117             | 0.68     | -0.14  | c     |
| 012      | HD001326B | 3571            | 4.81     | -0.57  | d     |
| 096      | HD016901  | 5345             | 0.85     | 0.00   | a     |
| 149      | HD027371  | 4995             | 2.76     | 0.15   | b     |
| 581      | HD143807  | 10727            | 3.84     | -0.01  | b     |

Atmospheric parameters adopted from: $^a$Cenarro et al. (2007); $^b$Prugniel et al. (2011); $^c$Sharma et al. (2016); $^d$Used different parameters than proposed in the literature to ensure model convergence.

where $f_{\lambda}^{\text{syn}}$ and $f_{\lambda}^{\text{obs}}$ are the synthetic and observed fluxes at a given $\lambda$, respectively. The standard deviation $\sigma_{\lambda}$ appearing in Eq. (1) was estimated for each star as follows. P. Sánchez-Blázquez (priv. comm.) kindly provided us with the error spectra for each star in MILES, which was used in turn to compute the signal-to-noise ratio SNR($\lambda$) for each star. Since very deviant values of SNR were obtained for some of the stars, we chose to use the median[SNR($\lambda$)] of the distribution of SNR at each $\lambda$ as a fiducial value to compute $\sigma_{\lambda} = f_{\lambda}^{\text{obs}}/\text{median}[\text{SNR($\lambda$)}]$. This fiducial SNR($\lambda$) ranges from $\approx 8$ to $\approx 190$ over the MILES wavelength range.

Fig. 1 shows the resulting distributions of $\chi^2$ and $\Delta$, as well as the corresponding values for each star plotted vs. $T_{\text{eff}}$. 

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We found that $T_{\text{eff}}$ is the only atmospheric parameter which correlates with the metrics in Eqs. 1 and 2. The patterns in Fig. 1 are in agreement with previous work: the larger values of $\chi^2$ and $\bar{\chi}$ for cool stars are in agreement with, e.g., Martins & Coelho (2007) and C14, and the larger values of $\chi^2$ are consistent with the larger errors in $T_{\text{eff}}$ for these stars reported by Prugniel et al. (2011). The red symbols in 1 correspond to 71 stars which we opted not to use in the remaining of this work (e.g., bottom panel in Fig. 2). Spectra in MILES which are not suitable for stellar population modelling have been identified previously in the literature (e.g., Prugniel et al. 2011; Barber et al. 2014, R. Peletier, priv. comm.). In the present work, a star is not used in the SPS models if any of the conditions below applies.

(i) The observed spectrum shows:
- emission lines,
- excessive noise or corrupted pixels,
- distortions in the continuum,
- $E(B-V) > 0.3$, as inferred by Prugniel et al. (2011),
- peculiar spectral features (e.g. HD055496).

(ii) $\chi^2$ and $T_{\text{eff}}$ fulfill any of:
- $T_{\text{eff}} < 4000 \text{K}$ and $\chi^2 > 1$,
- $4000 \leq T_{\text{eff}} \leq 7000 \text{K}$ and $\chi^2 > 0.05$,
- $T_{\text{eff}} > 7000 \text{K}$ and $\chi^2 > 0.15$.

(iii) $\bar{\chi}$ and $T_{\text{eff}}$ fulfill any of:
- $T_{\text{eff}} < 4000 \text{K}$ and $\bar{\chi} > 0.4$,
- $T_{\text{eff}} \geq 4000 \text{K}$ and $\bar{\chi} > 0.1$.

Table 2 lists the discarded stars. Most of the discarded stars satisfy more than one of these criteria. Stars which fall into the quantitative cuts listed above show strong continuum mismatches between model and observations. We hypothesise that these are due to either large errors in $T_{\text{eff}}$.

Table 2. MILES stars unsuitable for SPS modelling (abridged; the full table is available as supplementary online material; see Table A2).

| MILES ID | Star   | $T_{\text{eff}}$ | log $g$  | [Fe/H] | Notes          |
|----------|--------|------------------|----------|--------|----------------|
| 029      | HD004395| 5444             | 3.43     | -0.27  | b, 1, 6        |
| 044      | HD006474| 6781             | 0.49     | 0.26   | b, 6, 7        |
| 045      | HD006497| 4401             | 2.55     | 0.00   | c, 1, 6        |
| 054      | HD018391| 5750             | 1.20     | -0.13  | b, 5, 6, 7     |
| 149      | HD221679| 8542             | 2.50     | -1.43  | a, 6           |
| 204      | HD041117| 20000            | 2.40     | -0.12  | b, 3           |
| 212      | HD043042| 6480             | 4.18     | 0.06   | b, 2           |
| 246      | HD055496| 4858             | 2.05     | -1.48  | b, 4           |
| 780      | HD199478| 11200            | 1.90     | 0.00   | d, 3, 6        |

Atmospheric parameters adopted from:

* Cenarro et al. (2007);
* Prugniel et al. (2011);
* Sharma et al. (2016);
* same as * but unknown [Fe/H] assumed to be solar. Star discarded due to:

1. Excessive noise or corrupted spectrum;
2. Visible continuum distortions;
3. Visible emission lines;
4. Peculiar features;
5. $E(B-V) > 0.3$ from Prugniel et al. (2011);
6. Removed by cut in $\chi^2$;
7. Removed by cut in $\bar{\chi}$ (Section 2).

Table 2 lists the discarded stars. Most of the discarded stars satisfy more than one of these criteria. Stars which fall into the quantitative cuts listed above show strong continuum mismatches between model and observations. We hypothesise that these are due to either large errors in $T_{\text{eff}}$.

This star shows unusually strong molecular bands and is classified as a peculiar star in the SIMBAD Database.
3 METHODOLOGY

To address the questions outlined in Section 1, we compute four different sets of SPS models in which all the ingredients are the same except for the choice of the stellar flux library. The SPS models are computed using the GALAXEV code (Bruzual & Charlot 2003, recent updates). This is a flexible code which provides SPS models for a variety of stellar evolutionary tracks, stellar spectral libraries, chemical abundances, initial mass functions, and star formation histories, and probes ideal towards our goal of computing models which differ only in the stellar spectral library. We adopt the PARSEC stellar evolutionary tracks (Bressan et al. 2012; Chen et al. 2015) to describe the evolution of stellar populations of the five metallicities listed in Table 3. From the evolutionary tracks the GALAXEV code builds isochrones for the required age and metallicity.

Fig. 3 shows three isochrones for each stellar metallicity in Table 3, together with the coverage in the HRD of the MILES, SynCoMiL, and C14 libraries. This coverage is complete for C14 but very sparse for MILES. The sparse coverage of the HRD by the MILES and other empirical libraries is what forces us to supplement these libraries with synthetic stellar spectra in the Bruzual & Charlot (2003, and recent updates) models. One of the goals of the present paper is to quantify the effects on the SPS models of assigning stellar spectra with \( T_{\text{eff}}, \log g, [\text{Fe/H}] \) relatively far from the true values.

We consider four different sets of SPS models\(^8\) for each mixture in Table 3, denoted sps-M, sps-s, sps-c and sps-r, which differ only in the stellar spectral library, as follows:

sps-M: the empirical MILES library.

sps-s: the synthetic SynCoMiL library.

sps-c: the synthetic C14 library\(^9\).

sps-r: 10 realisations of sps-s (details below).

To each star along an isochrone, the GALAXEV code assigns a spectrum drawn from the selected library. The stellar spectrum is assigned on the basis of the proximity of the stellar parameters of the library stars to the corresponding parameters of the problem star in the HRD, interpolating between neighbouring spectra when required. For the sps-c models, each problem star in the isochrone is bracketed by four C14 stellar models (see Fig. 3), characterized each by \((\theta, \log g)\), where \(\theta = 5040/T_{\text{eff}}\). In this case, we interpolate the stellar models logarithmically in flux, first in \(\theta\) at constant \(\log g\) and then in \(\log g\). This interpolation scheme is possible only in very few instances when using the MILES library in the sps-M models. In some cases, we can interpolate in \(T_{\text{eff}}\) two MILES spectra of the required \(\log g\), but in most cases we use the MILES spectrum closest in \((T_{\text{eff}}, \log g)\) to the problem star on the isochrone.

For the sps-s models, we use the same spectral assignment as in the sps-M models, but draw the corresponding stellar spectra from the SynCoMiL instead of the MILES library.

For the sps-r models, we modify the stellar parameters of each SynCoMiL star by adding to each parameter a Gaussian random error. Then we replace each star in the sps-s models with the star with closest parameters in the modified table. This exercise is repeated 10 times for each set of SPS models listed in Table 3. We adopt errors for \(T_{\text{eff}}\) and \(\log g\) as compiled by C14 (see her table 5): for \(T_{\text{eff}}\) the error ranges from 120 K for cool stars to 3000 K for hot stars; for \(\log g\) the errors range from 0.1 to 0.3 depending on \(T_{\text{eff}}\). For \([\text{Fe/H}]\) we adopt conservative errors of 0.15 (e.g., Soubiran et al. 1998).

4 RESULTS

The different SPS models described in Section 3 were compared to each other in two ways: (1) via direct model – model comparisons (Section 4.1), and (2) using the models to derive stellar population parameters via spectral fits to a sample of galaxy spectra (Section 4.2).

\(^8\) All SPS models were computed for the Chabrier (2003) IMF.

\(^9\) The C14 spectra were convolved, rebinned and trimmed to match the resolution, dispersion and wavelength range of MILES.
4.1 Model – model comparisons

From the direct comparison of the colours and spectral line indices predicted by the different models we aim at understanding the following three effects:

Synthetic effect: comparing the predictions of the sps-m and sps-s models we can assess the consequences of using theoretical instead of empirical stellar spectra for a fixed coverage of the HRD.

Coverage effect: comparing the predictions of the sps-s and sps-c models we can isolate the consequences of limited vs. complete HRD spectral coverage on the observables.

Random error effect: comparing the sps-r and sps-s models, we can assess the effects of random errors in the stellar atmospheric parameters on the model predictions.

4.1.1 Broad-band colors

For each set of models, we compute 5 colours, $u - g$, $u - r$, $g - r$, $g - i$, and $r - i$, using the SDSS ugr'i filter response functions (Doi et al. 2010). For each age and metallicity of the SPS models we compute the following colour differences in direct relation to the effects listed above:

$$\Delta \text{colour}_{\text{Synthetic}} = c_{\text{sps-m}} - c_{\text{sps-s}}, \quad (3a)$$
$$\Delta \text{colour}_{\text{Coverage}} = c_{\text{sps-c}} - c_{\text{sps-s}}, \quad (3b)$$
$$\Delta \text{colour}_{\text{RanError}} = c_{\text{sps-r}} - c_{\text{sps-s}}, \quad (3c)$$

where $c$ is a colour. Results are shown in Figs. 4, 5 and 6, and listed in Table 4.

Fig. 4 shows the distributions of $\Delta \text{colour}$ for the different colours (rows) and effects (columns). We notice that the distributions are not always symmetric, and that they are typically broader for the coverage effect than for the synthetic and randomised-parameter effects. These results are

10 The MILES spectra extend from 3540 to 7410 Å and do not cover the full widths of the $u$ and $i$ bands. The $u$ band extends from 2980 to 4130 Å, with $\lambda_{\text{eff}}(u) = 3560$ Å inside the MILES range, while the $i$ band extends from 6430 to 8630 Å, with $\lambda_{\text{eff}}(i) = 7500$ Å not far from the MILES edge. The stellar flux is considered to be zero for $\lambda < 3540$ Å and $\lambda > 7410$ Å when computing the $u$ and $i$ magnitudes. Given that all our SPS models cover the same wavelength range as the MILES library, we consider that the use of the $u$ and $i$ bands is still useful and informative.
illustrated in a condensed manner as a boxplot in Fig. 5, indicating the corresponding median and interquartile range (IQR)\textsuperscript{11} given in Table 4. In Fig. 6, we show Δcolour as a function of stellar population age for the different colours and effects. A large variance in colours involving the $u$ band arises at ages younger than 1 Gyr, especially at low metallicity, which is not surprising given the limited number of hot metal poor stars in empirical libraries.

In summary, the coverage effect dominates the systematics and variance in Δcolour. The most affected colours are those involving the $u$ band, and the largest Δcolour is Δ($u - r$)\textsubscript{Coverage} = 0.06.

### 4.1.2 Spectral indices

The spectral indices listed in Table 5 were measured in all SPS models. We define Δidx as the index difference between

\begin{align}
\Delta idx\textsuperscript{Synthetic} &= I_{SPS-M} - I_{SPS-S}, \\
\Delta idx\textsuperscript{Coverage} &= I_{SPS-C} - I_{SPS-S}, \\
\Delta idx\textsuperscript{RanError} &= I_{SPS-R} - I_{SPS-S},
\end{align}

where $I$ is any spectral index. We measure Δidx for all ages and metallicities. Results are shown in Figs. 7 – 11, and listed in Table 6.

Fig. 7 shows the distributions of Δidx for each index. The impact of the three effects on the indices is complex and defies simple conclusions. In all cases, the effect of the random errors on the atmospheric parameters is the least important. The indices for which the synthetic effect is most prominent are: CaHK, Fe4668, Fe5270, Fe5709 and NaD. The impact of HRD coverage in the indices is not negligible and dominates over the synthetic effect in the case of, e.g., H8, B4000, and G4300. For many indices the synthetic and coverage effects are comparable and may introduce different

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**Table 4.** Median and IQR values of Δcolour in magnitude units.

| Colour | Synthetic effect | Coverage effect | Random error effect |
|--------|------------------|-----------------|--------------------|
|        | (SPS-M - SPS-S)  | (SPS-C - SPS-S) | (SPS-R - SPS-S)    |
| $u - g$ | -0.002 0.043 | -0.038 0.068 | 0.003 0.021 |
| $u - r$ | -0.018 0.059 | -0.061 0.085 | 0.001 0.031 |
| $g - r$ | -0.017 0.017 | -0.018 0.043 | 0.001 0.011 |
| $g - i$ | -0.009 0.035 | -0.017 0.062 | -0.001 0.020 |
| $r - i$ | 0.007 0.019 | 0.013 0.017 | -0.001 0.009 |

**Table 5.** Spectral indices measured in the present work.

| Indices | Reference |
|---------|-----------|
| H10, H9, H8 | Marcillac et al. (2006) |
| HK | Brodie & Hanes (1986) |
| B4000 | Kauffmann et al. (2003) |
| HαA, HαF, HγA, HγF | Worthey & Ottaviani (1997) |
| CN1, CN2, Ca4227, G4300, Fe4383, Ca4455, Fe4531, Fe4668, Hγ, Fe5015, Mg1, Mg2, Mgb, Fe5270, Fe5335, Fe5406, Fe5709, Fe5782, NaD, TiO1, TiO2 | Trager et al. (1998) |

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\textsuperscript{11} IQR is equal to the difference between the 75th and 25th percentiles. For a normal distribution, IQR = 1.35 × $\sigma$. 

**Figure 6.** Δcolour differences for the three effects (columns) described in Section 4.1, plotted as a function of stellar population age (in yr). Different colours are shown in rows, and different metallicities are identified as indicated in the label.
systematic effects. Table 6 lists the median and IQR values of $\Delta x$ for each index and effect.

In Figs. 8, 9 and 10 we plot the indices computed from sps-m, sps-c and sps-r against those of sps-s models, respectively. The dependence with the age of the population is apparent: as the largest deviations from the 1-to-1 line occur for the old population in the case of the synthetic effect, and for the young population in the case of the coverage effect. In these plots we can locate opacity related problems, e.g., Fe4668 (see discussion in Knowles et al. 2019), or the high sensitivity to HRD coverage of the Balmer line (see Table 6).

Table 6. Median and IQR values of $\Delta x$.

| Index     | Synthetic effect | Coverage effect | Random error effect |
|-----------|------------------|-----------------|---------------------|
|           | (sps-m – sps-s)  | (sps-c – sps-s) | (sps-r – sps-s)     |
|           | Median | IQR   | Median | IQR   | Median | IQR   |
| H103798   | -0.093 | 0.365 | 0.116 | 0.399 | 0.005  | 0.081 |
| H93835    | -0.154 | 0.997 | 0.088 | 0.730 | 0.017  | 0.151 |
| H83889    | 0.046  | 0.472 | 0.068 | 1.095 | 0.003  | 0.159 |
| CaHK      | -0.013 | 0.018 | 0.000 | 0.020 | 0.001  | 0.006 |
| B4000     | 0.014  | 0.027 | -0.038| 0.071 | 0.002  | 0.019 |
| HαA       | 0.138  | 1.068 | 0.520 | 1.467 | -0.006 | 0.250 |
| HαF       | 0.052  | 0.568 | 0.242 | 0.903 | 0.000  | 0.134 |
| HyA       | 0.458  | 1.285 | 0.653 | 1.820 | -0.010 | 0.308 |
| HyF       | -0.058 | 0.473 | 0.478 | 0.977 | -0.003 | 0.148 |
| CN1       | 0.009  | 0.016 | -0.006| 0.024 | 0.000  | 0.005 |
| CN2       | 0.005  | 0.010 | -0.006| 0.017 | 0.000  | 0.004 |
| Ca4227    | -0.104 | 0.257 | -0.052| 0.070 | 0.001  | 0.037 |
| G4300     | 0.014  | 0.439 | -0.225| 0.647 | 0.025  | 0.163 |
| Fe4383    | -0.288 | 0.450 | -0.150| 0.624 | 0.003  | 0.144 |
| Ca4455    | -0.071 | 0.072 | -0.057| 0.227 | 0.002  | 0.045 |
| Fe4531    | -0.181 | 0.370 | -0.109| 0.143 | 0.012  | 0.080 |
| Fe4668    | 0.409  | 1.204 | -0.150| 0.622 | 0.011  | 0.081 |
| Hβ        | 0.074  | 0.550 | 0.146 | 0.661 | 0.003  | 0.095 |
| Fe5015    | -0.378 | 0.631 | 0.019 | 0.462 | 0.034  | 0.138 |
| Mg1       | -0.006 | 0.015 | -0.009| 0.013 | 0.000  | 0.003 |
| Mg2       | -0.016 | 0.021 | -0.011| 0.012 | 0.000  | 0.007 |
| Mg3       | -0.026 | 0.091 | -0.112| 0.184 | -0.001 | 0.101 |
| Fe5270    | -0.294 | 0.248 | -0.109| 0.155 | 0.008  | 0.079 |
| Fe5335    | -0.131 | 0.179 | -0.123| 0.153 | 0.008  | 0.086 |
| Fe5406    | -0.101 | 0.179 | -0.074| 0.113 | 0.004  | 0.056 |
| Fe5709    | -0.114 | 0.162 | -0.011| 0.080 | 0.005  | 0.040 |
| Fe5782    | 0.031  | 0.090 | -0.025| 0.056 | 0.003  | 0.032 |
| NaD       | 0.084  | 0.393 | -0.163| 0.151 | -0.001 | 0.102 |
| TiO1      | 0.003  | 0.004 | 0.000 | 0.005 | 0.000  | 0.003 |
| TiO2      | -0.004 | 0.007 | 0.001 | 0.008 | -0.000 | 0.005 |

Table 6 lists the median and IQR values of $\Delta x$ for each index and effect. The boxplot in Fig. 11 is convenient to easily rank the indices according to increasing order of $\Delta x$. Deviations from the zero-line indicate systematic effects and the size of the box indicates the IQR. The further away from the zero-line the midline of a box is, the more the index is affected by systematics.

In summary, the consequences of the synthetic and the coverage effects on the indices are multiple and difficult to summarise in simple terms. The outcome of randomising the stellar parameters is small compared to the other effects.

4.2 Spectral fitting of galaxies

The model – model comparisons of the previous section illustrate interesting differences between the sets of SPS models, but cannot be easily translated into the question that matters the most: how does the adoption of different spectral libraries change the age and metallicity of galaxies derived from their integrated light?

To address this question, we use the sps-m, sps-s, and sps-c models to derive stellar population parameters from the spectra of ~1000 nearby galaxies (0.04 < z < 0.06). We use the sample of Gadotti (2009) which encompasses galaxies of different morphology: ellipticals, spirals (with classical or pseudo-bulges, with and without bars), and bulgeless discs. The spectra were obtained from the SDSS database (Abazajian et al. 2004) and processed as in Coelho & Gadotti (2011). We use the STARLIGHT spectral fitting code (Cid Fernandes et al. 2005) to infer the stellar population parameters, processing the sample three times, once for each set of SPS models. We refer the reader to the quoted work for details on the sample and technique.

We show in Fig. 12 the results for two parameters related to the fit-quality and three parameters related to the stellar population. The parameters related to the fit-quality are $\chi^2$ (as in equation 1) and an average relative deviation $\text{adev}$, defined as

$$\text{adev} = \frac{1}{N} \sum \frac{f_{\text{model}} - f_{\text{obs}}}{f_{\text{obs}}}.$$  

where N is the number of wavelength points in the spectrum, $f_{\text{model}}$ is the model spectrum fitted by STARLIGHT, and $f_{\text{obs}}$ is the observed galaxy spectrum.

The synthetic effect can be inspected in the left hand side column of Fig. 12, which compares the results from sps-m (y-axis) vs. those from sps-s (x-axis). We highlight that spectral fits performed with sps-s models tend to have larger $\chi^2$ and $\text{adev}$ than those obtained with sps-m models, even though there are no noticeable differences in the retrieved values of $\text{[Fe/H]}$ and log (age). The values of $\text{[Fe/H]}$ obtained with the sps-s models are systematically lower than those obtained with the sps-m models. The differences in $\text{[Fe/H]}$ correlate with $\text{[Fe/H]}$, lower metallicities showing larger differences.

The coverage effect can be inspected in the right hand side column of Fig. 12, which shows the results from sps-c (y-axis) vs. results from sps-s (x-axis) models. We notice that spectral fits performed with the sps-s and sps-c models have similar $\text{adev}$, but $\chi^2$ is slightly larger for the sps-c fits. There are no noticeable differences in the retrieved values of $A_V$. Whereas the values of log(age) obtained from the sps-c models are larger than for the sps-s models, there are no systematic differences in the retrieved mean $\text{[Fe/H]}$, even
Figure 7. Density plots showing the distributions of index differences ($\Delta$idx, as defined in Section 4.1.2) for the indices listed in Table 5. The different effects are shaded as indicated in the label.

though there are some outliers from the 1-to-1 line, which remain to be investigated.

Table 7 shows the median residuals and IQRs for the parameters obtained from SPS-M vs. SPS-S fits (synthetic effect), and SPS-C vs. SPS-S fits (coverage effect). In all cases, the systematic differences are inside the IQR ranges. We note that the median residuals on [Fe/H] and log(age) are of the same order of the IQR for the synthetic effect and the coverage effect, respectively.

5 DISCUSSION

5.1 Semi-empirical vs. theoretical SPS models

How do uncertainties in theoretical stellar libraries affect integrated colours and line indices measured in SPS models?

Several works in the literature compare synthetic stellar spectra to empirical ones on a star-by-star basis (e.g. Martins & Coelho 2007; Bertone et al. 2008). Recent work by Martins et al. (2019) provides insight into how synthetic vs. empirical spectra compare at the level of the integrated properties of stellar populations. These authors model integrated spectra of clusters combining CMDs and stellar libraries from different sources. Their conclusions depend on the wavelength range. From 3900 to 6300 Å, or when considering specific spectral features, empirical libraries do better.

| Parameter          | Synthetic effect (SPS-M – SPS-S) | Coverage effect (SPS-C – SPS-S) |
|--------------------|----------------------------------|---------------------------------|
|                    | median | IQR | median | IQR |
| $\chi^2$           | -0.05  | 0.13 | 0.04   | 0.06 |
| adev               | -0.16  | 0.29 | 0.09   | 0.10 |
| $A_V$              | 0.00   | 0.04 | 0.01   | 0.05 |
| mean log (age)     | 0.12   | 0.11 | 0.14   |
| mean [Fe/H]        | 0.13   | 0.13 | -0.01  | 0.12 |
In the range 3525 to 6300 Å, a theoretical library outperformed the empirical ones in 70% of their tests, essentially because the shape of the continuum is more in agreement with the observations in the theoretical case.

Our results add more information to the theoretical vs. empirical library debate. The SPS models built in this work are largely based on the theoretical library by C14. Her fig. 10 illustrates the systematic differences between synthetic spectra for given $T_{\text{eff}}$ and $\log g$, and MILES spectra averaged over all stars in the library with the same atmospheric parameters (within uncertainties). The two main possible reasons for these differences are: either they result from abundance patterns unaccounted for in the synthetic grid (such as variations of C and N due to dredge-up in giants stars), or they reflect true deficiencies in the spectral modelling, related to either the physics of the stellar atmosphere or to the...
adopted atomic opacities. In the present analysis we assume that all differences are due to the opacities.

In Section 4.1, colours and spectral indices from the sps-m and sps-s models were compared to quantify how the inaccuracies in the opacities translate into the integrated light of the stellar population. The results from Table 4 show that the systematic effect on broad-band colours ranges from $-0.002$ in $u-g$ to $-0.018$ in $u-r$. The IQR of the distributions range from $0.017$ in $g-r$ to $0.059$ in $u-r$. For comparison, the reported accuracy (global rms dispersion) of the flux calibration for the MILES library is $0.013$ mag in $B-V$.

Comparing the spectral indices we get a closer view of the role played by the opacities. Figs. 7, 8 and 11 show a complex and index-dependent behaviour. One may argue that the best performance of the sps-s models occurs for the indices H10, B4000, H\delta F, CN2, G4300, HyF, Fe4383,
Figure 10. Spectral indices predicted by sps-r (y-axis) vs. sps-s (x-axis) models. The points are colour-coded by the age of the population, as indicated by the auxiliary axis.

Hβ, Mgб, and Fe5782, whereas the indices that deserve most attention from modellers are Fe5270, Fe5015, CaHK, Fe5709, Fe4383 and Fe4668 (the latter had already been pointed out by Knowles et al. 2019).

It is unclear to what extent the results presented here can be safely applied to other theoretical libraries. Given that the broad-band colours depend mostly on averaged opacities and on the physics of the stellar atmosphere, we expect the results for the colours to be similar for other modern libraries of statistical fluxes (e.g. Gustafsson et al. 2008; Castelli & Kurucz 2003), or in high-resolution spectral libraries as long as the effect of predicted lines has been taken into account (see discussion in section 3 of C14). On the other hand, the results for the spectral indices depend on the details of the specific opacities, and it is less likely that they can be reliably adopted for other synthetic libraries.
As such, the reader should see our results on the spectral indices as guidelines for the use of the C14 library.

5.2 The effect of the HRD coverage

How does the non-ideal or poor coverage of the HRD by empirical libraries affect the predictions of SPS models?

Empirical libraries cannot cover the HRD homogeneously and completely due to observational constrains. We do not harbour in our Galaxy massive metal-poor stars, which are likely to be present in high redshift galaxies, nor can we cover the abundance patterns of galaxies with diverse star formation and chemical enrichment histories. By construction, with semi-empirical SPS models we can reproduce to a better degree the properties of populations similar to the solar neighbourhood than others.

Vazdekis et al. (2010) discuss this issue in the context of three empirical libraries MILES, STELIB (Le Borgne et al. 2003), and Lick/IDS (Worthey et al. 1994). They define the quality parameter $Q_n$ to quantify the reliability of their semi-empirical SPS models as a function of age, metallicity and IMF (see their Section 3.2). The authors conclude that the minimum age at which a model is reliable ranges from 60 Myr around solar metallicity to 10 Gyr in the most metal-poor regime, with a varying degree of quality $Q_n$.

Here we retake this discussion comparing our sps-s and sps-c models: the first mimics the HRD coverage of an empirical library, and the second covers the HRD completely and homogeneously for populations older than 30 Myr (cf. Fig. 3). Differences found in this experiment will be due to the incomplete HRD coverage of the empirical library, since SYNCoMiL and C14 share the same codes and opacities.

The effects that the different HRD coverage have on colours can be seen in Figs. 4, 5 and 6, and are summarised.

Figure 11. Boxplots of $\Delta$idx are shown for the synthetic (top), coverage (middle) and randomised parameters (bottom) effects. In each row, $\Delta$idx are sorted in crescent order to facilitate identification of most affected indices in each case. The values of $\Delta$idx have been scaled to their standard score to facilitate comparison (see Section 4.1.2).
Figure 12. Results from the spectral fitting of a sample of nearby galaxies. The left-side column shows the results obtained from SPS-M (y-axis) vs. SPS-S (x-axis) models. The right-side column shows the results obtained from SPS-C (y-axis) vs. SPS-S (x-axis) models. The different parameters inferred are given in rows: $\chi^2$, $\text{adev}$ (Eq. 6), reddening $\text{Av}$, light-weighted log(age), and light-weighted $[\text{Fe/H}]$. The smooth line corresponds to a LOESS (locally estimated scatterplot smoothing) regression to the points and is shown to guide the eye.

in Table 4. For all colours, except $r - i$, the coverage effect introduces systematic differences and variances larger than the synthetic effect. The largest difference occurs in $u - r$, with a systematic value of $-0.061$ and IQR of $0.085$. The effect is largest in the most metal-poor regime, in accordance with the results of Vazdekis et al. (2010). This is expected since the coverage of the HRD is poorest at the lowest metallicities.

The effects on spectral indices are shown in Figs. 7, 9, and 11, and are difficult to generalise. Some indices seem to
be little affected (at least in comparison to the other effects) such as Fe5709 and Fe5782, while in other cases, such as B4000, the difference is prominent. Fig. 11 shows that the most affected indices are, at one extreme, B4000 and Mg1 (SPS-s models, on average, underestimate the indices), and, at the other extreme, Hδ and Hy (SPS-s models, on average, overestimate the indices).

5.3 Errors in the atmospheric parameters

How do errors in the stellar atmospheric parameters translate into SPS models?

Percival & Salaris (2009) performed an interesting investigation on the possible impact of systematic uncertainties in the atmospheric parameters on the integrated spectra of stellar populations. These authors simulated a systematic difference between the $T_{\text{eff}}$ scale of the isochrones and that of the stellar flux libraries, and considered errors within the typical offsets found in the literature (100 K in $T_{\text{eff}}$, 0.25 in log $g$ and 0.15 in [Fe/H]). Their results raised a caution, by showing that small systematic differences between the atmospheric parameter scales can mimic non-solar abundance ratios or multiple populations in the analysis of integrated spectra. If this result is confirmed, much of what the community is concluding in terms of abundance patterns in galaxies can be an artefact, due to offsets between parameter scales and not truly a tracer of different chemical evolution.

At the suggestion of the referee, we compare our results to Percival & Salaris (2009). See their tables 1 and 2, where these authors show the impact of their tests on Lick indices for 2 choices of SSPs. In Table 8, we list $\Delta$idx and IQR($\Delta$idx) from our experiments for the same choices of age, metallicity and indices as in Percival & Salaris (2009). The effect of random errors on the stellar parameters is typically smaller than the effect introduced by adding a systematic difference of 100 K in $T_{\text{eff}}$ scale, and of comparable magnitude to the effect of adding systematic differences in log $g$ and [Fe/H] of 0.25 and 0.15, respectively. The exact reason why a systematic difference in the $T_{\text{eff}}$ scale has a larger impact than adding random errors to the stellar parameters is difficult to trace. We can hypothesise that random errors tend to cancel out, while a systematic difference in the $T_{\text{eff}}$ scale is equivalent to selecting a younger (hotter) or older (cooler) isochrone when building an SSP model without changing the selection of stellar spectra.

In any case, a look at table 3 of Percival & Salaris (2009) shows that the deviations introduced by tampering with the atmospheric parameters is comparable to (or larger than) typical observational errors on the spectral indices. As such, these effects cannot be safely neglected. Here we complement this investigation with the SPS-R models, simulating the effect of random rather than systematic variations in the atmospheric parameters. Our tests reveal that both in colours (Figs. 5 and 6, Table 4) and spectral indices (Fig. 7 and 11), the effect of randomising the atmospheric parameters is small compared to the other effects. We conclude then that random errors in the stellar parameters (within the uncertainties adopted here, see Section 3) are not a major source of concern for current SPS models.

Table 8. $\Delta$idx and IQR($\Delta$idx) for Lick indices (Z = 0.017)

| Index | $\Delta$idx | IQR($\Delta$idx) | $\Delta$idx | IQR($\Delta$idx) |
|-------|-------------|------------------|-------------|------------------|
| Fe4383 | 0.166 | 0.316 | 0.174 | 0.264 |
| Fe4531 | -0.004 | 0.087 | 0.051 | 0.033 |
| Fe5015 | 0.025 | 0.163 | 0.164 | 0.182 |
| Mg1 | -0.001 | 0.009 | -0.002 | 0.018 |
| Mg2 | -0.004 | 0.014 | 0.005 | 0.031 |
| Mggb | -0.154 | 0.121 | 0.153 | 0.387 |
| Fe5270 | -0.037 | 0.141 | 0.085 | 0.119 |
| Fe5335 | -0.018 | 0.140 | 0.054 | 0.227 |
| Fe5406 | -0.021 | 0.125 | 0.034 | 0.130 |
| Fe5709 | 0.005 | 0.066 | 0.035 | 0.066 |
| Fe5782 | 0.009 | 0.061 | 0.017 | 0.059 |
| NaD | -0.009 | 0.137 | 0.001 | 0.445 |
| TiO1 | 0.001 | 0.004 | -0.001 | 0.006 |
| TiO2 | 0.001 | 0.004 | 0.000 | 0.007 |

5.4 Inferring stellar-population parameters from integrated light

To what extent does the choice of an empirical or a theoretical library in the SPS model affect age, metallicity and reddening estimates from integrated light?

Possibly, the most important result of the experiments performed in this work is to estimate to what extent stellar population parameters – age, metallicity, reddening – derived from SPS models vary if we adopt in the model an empirical or a theoretical library. Given our current inability to have both complete coverage of the HRD with high quality stellar spectra, what should one favour: complete coverage of the HRD (theoretical library) or accurate spectra on a star-by-star basis (empirical library)?

There are several ways proposed in the literature to derive the stellar population parameters from integrated light, but for the purpose of the present paper we choose to investigate results obtained from spectral fitting. To that end we adopt the widely used code STARLIGHT (Cid Fernandes et al. 2005) to fit a sample of nearby galaxies (Gadotti 2009; Coelho & Gadotti 2011). In Section 4.1 we show that the synthetic and coverage effect impact both colours and spectral features. A code such as STARLIGHT, which fits the continuum and the spectral features together, is a good option to evaluate in a global manner how the stellar library of choice will influence the derived galaxy properties.

Results are shown in Fig. 12 and summarised in Table 7. The first noticeable feature is that the use of synthetic spectra tends to increase $\chi^2$ and $\text{adev}$ for the fit, i.e., the fits tend to be statistically worse. This is not surprising, and reminds us that atomic and molecular opacities still need improvement. Nevertheless, and to some extent a surprising result, there are no important differences in the reddening or the ages derived using SPS-M and SPS-S models. There is only a hint that for intermediate ages ($9 \lesssim \log(\text{age}) \lesssim 9.5$), the
values obtained with sps-s are slightly lower than for sps-m. On the other hand, the effect of HRD coverage on inferred ages is more significant: the use of models with non-optimal HRD coverage underestimates virtually all ages, the effect being more pronounced for log(age) ∼ 9.0.

The effects on the derived metallicities are shown in the bottom panels of Fig. 12. sps-s models recover lower metallicities than sps-m models, with a median difference of 0.13. This result is consistent with the top-panel of Fig. 11, which shows more indices below the zero-line than around or above it. This is also in agreement with results from the literature that show that in general synthetic stellar spectra are stronger-lined than observed stellar spectra (e.g. Martins & Coelho 2007; Coelho 2014). There is an indication that the difference is stronger towards lower-metallicities, but the origin of this tendency is unclear. Having a complete coverage of the HRD does not seem to affect the derived mean metallicities, although the dispersion increases.

6 CONCLUSIONS

It has been traditionally accepted that SPS models tailored to study young populations favour the use of theoretical stellar libraries, due to their better HRD and wavelength coverage, while models targeting intermediate and old populations favour empirical stellar libraries, whose detailed spectral features are more reliable than in synthetic spectra.

In this paper we perform experiments with especially built SPS models to investigate and quantify the impact of the choice of stellar library type on: (i) the predicted colours and magnitudes of evolving simple stellar populations, and (ii) the inferred age, metallicity and reddening of a galaxy from spectral fits to its integrated spectrum.

We build a new synthetic stellar library which mimics the HRD coverage of a widely used empirical library (Section 3). We name synthetic effect the differences introduced in the SPS model predictions by using a theoretical vs. an empirical library, for identical HRD coverage. Analogously, we name coverage effect the differences introduced in the SPS models by using libraries with a limited vs. a complete HRD coverage. The results of our tests are given in Section 4, and further discussed in Section 5. The lessons learned are as follows.

In the majority of the cases the coverage effect is responsible for the larger deviations in the predicted colours, especially those involving the u band, for which the lack of hot stars in the empirical library is more noticeable.

For spectral indices, the coverage and synthetic effects are comparable for most features in the wavelength range considered. Some indices are more sensitive to the synthetic effect (e.g. CaHK, Ca4227, Fe4668, Fe5270), indicating spectral regions that deserve more attention from the modellers to improve the theoretical grids. Other indices are more sensitive to the coverage effect (H8, B4000, G4300), and we warn users of semi-empirical SPS models to take the predictions for these indices with caution.

We test the effects that random errors in the atmospheric parameters of the stars have on the SPS model predictions, and conclude that, for the typical errors in atmospheric parameters adopted in our experiments, this effect is minor in comparison to the other effects.

We use different SPS models to infer the stellar population parameters of a sample of nearby galaxies by spectral fitting. The synthetic effect is null for the mean light-weighted log(age) of the galaxies, but metallicity is under-estimated by an average of ∼ 0.13. The coverage effect results in galaxy ages being underestimated (for all ages but more strongly around log(age) ∼ 9), but has little impact on the inferred metallicities other than increasing the dispersion. The inferred reddening is virtually unaffected by either effect.

Strictly speaking, our results are valid for the specific HRD coverage of the MILES library and the synthetic grid of C14. Nonetheless, we believe that our conclusions on the coverage effect will not change much in the near future, given that MILES already has an optimal coverage of the HRD for solar neighbourhood stars. More stars from different populations (LMC, SMC, galactic bulge) need to be introduced in the library to possibly produce a significant change, at the expense of lowering the spectral resolution and/or the SNR, due to current observational constraints. We expect that the synthetic effect on optical colours will be similar for most modern theoretical libraries currently in use. The effect on the spectral indices is more sensitive to the specific choice of the synthetic grid and atomic and molecular opacities.

Overall, we conclude that in several instances a sparse coverage of the HRD can introduce larger errors than the inaccuracies of the synthetic spectra. As such, one has to decide with care which kind of SPS models – semi-empirical or fully theoretical – to favour, depending on the application. As of now, SPS models built on current theoretical grids of synthetic spectra are very competitive, for all ages.

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APPENDIX A: ONLINE-ONLY MATERIAL

Table A1: Atmospheric parameters used as input values in the computation of SynCoMiL (Section 2). References for the source of the stellar parameters are given in column (f): \(^a\)Cenarro et al. (2007); \(^b\)Prugniel et al. (2011); \(^c\)Sharma et al. (2016); \(^d\)Computed with different parameters than proposed in the literature to ensure model convergence. Stars with MILES ID not listed in this table were not used in the SPS models of this work and are reported separately in Table A2.

| MILES ID | Star | \(T_{\text{eff}}\) | \(\log g\) | [Fe/H] | Reference |
|----------|------|------------------|-----------|--------|-----------|
| (a)      | (b)  | (c)              | (d)       | (e)    | (f)       |
| 1        | HD224930 | 5411            | 4.19      | -0.78  | b         |
| 2        | HD225212 | 4117            | 0.68      | 0.14   | c         |
| 3        | HD225239 | 5559            | 3.72      | -0.51  | b         |
| 4        | HD000004 | 6779            | 3.87      | 0.21   | b         |
| 5        | HD000249 | 4731            | 2.83      | -0.31  | c         |
| 6        | HD000319 | 8641            | 4.29      | -0.35  | b         |
| 7        | HD000400 | 6190            | 4.15      | -0.22  | b         |
| 8        | HD000245 | 5749            | 4.13      | -0.57  | b         |
| 9        | HD000448 | 4770            | 2.61      | 0.02   | c         |
| 10       | BD+130013 | 5000           | 3.00      | -0.75  | b         |
| 11       | HD000886 | 20454           | 3.79      | -0.03  | b         |
| 12       | HD01326b | 3571            | 4.81      | -0.57  | d         |
| 13       | HD01461  | 5666            | 4.21      | 0.19   | b         |
| 14       | HD01918  | 4888            | 2.44      | -0.40  | b         |
| 15       | HD02628  | 7335            | 3.95      | -0.09  | b         |
| 16       | HD02665  | 4986            | 2.28      | -1.96  | b         |
| 17       | HD02796  | 4837            | 1.78      | -2.23  | b         |
| 18       | HD02857  | 8000            | 2.70      | -1.50  | b         |
| 19       | HD03008  | 4364            | 0.68      | -1.83  | c         |
| 20       | HD03369  | 16005           | 3.71      | 0.04   | b         |
| 21       | HD03360  | 20375           | 3.80      | -0.04  | b         |
| 22       | HD03567  | 6094            | 4.18      | -1.14  | b         |
| 23       | HD03546  | 4945            | 2.36      | -0.66  | b         |
| 24       | HD03574  | 4019            | 1.13      | 0.01   | c         |
| 25       | HD03951  | 5211            | 4.48      | 0.21   | b         |
| 26       | HD03795  | 5345            | 3.72      | -0.63  | b         |
| 27       | HD03883  | 7616            | 3.81      | 0.68   | b         |
| 28       | HD04307  | 5773            | 3.97      | -0.24  | b         |
| 29       | HD04359  | 25000           | 5.40      | 0.00   | b         |
| 30       | HD04628  | 4964            | 4.65      | -0.23  | b         |
| 31       | HD04656  | 3934            | 1.67      | -0.13  | c         |
| 32       | HD04744  | 4590            | 2.32      | -0.74  | c         |
| 33       | HD04906  | 5157            | 3.58      | -0.66  | b         |
| 34       | HD05268  | 4904            | 2.35      | -0.57  | b         |
| 35       | HD05384  | 3933            | 1.79      | 0.18   | c         |
| 36       | HD05395  | 4845            | 2.45      | -0.43  | c         |
| 37       | HD05780  | 3917            | 1.64      | -0.71  | c         |
| 38       | HD05916  | 4954            | 2.31      | -0.75  | b         |
| 39       | HD06186  | 4865            | 2.36      | -0.35  | b         |
| 40       | HD06203  | 4506            | 2.20      | -0.41  | c         |
| 41       | HD06268  | 4571            | 1.13      | -2.63  | c         |
| 42       | HD06229  | 5181            | 2.50      | -1.14  | b         |
| 43       | HD06582  | 5323            | 4.33      | -0.79  | b         |
| 44       | HD06805  | 4505            | 2.48      | 0.07   | c         |
| 45       | HD05848  | 4451            | 2.25      | 0.09   | c         |
| 46       | HD06834  | 6482            | 4.22      | -0.58  | b         |
| 47       | HD06755  | 5097            | 2.53      | -1.58  | b         |
| 48       | HD06833  | 4502            | 1.78      | -0.84  | c         |
| 49       | HD07106  | 4678            | 2.55      | -0.02  | c         |
| MILES ID (a) | Star (b) | $T_{\text{eff}}$ (c) | log $g$ (d) | [Fe/H] (e) | Reference (f) |
|-------------|---------|----------------|---------|---------|-------------|
| 53          | HD007351 | 3619           | 0.36    | -0.35   | c           |
| 54          | HD007374 | 12247          | 4.16    | 0.16    | b           |
| 55          | HD007595 | 4327           | 1.82    | -0.68   | c           |
| 56          | HD007672 | 4939           | 2.78    | -0.42   | b           |
| 57          | HD008724 | 4792           | 1.76    | -1.63   | c           |
| 58          | HD008829 | 7129           | 4.10    | -0.17   | b           |
| 59          | HD009138 | 4041           | 1.89    | -0.50   | c           |
| 60          | HD009356 | 6800           | 4.24    | -0.80   | b           |
| 61          | HD009562 | 5766           | 3.89    | 0.14    | b           |
| 63          | HD009826 | 6139           | 4.06    | 0.11    | b           |
| 65          | HD010380 | 4154           | 1.85    | -0.24   | c           |
| 66          | HD010307 | 5875           | 4.28    | 0.06    | b           |
| 67          | HD010700 | 5348           | 4.39    | -0.46   | b           |
| 69          | HD010780 | 5406           | 4.63    | 0.15    | b           |
| 70          | HD010975 | 4843           | 2.44    | -0.23   | c           |
| 71          | HD011257 | 7103           | 4.08    | -0.27   | b           |
| 72          | HD011397 | 5526           | 4.24    | -0.58   | b           |
| 73          | HD011964 | 5272           | 3.85    | 0.05    | b           |
| 75          | HD012438 | 4937           | 2.35    | -0.73   | b           |
| 76          | HD013043 | 5823           | 4.11    | 0.06    | b           |
| 77          | BD+290366 | 5666         | 4.25    | -0.95   | b           |
| 78          | HD013267 | 15500          | 2.57    | -0.10   | b           |
| 79          | HD013555 | 6515           | 4.07    | -0.16   | b           |
| 80          | HD013520 | 4023           | 1.61    | -0.27   | c           |
| 81          | BD-010306 | 5723         | 4.28    | -0.89   | b           |
| 82          | HD013783 | 5516           | 4.37    | -0.49   | b           |
| 83          | HD014221 | 6619           | 4.07    | -0.17   | b           |
| 84          | HD014802 | 5777           | 3.89    | -0.07   | b           |
| 85          | HD014829 | 8750           | 3.15    | -1.57   | b           |
| 86          | HD014938 | 6275           | 4.22    | -0.25   | b           |
| 88          | HD015798 | 6527           | 4.07    | -0.12   | b           |
| 89          | HD016031 | 6039           | 4.09    | -1.63   | b           |
| 90          | HD016234 | 6225           | 4.18    | -0.19   | b           |
| 91          | HD016232 | 6314           | 4.29    | 0.11    | b           |
| 92          | HD016673 | 6260           | 4.30    | 0.00    | b           |
| 93          | HD016784 | 5782           | 4.08    | -0.68   | b           |
| 94          | BD+460610 | 5889         | 4.13    | -0.86   | b           |
| 95          | G004-036 | 6073           | 4.20    | -1.66   | b           |
| 96          | HD016901 | 5345           | 0.85    | 0.00    | a           |
| 97          | HD017081 | 12722          | 4.20    | 0.28    | b           |
| 98          | HD017361 | 4630           | 2.53    | 0.02    | c           |
| 99          | HD017491 | 3258           | 0.65    | -0.15   | c           |
| 100         | HD017382 | 5339           | 4.64    | 0.17    | b           |
| 101         | HD017548 | 6013           | 4.20    | -0.53   | b           |
| 102         | HD017378 | 8477           | 1.25    | 0.00    | b           |
| 103         | HD018191 | 3199           | 0.78    | -0.05   | c           |
| 105         | HD018907 | 4569           | 3.43    | -0.65   | b           |
| 106         | HD019445 | 5900           | 4.20    | -2.07   | b           |
| 108         | HD019373 | 5947           | 4.15    | 0.11    | b           |
| 109         | HD019994 | 6051           | 4.02    | 0.16    | b           |
| 110         | HD020041 | 11509          | 2.01    | 0.23    | b           |
| 111         | HD020512 | 5267           | 3.81    | -0.13   | b           |
| 112         | HD020619 | 5710           | 4.47    | -0.18   | b           |
| 113         | HD020630 | 5733           | 4.45    | 0.12    | b           |
| 114         | HD020803 | 4363           | 2.26    | 0.07    | c           |
| 115         | BD+430699 | 4736         | 4.72    | -0.38   | c           |
| 116         | HD021017 | 4419           | 2.67    | 0.07    | c           |
| 117         | HD021197 | 4376           | 4.50    | 0.13    | c           |
Table A1: continued.

| MILES ID (a) | Star (b) | \(T_{\text{eff}}\) (c) | \(\log g\) (d) | \([\text{Fe/H}]\) (e) | Reference (f) |
|--------------|----------|-----------------|-------------|-----------------|--------------|
| 118          | HD021581 | 4825            | 2.00        | -1.70           | a            |
| 119          | BD+660268| 5300            | 4.20        | -2.00           | b            |
| 120          | HD022049 | 5115            | 4.72        | 0.05            | b            |
| 121          | HD022484 | 5987            | 4.07        | -0.05           | b            |
| 122          | HD021910 | 4798            | 2.48        | -0.45           | c            |
| 123          | HD022879 | 5870            | 4.23        | -0.80           | b            |
| 124          | HD023249 | 5020            | 3.73        | 0.08            | b            |
| 125          | HD023261 | 5165            | 4.56        | 0.24            | b            |
| 126          | HD023194 | 8031            | 4.00        | -0.17           | b            |
| 127          | HD023439 | 5181            | 4.47        | -0.90           | b            |
| 128          | HD023439 | 4786            | 4.63        | -1.09           | c            |
| 129          | HD023607 | 7586            | 3.97        | -0.03           | b            |
| 130          | HD023841 | 4306            | 2.05        | -0.66           | c            |
| 131          | HD023924 | 7776            | 3.94        | 0.07            | b            |
| 132          | HD024616 | 5014            | 3.16        | -0.71           | b            |
| 133          | HD024341 | 5405            | 3.71        | -0.62           | b            |
| 134          | HD024421 | 6168            | 4.20        | -0.29           | b            |
| 135          | HD02451  | 4418            | 4.57        | -0.09           | c            |
| 136          | HD025329 | 4964            | 4.60        | -1.58           | c            |
| 137          | HD025532 | 5600            | 2.50        | -1.35           | b            |
| 138          | HD025673 | 5112            | 4.54        | -0.40           | b            |
| 139          | HD026297 | 4497            | 1.11        | -1.79           | c            |
| 140          | HD026322 | 7008            | 3.94        | 0.13            | b            |
| 141          | HD026428 | 6113            | 4.14        | -1.55           | b            |
| 142          | BD-660855| 5442            | 4.60        | -0.69           | b            |
| 143          | HD026965 | 5114            | 4.41        | -0.26           | b            |
| 144          | HD026909 | 4971            | 4.70        | 0.18            | c            |
| 145          | HD027126 | 5425            | 4.14        | -0.38           | b            |
| 146          | HD02795  | 11034           | 3.99        | -0.11           | b            |
| 147          | HD027371 | 4995            | 2.76        | 0.15            | b            |
| 148          | HD027771 | 5285            | 4.59        | 0.27            | b            |
| 149          | HD027919 | 7871            | 3.89        | -0.06           | b            |
| 150          | HD028305 | 4964            | 2.72        | 0.20            | b            |
| 151          | HD028573 | 5348            | 4.56        | 0.25            | b            |
| 152          | HD028946 | 5314            | 4.55        | -0.10           | b            |
| 153          | HD028978 | 8864            | 3.42        | -0.26           | b            |
| 154          | HD029065 | 4034            | 1.69        | -0.35           | c            |
| 155          | HD029139 | 3851            | 1.62        | -0.13           | c            |
| 156          | BD+501021| 5081            | 4.48        | -0.65           | b            |
| 157          | BD-450983| 5155            | 4.45        | -0.22           | b            |
| 158          | HD030771 | 6484            | 4.16        | -0.34           | b            |
| 159          | HD030504 | 4022            | 1.75        | -0.50           | c            |
| 160          | HD030649 | 5791            | 4.21        | -0.48           | b            |
| 161          | HD031128 | 5949            | 4.18        | -1.45           | b            |
| 162          | HD030959 | 3562            | 0.37        | -0.09           | c            |
| 163          | HD030834 | 4194            | 1.61        | -0.35           | c            |
| 164          | HD031295 | 8822            | 4.11        | -0.73           | b            |
| 165          | HD031767 | 4367            | 1.50        | -0.02           | c            |
| 166          | HD032147 | 4650            | 4.58        | 0.16            | c            |
| 167          | HD032655 | 7114            | 3.47        | 0.23            | b            |
| 168          | HD033256 | 6477            | 4.15        | -0.27           | b            |
| 169          | HD033276 | 7223            | 3.80        | 0.22            | b            |
| 170          | HD033857 | 5628            | 4.38        | 0.10            | b            |
| 171          | HD035068 | 6461            | 4.03        | 0.21            | b            |
| 172          | HD034538 | 4870            | 2.96        | -0.36           | b            |
| 173          | MS0515.4-0710| 5206   | 4.41        | 0.05            | c            |
| 174          | HD034411 | 5842            | 4.16        | 0.08            | b            |
| 175          | HD035155 | 3637            | 0.09        | -0.53           | c            |
| MILES ID (a) | Star (b) | T\(_{\text{eff}}\) (c) | log g (d) | [Fe/H] (e) | Reference (f) |
|-------------|----------|-----------------|--------|--------|-----------|
| 178 | HD035179 | 4942 | 2.48 | -0.60 | c |
| 179 | HD035369 | 4915 | 2.49 | -0.24 | b |
| 180 | HD035296 | 6171 | 4.31 | 0.01 | b |
| 182 | HD036003 | 4378 | 4.58 | -0.15 | c |
| 183 | HD036395 | 3579 | 4.72 | -0.05 | c |
| 184 | HD037160 | 4754 | 2.64 | -0.64 | c |
| 185 | HD037792 | 6509 | 4.17 | -0.54 | b |
| 186 | HD037536 | 3775 | 0.22 | 0.14 | c |
| 187 | HD037282 | 4505 | 1.36 | -1.41 | c |
| 188 | HD037394 | 5279 | 4.60 | 0.20 | b |
| 189 | HD037984 | 4445 | 2.15 | -0.52 | c |
| 190 | HD038392 | 4941 | 4.75 | -0.02 | c |
| 191 | HD038393 | 6316 | 4.23 | -0.09 | b |
| 192 | HD038007 | 5705 | 3.98 | -0.31 | b |
| 193 | HD038545 | 8673 | 3.68 | -0.48 | b |
| 194 | HD038751 | 4776 | 2.71 | 0.11 | c |
| 195 | HD038656 | 4943 | 2.55 | -0.15 | b |
| 196 | HD039364 | 4660 | 2.46 | -0.74 | c |
| 197 | HD039853 | 3858 | 1.58 | -0.61 | c |
| 198 | HD039833 | 5869 | 4.39 | 0.18 | b |
| 199 | HD039801 | 3666 | 0.20 | 0.07 | c |
| 200 | HD039970 | 12006 | 2.13 | 0.19 | b |
| 201 | HD040657 | 4264 | 1.81 | -0.73 | c |
| 202 | HD250792 | 5554 | 4.33 | -1.01 | b |
| 203 | HD041312 | 4044 | 1.77 | -0.75 | c |
| 205 | HD251611 | 5382 | 3.40 | -1.44 | b |
| 206 | HD041692 | 14800 | 3.30 | -0.01 | b |
| 207 | HD041636 | 4688 | 2.42 | -0.29 | c |
| 208 | HD042182 | 5041 | 4.63 | 0.13 | b |
| 209 | HD041597 | 4607 | 2.01 | -0.54 | c |
| 211 | HD042543 | 3707 | 0.17 | 0.18 | c |
| 213 | HD043318 | 6330 | 4.04 | -0.07 | b |
| 214 | BD+371458 | 5450 | 3.38 | -2.12 | b |
| 215 | HD043380 | 4521 | 2.40 | -0.05 | c |
| 216 | HD044007 | 4987 | 2.33 | -1.53 | b |
| 217 | HD043378 | 9284 | 4.05 | -0.27 | b |
| 218 | HD043947 | 5983 | 4.28 | -0.27 | b |
| 219 | HD044030 | 4026 | 1.75 | -0.51 | c |
| 222 | HD045282 | 5309 | 3.19 | -1.42 | b |
| 223 | HD045829 | 4499 | 0.56 | 0.11 | c |
| 224 | HD046341 | 5835 | 4.28 | -0.66 | b |
| 225 | HD047205 | 4728 | 3.10 | 0.19 | c |
| 226 | HD046703 | 6250 | 1.00 | -1.50 | b |
| 227 | HD047914 | 3938 | 1.79 | 0.04 | c |
| 228 | HD048329 | 4496 | 0.75 | 0.08 | c |
| 229 | HD048433 | 4464 | 2.01 | -0.22 | c |
| 230 | BD+151305 | 4901 | 4.66 | 0.11 | b |
| 231 | HD048565 | 6030 | 3.94 | -0.63 | b |
| 232 | HD048682 | 6088 | 4.28 | 0.11 | b |
| 233 | HD049161 | 4168 | 1.82 | 0.17 | c |
| 234 | HD049331 | 3830 | 0.44 | 0.13 | c |
| 235 | HD049933 | 6647 | 4.19 | -0.45 | b |
| 236 | HD050778 | 4099 | 1.77 | -0.43 | c |
| 237 | HD050420 | 7319 | 3.75 | 0.11 | b |
| 238 | HD051440 | 4313 | 1.72 | -0.66 | c |
| 239 | HD052005 | 4071 | 0.66 | 0.08 | c |
| 240 | HD052973 | 5657 | 1.12 | 0.09 | b |
| 241 | HD053927 | 4911 | 4.71 | -0.28 | b |
Table A1: continued.

| MILES ID (a) | Star (b) | $T_{\text{eff}}$ (c) | log g (d) | [Fe/H] (e) | Reference (f) |
|--------------|----------|----------------------|----------|----------|--------------|
| 242          | HD654605 | 6268                 | 0.97     | 0.10     | a            |
| 243          | BD+371665| 5128                 | 3.50     | -0.65    | b            |
| 244          | HD054810 | 4726                 | 2.58     | -0.33    | c            |
| 245          | HD054719 | 4405                 | 2.14     | 0.13     | c            |
| 247          | HD055693 | 5773                 | 4.16     | 0.25     | b            |
| 248          | HD055575 | 5811                 | 4.19     | -0.38    | b            |
| 249          | HD056274 | 5769                 | 4.40     | -0.53    | b            |
| 250          | HD056577 | 3904                 | 0.48     | 0.12     | c            |
| 253          | HD057264 | 4599                 | 2.41     | -0.40    | c            |
| 254          | HD058207 | 4806                 | 2.55     | -0.11    | c            |
| 255          | HD058551 | 6306                 | 4.27     | -0.42    | b            |
| 257          | HD059374 | 5873                 | 4.21     | -0.82    | b            |
| 258          | BD+241676| 6230                 | 3.81     | -2.55    | b            |
| 259          | HD059984 | 5973                 | 4.07     | -0.68    | b            |
| 260          | HD059881 | 7623                 | 3.64     | 0.15     | b            |
| 261          | HD060219 | 5900                 | 1.83     | -0.49    | a            |
| 262          | HD060179 | 9550                 | 3.83     | -0.13    | b            |
| 263          | LHS1930  | 5420                 | 4.33     | -1.11    | b            |
| 264          | HD06522  | 3834                 | 1.54     | -0.02    | c            |
| 265          | HD061064 | 6646                 | 3.69     | 0.27     | b            |
| 266          | BD-011792| 5131                 | 3.38     | -0.81    | b            |
| 267          | HD061606 | 4890                 | 4.67     | 0.05     | b            |
| 268          | HD061772 | 4096                 | 1.46     | -0.04    | c            |
| 269          | HD061603 | 3953                 | 1.43     | 0.19     | c            |
| 270          | HD061935 | 4802                 | 2.57     | -0.06    | c            |
| 271          | HD061913 | 3568                 | 0.55     | 0.06     | c            |
| 272          | BD+002058a| 6096              | 4.17     | -1.22    | b            |
| 273          | HD062345 | 5029                 | 2.61     | -0.01    | b            |
| 274          | HD062301 | 5933                 | 4.12     | -0.62    | b            |
| 275          | HD062721 | 3913                 | 1.81     | -0.36    | c            |
| 276          | HD063902 | 4264                 | 0.12     | 0.12     | c            |
| 277          | HD063352 | 4149                 | 1.71     | -0.60    | c            |
| 278          | BD-182065| 4878                 | 2.43     | -0.71    | c            |
| 279          | HD064332 | 3515                 | 0.19     | -0.11    | c            |
| 280          | HD064090 | 5405                 | 4.19     | -1.65    | b            |
| 281          | HD063791 | 4822                 | 1.94     | -1.62    | c            |
| 282          | HD064606 | 5302                 | 4.42     | -0.76    | b            |
| 283          | HD064488 | 8837                 | 3.65     | -0.36    | b            |
| 284          | HD065228 | 5861                 | 1.24     | 0.06     | b            |
| 285          | HD065583 | 5281                 | 4.33     | -0.65    | b            |
| 286          | HD065714 | 4983                 | 2.50     | 0.18     | b            |
| 287          | HD065953 | 3986                 | 1.73     | -0.34    | c            |
| 288          | HD065900 | 9235                 | 3.69     | -0.16    | b            |
| 289          | HD066141 | 4265                 | 1.98     | -0.51    | c            |
| 290          | HD066573 | 5680                 | 4.26     | -0.58    | b            |
| 291          | HD067523 | 6810                 | 3.59     | 0.60     | b            |
| 292          | HD067228 | 5732                 | 3.84     | 0.12     | b            |
| 293          | BD+800245| 5509                 | 3.74     | -1.85    | b            |
| 294          | HD068281 | 5945                 | 3.97     | -0.52    | b            |
| 295          | HD069267 | 4068                 | 1.49     | -0.19    | c            |
| 296          | HD069611 | 5773                 | 4.09     | -0.58    | b            |
| 297          | HD069830 | 5412                 | 4.49     | 0.04     | b            |
| 298          | HD233511 | 6005                 | 4.13     | -1.52    | b            |
| 299          | HD069897 | 6328                 | 4.18     | -0.23    | b            |
| 300          | HD070272 | 3921                 | 1.46     | -0.02    | c            |
| 301          | HD071030 | 6541                 | 4.03     | -0.15    | b            |
| 302          | HD072184 | 4606                 | 2.87     | 0.18     | c            |
| 303          | HD072324 | 4881                 | 2.43     | 0.00     | b            |
Table A1: continued.

| MILES ID | Star     | $T_{\text{eff}}$ (c) | $\log g$ (d) | [Fe/H] (e) | Reference (f) |
|----------|----------|----------------------|-------------|-----------|---------------|
| 304      | HD072660 | 9290                 | 3.39        | -0.20     | b             |
| 305      | HD073471 | 4495                 | 2.13        | 0.10      | c             |
| 306      | HD072905 | 5919                 | 4.47        | 0.01      | b             |
| 307      | HD073898 | 4912                 | 2.30        | -0.56     | b             |
| 308      | HD073665 | 5024                 | 2.70        | 0.21      | b             |
| 309      | HD073394 | 4612                 | 1.48        | -1.49     | c             |
| 310      | HD074000 | 6178                 | 4.03        | -1.85     | b             |
| 311      | HD073593 | 4815                 | 2.82        | -0.17     | c             |
| 312      | HD074011 | 5795                 | 4.08        | -0.56     | b             |
| 313      | HD074395 | 5546                 | 1.41        | 0.09      | b             |
| 314      | BD+251981| 6668                 | 4.28        | -1.20     | b             |
| 315      | HD074442 | 4689                 | 2.49        | -0.03     | c             |
| 316      | HD074377 | 4674                 | 4.47        | -0.37     | b             |
| 317      | HD074721 | 8900                 | 3.38        | -1.32     | b             |
| 318      | BD-122669| 6800                 | 4.10        | -1.50     | b             |
| 319      | HD074642 | 4747                 | 1.83        | -1.40     | c             |
| 320      | HD075318 | 5432                 | 4.48        | -0.13     | b             |
| 321      | HD075691 | 4299                 | 2.10        | -0.16     | c             |
| 322      | HD075732 | 5260                 | 4.35        | 0.43      | b             |
| 323      | HD076151 | 5748                 | 4.42        | 0.15      | b             |
| 324      | HD076292 | 6958                 | 3.88        | 0.16      | b             |
| 325      | HD076932 | 5908                 | 4.09        | -0.82     | b             |
| 326      | HD076780 | 5704                 | 4.28        | 0.18      | b             |
| 327      | BD-052678| 5492                 | 3.85        | -2.02     | b             |
| 328      | HD076010 | 6397                 | 4.23        | -0.51     | b             |
| 329      | BD-032525| 5869                 | 4.09        | -1.60     | b             |
| 331      | HD077338 | 5290                 | 4.30        | 0.36      | b             |
| 332      | HD077236 | 4343                 | 1.89        | -0.89     | c             |
| 333      | HD078541 | 3917                 | 1.45        | -0.37     | c             |
| 334      | HD078234 | 6976                 | 4.04        | -0.06     | b             |
| 335      | HD078558 | 5651                 | 4.06        | -0.45     | b             |
| 336      | HD078209 | 7519                 | 3.77        | 0.55      | b             |
| 337      | HD078737 | 6550                 | 4.19        | -0.46     | b             |
| 338      | HD078732 | 4939                 | 2.27        | -0.07     | b             |
| 339      | HD079211 | 3846                 | 4.63        | -0.17     | c             |
| 340      | HD079452 | 4982                 | 2.31        | -0.79     | b             |
| 341      | HD079765 | 7146                 | 4.11        | -0.26     | b             |
| 342      | HD079633 | 7223                 | 4.06        | -0.26     | b             |
| 343      | HD080390 | 3366                 | 0.53        | -0.10     | c             |
| 344      | HD081009 | 8829                 | 3.79        | 0.84      | b             |
| 345      | HD081029 | 6714                 | 4.14        | -0.08     | b             |
| 346      | HD081192 | 4745                 | 2.57        | -0.76     | c             |
| 348      | BD+092190| 6270                 | 4.11        | -2.86     | a             |
| 349      | HD082074 | 5090                 | 3.21        | -0.43     | b             |
| 350      | HD082590 | 6669                 | 4.22        | -0.81     | b             |
| 351      | HD082734 | 4906                 | 2.56        | 0.20      | c             |
| 352      | HD082210 | 5445                 | 3.64        | -0.10     | b             |
| 353      | HD082885 | 5520                 | 4.41        | 0.40      | b             |
| 354      | HD083212 | 4472                 | 0.99        | -1.64     | c             |
| 355      | HD081817 | 4168                 | 1.40        | 0.15      | c             |
| 356      | HD083425 | 4150                 | 1.99        | -0.47     | c             |
| 357      | HD083618 | 4244                 | 1.88        | -0.20     | c             |
| 358      | HD083632 | 4167                 | 1.41        | -0.85     | c             |
| 359      | HD083666 | 5161                 | 2.42        | -1.62     | b             |
| 360      | HD083506 | 4875                 | 2.36        | 0.12      | c             |
| 361      | HD084441 | 5398                 | 2.02        | -0.06     | b             |
| 362      | HD084737 | 5872                 | 4.05        | 0.12      | b             |
| 363      | HD084937 | 6211                 | 4.00        | -2.05     | b             |
Table A1: continued.

| MILES ID   | Star (a) | T\textsubscript{eff} (b) | log g (c) | [Fe/H] (d) | Reference (e) | (f) |
|------------|----------|--------------------------|---------|-----------|----------------|-----|
| 364        | HD085235 | 8769                     | 3.69    | -0.23     | b              |     |
| 366        | HD085503 | 4425                     | 2.56    | 0.27      | c              |     |
| 367        | HD085773 | 4345                     | 0.66    | -2.48     | c              |     |
| 368        | HD086086 | 8000                     | 2.55    | -1.70     | b              |     |
| 369        | HD087141 | 6359                     | 3.90    | 0.09      | b              |     |
| 370        | HD087140 | 5092                     | 2.48    | -1.70     | b              |     |
| 371        | HD087373 | 10958                    | 2.11    | 0.11      | b              |     |
| 372        | HD087822 | 6573                     | 4.06    | 0.10      | b              |     |
| 373        | HD088230 | 4017                     | 4.67    | -0.01     | c              |     |
| 374        | HD088446 | 5848                     | 3.89    | -0.51     | b              |     |
| 375        | HD088725 | 5647                     | 4.24    | -0.64     | b              |     |
| 377        | HD088737 | 6106                     | 3.89    | 0.20      | b              |     |
| 378        | HD088986 | 5766                     | 4.04    | 0.04      | b              |     |
| 379        | HD089010 | 5642                     | 3.80    | 0.00      | b              |     |
| 380        | HD089254 | 7166                     | 3.83    | 0.31      | b              |     |
| 381        | HD089449 | 6467                     | 4.11    | 0.11      | b              |     |
| 382        | HD089484 | 4381                     | 1.79    | -0.50     | c              |     |
| 383        | HD089707 | 5937                     | 4.25    | -0.47     | b              |     |
| 384        | HD089744 | 6169                     | 3.93    | 0.18      | b              |     |
| 385        | HD089995 | 6472                     | 4.08    | -0.24     | b              |     |
| 386        | HD089822 | 10182                    | 3.85    | 0.07      | b              |     |
| 387        | HD090508 | 5776                     | 4.31    | -0.30     | b              |     |
| 388        | HD237903 | 4106                     | 4.64    | -0.16     | c              |     |
| 389        | HD091347 | 5887                     | 4.26    | -0.44     | b              |     |
| 390        | HD091889 | 6109                     | 4.16    | -0.21     | b              |     |
| 391        | HD092523 | 4112                     | 1.77    | -0.43     | c              |     |
| 392        | HD093329 | 8400                     | 3.10    | -1.20     | b              |     |
| 393        | HD093487 | 5215                     | 2.41    | -1.06     | b              |     |
| 394        | HD094028 | 6076                     | 4.23    | -1.30     | b              |     |
| 395        | BD-103166| 5329                     | 4.38    | 0.42      | b              |     |
| 396        | HD095128 | 5852                     | 4.24    | 0.02      | b              |     |
| 397        | HD095578 | 3849                     | 1.26    | -0.01     | c              |     |
| 398        | HD095735 | 3454                     | 4.78    | -0.27     | c              |     |
| 399        | BD+442051a | 3628                     | 4.87    | -0.48     | c              |     |
| 400        | HD096360 | 3471                     | 0.80    | 0.00      | c              |     |
| 401        | BD+362165 | 6144                     | 4.18    | -1.45     | b              |     |
| 402        | HD097560 | 5328                     | 2.69    | -1.04     | b              |     |
| 403        | HD097633 | 9201                     | 3.68    | -0.16     | b              |     |
| 404        | HD097907 | 4307                     | 2.16    | -0.19     | c              |     |
| 405        | HD097916 | 6478                     | 4.28    | -0.73     | b              |     |
| 406        | HD097855 | 6416                     | 4.18    | -0.39     | b              |     |
| 407        | HD098468 | 4528                     | 2.06    | -0.36     | b              |     |
| 408        | HD098553 | 5832                     | 4.27    | -0.44     | b              |     |
| 409        | HD099109 | 5242                     | 4.29    | 0.40      | b              |     |
| 410        | HD233832 | 4970                     | 4.49    | -0.59     | b              |     |
| 411        | HD099648 | 4977                     | 2.24    | -0.03     | b              |     |
| 412        | HD099747 | 6738                     | 4.19    | -0.46     | b              |     |
| 413        | HD099998 | 3979                     | 1.53    | -0.37     | c              |     |
| 414        | HD100906 | 5042                     | 2.31    | -0.46     | b              |     |
| 415        | HD101227 | 5534                     | 4.52    | -0.32     | b              |     |
| 416        | HD101501 | 5535                     | 4.52    | 0.03      | b              |     |
| 417        | HD101606 | 6362                     | 4.13    | -0.57     | b              |     |
| 418        | HD102224 | 4455                     | 2.02    | -0.40     | c              |     |
| 419        | BD+511696 | 5656                     | 4.28    | -1.30     | b              |     |
| 420        | HD102282 | 4380                     | 2.56    | 0.28      | c              |     |
| 421        | HD102634 | 6281                     | 4.15    | 0.22      | b              |     |
| 422        | HD102870 | 6081                     | 4.07    | 0.14      | b              |     |
| 423        | HD103095 | 5165                     | 4.74    | -1.21     | b              |     |
Table A1: continued.

| MILES ID (a) | Star (b) | T$_{\text{eff}}$ (c) | log g (d) | [Fe/H] (e) | Reference (f) |
|--------------|----------|----------------------|-----------|------------|---------------|
| 424          | HD103578 | 8509                 | 3.80      | -0.19      | b             |
| 425          | HD103877 | 7170                 | 3.76      | 0.65       | b             |
| 426          | HD103932 | 4431                 | 4.55      | 0.06       | c             |
| 427          | HD104307 | 4423                 | 2.24      | -0.07      | e             |
| 428          | HD104304 | 5485                 | 4.23      | 0.30       | b             |
| 429          | HD104833 | 7588                 | 3.51      | 0.49       | b             |
| 430          | HD105262 | 8500                 | 1.50      | -1.87      | b             |
| 431          | HD105452 | 7041                 | 4.13      | -0.19      | b             |
| 432          | HD105546 | 5131                 | 2.36      | -1.46      | b             |
| 433          | HD105740 | 4791                 | 2.78      | -0.54      | c             |
| 434          | HD106038 | 6014                 | 4.18      | -1.25      | b             |
| 435          | CD-2809374 | 4995            | 3.11      | -0.76      | b             |
| 436          | HD106516 | 6207                 | 4.25      | -0.69      | b             |
| 437          | HD107113 | 6543                 | 4.19      | -0.42      | b             |
| 438          | HD107213 | 6209                 | 4.00      | 0.24       | b             |
| 439          | BD+172473 | 5283             | 3.37      | -1.04      | b             |
| 440          | BD+312360 | 4716              | 2.44      | -0.79      | c             |
| 441          | HD108177 | 6278                 | 4.19      | -1.41      | b             |
| 442          | HD108564 | 4634                 | 4.67      | -1.00      | c             |
| 443          | HD108915 | 5037                 | 3.32      | -0.10      | b             |
| 444          | HD109443 | 6758                 | 4.17      | -0.60      | b             |
| 445          | HD109871 | 3979                 | 1.77      | -0.15      | b             |
| 446          | HD109995 | 8550                 | 2.39      | -1.66      | b             |
| 447          | HD110014 | 4425                 | 2.34      | 0.25       | c             |
| 448          | HD110379 | 6857                 | 4.17      | -0.19      | b             |
| 449          | HD110897 | 5851                 | 4.28      | -0.53      | b             |
| 450          | HD110885 | 5545                 | 2.99      | -1.06      | b             |
| 451          | HD112028 | 9443                 | 2.88      | -0.39      | b             |
| 452          | HD111631 | 3908                 | 4.67      | 0.02       | c             |
| 453          | HD111786 | 8080                 | 3.88      | -1.50      | b             |
| 454          | HD111980 | 5876                 | 4.04      | -1.02      | b             |
| 455          | HD112127 | 4384                 | 2.46      | 0.22       | c             |
| 456          | HD112413 | 12303                | 4.09      | 0.90       | b             |
| 457          | HD113092 | 4269                 | 1.47      | -0.81      | c             |
| 458          | HD113022 | 6491                 | 4.09      | 0.11       | b             |
| 460          | HD114038 | 4567                 | 2.33      | -0.02      | c             |
| 461          | HD114330 | 9570                 | 3.95      | -0.13      | b             |
| 462          | HD114606 | 5584                 | 4.15      | -0.53      | b             |
| 463          | HD114710 | 5994                 | 4.35      | 0.05       | b             |
| 464          | HD114642 | 6491                 | 4.04      | -0.04      | b             |
| 465          | HD114946 | 4999                 | 3.12      | -0.36      | b             |
| 466          | HD115383 | 6047                 | 4.24      | 0.17       | b             |
| 467          | HD115589 | 5227                 | 4.39      | 0.28       | b             |
| 468          | HD115617 | 5539                 | 4.35      | 0.02       | b             |
| 469          | HD115659 | 5104                 | 2.64      | 0.04       | b             |
| 470          | HD116114 | 8226                 | 4.10      | 0.67       | b             |
| 471          | HD116316 | 6487                 | 4.26      | -0.51      | b             |
| 472          | HD116544 | 4417                 | 3.31      | 0.15       | c             |
| 473          | HD117200 | 6843                 | 4.02      | 0.03       | c             |
| 474          | HD117176 | 5467                 | 3.86      | -0.10      | b             |
| 475          | HD117635 | 5175                 | 4.48      | -0.42      | b             |
| 476          | HD117876 | 4688                 | 2.26      | -0.51      | c             |
| 479          | HD118241 | 6391                 | 4.19      | -0.46      | b             |
| 480          | BD-3+302431 | 16904         | 4.20      | 0.77       | a             |
| 481          | HD119228 | 3705                 | 1.06      | -0.10      | c             |
| 482          | HD119288 | 6595                 | 4.18      | -0.23      | b             |
| 483          | HD119291 | 4295                 | 4.57      | 0.04       | c             |
| 484          | HD119667 | 3740                 | 0.89      | -0.11      | c             |
Table A1: continued.

| MILES ID | Star         | $T_{\text{eff}}$ | log $g$ | [Fe/H] | Reference |
|----------|--------------|------------------|---------|--------|-----------|
| (a)      | (b)          | (c)              | (d)     | (e)    | (f)       |
| 485      | HD120136     | 6386             | 4.15    | 0.24   | b         |
| 486      | HD121130     | 3543             | 0.85    | -0.02  | b         |
| 487      | HD120933     | 3594             | 1.05    | -0.15  | c         |
| 488      | HD121370     | 5967             | 3.78    | 0.28   | b         |
| 489      | HD121299     | 4695             | 2.58    | 0.10   | c         |
| 490      | HD121258     | 6570             | 4.00    | -0.92  | a         |
| 491      | BD+342476    | 6200             | 3.96    | -2.05  | b         |
| 492      | HD122106     | 6321             | 3.84    | 0.16   | b         |
| 493      | HD122563     | 4618             | 1.32    | -2.67  | c         |
| 494      | HD122742     | 5485             | 4.35    | 0.03   | b         |
| 495      | HD123299     | 10371            | 3.95    | -0.19  | b         |
| 496      | HD122956     | 4734             | 1.59    | -1.68  | c         |
| 497      | HD123657     | 3408             | 0.66    | -0.05  | c         |
| 498      | HD123821     | 4900             | 2.28    | -0.13  | b         |
| 499      | HD124186     | 4384             | 2.56    | 0.27   | c         |
| 500      | HD124292     | 5398             | 4.35    | -0.11  | b         |
| 502      | HD124850     | 6207             | 3.86    | -0.06  | b         |
| 503      | HD125184     | 5336             | 3.85    | 0.24   | b         |
| 504      | HD125451     | 6700             | 4.12    | 0.01   | b         |
| 505      | BD+012916    | 4375             | 0.77    | -1.86  | c         |
| 506      | HD126141     | 6699             | 4.14    | -0.05  | b         |
| 507      | HD126053     | 5598             | 4.22    | -0.37  | b         |
| 509      | HD126218     | 5137             | 2.70    | 0.24   | b         |
| 510      | HD126660     | 6293             | 4.13    | 0.02   | b         |
| 511      | HD126614     | 5399             | 4.02    | 0.52   | b         |
| 512      | HD126778     | 4832             | 2.41    | -0.52  | b         |
| 513      | HD126681     | 5777             | 4.25    | -1.12  | b         |
| 514      | HD127243     | 4903             | 2.27    | -0.78  | b         |
| 515      | HD127334     | 5579             | 4.10    | 0.20   | b         |
| 516      | BD+182890    | 5024             | 2.31    | -1.54  | b         |
| 517      | HD128167     | 6777             | 4.18    | -0.39  | b         |
| 518      | HD128429     | 6427             | 4.22    | -0.08  | b         |
| 519      | HD128801     | 10200            | 3.50    | -1.40  | b         |
| 520      | CD-2610417   | 4625             | 4.62    | -0.21  | c         |
| 521      | HD128959     | 5857             | 3.84    | -0.51  | b         |
| 522      | HD129174     | 12052            | 3.99    | 0.18   | b         |
| 523      | HD130095     | 8900             | 3.35    | -1.70  | b         |
| 524      | HD130322     | 5391             | 4.52    | 0.12   | b         |
| 525      | HD130817     | 6749             | 4.14    | -0.29  | b         |
| 526      | HD130705     | 4375             | 2.56    | 0.34   | c         |
| 527      | HD130694     | 4093             | 1.74    | -0.77  | c         |
| 528      | HD131430     | 4287             | 2.19    | 0.09   | c         |
| 529      | HD132142     | 5163             | 4.38    | -0.37  | b         |
| 530      | HD131918     | 4118             | 1.56    | -0.10  | c         |
| 531      | HD131976     | 3541             | 4.72    | -0.14  | c         |
| 532      | HD131977     | 4501             | 4.59    | -0.05  | c         |
| 533      | HD132345     | 4403             | 2.54    | 0.31   | c         |
| 534      | HD132475     | 5823             | 3.93    | -1.37  | b         |
| 535      | HD132933     | 3797             | 1.30    | -0.71  | c         |
| 536      | HD133124     | 4006             | 1.76    | -0.01  | c         |
| 537      | BD+062986    | 3965             | 4.59    | -0.42  | c         |
| 538      | BD+302611    | 4400             | 1.04    | -1.45  | c         |
| 539      | HD134063     | 4880             | 2.31    | -0.69  | b         |
| 540      | HD134083     | 6573             | 4.17    | -0.01  | b         |
| 541      | HD134169     | 5807             | 3.99    | -0.81  | b         |
| 542      | HD134440     | 4955             | 4.70    | -1.34  | c         |
| 543      | HD134439     | 5172             | 4.68    | -1.27  | b         |
| 544      | HD134987     | 5623             | 4.09    | 0.26   | b         |
## Table A1: continued.

| MILES ID (a) | Star (b)  | $T_{\text{eff}}$ (c) | log g (d) | [Fe/H] (e) | Reference (f) |
|--------------|-----------|----------------------|----------|-----------|--------------|
| 545 | HD136064 | 6083 | 3.94 | 0.03 | b |
| 546 | HD135482 | 4530 | 2.32 | -0.04 | c |
| 547 | HD135722 | 4850 | 2.39 | -0.39 | b |
| 548 | HD135485 | 15500 | 4.00 | 0.50 | b |
| 549 | HD136726 | 4176 | 1.85 | -0.09 | c |
| 550 | HD136202 | 6139 | 4.00 | 0.05 | b |
| 551 | HD137071 | 3929 | 1.10 | 0.06 | c |
| 552 | HD136834 | 4856 | 4.50 | 0.23 | c |
| 553 | HD137391 | 7186 | 3.93 | 0.10 | b |
| 554 | HD137759 | 4459 | 2.43 | 0.08 | c |
| 555 | HD137471 | 3793 | 1.13 | -0.04 | c |
| 556 | HD137510 | 5872 | 3.90 | 0.30 | b |
| 557 | HD137704 | 4044 | 1.74 | -0.47 | c |
| 558 | HD137909 | 8466 | 4.06 | 0.96 | b |
| 559 | HD138290 | 6822 | 4.14 | -0.10 | b |
| 560 | HD138481 | 3898 | 1.25 | -0.07 | c |
| 561 | HD139669 | 3930 | 1.44 | 0.12 | c |
| 562 | HD138776 | 5524 | 3.99 | 0.35 | b |
| 563 | HD138764 | 14054 | 3.88 | 0.08 | b |
| 564 | HD139195 | 4946 | 2.64 | -0.13 | b |
| 565 | HD139641 | 4945 | 2.82 | -0.51 | b |
| 566 | HD139446 | 5065 | 2.65 | -0.27 | b |
| 567 | HD140160 | 9557 | 3.66 | 0.35 | b |
| 568 | HD140283 | 5687 | 3.55 | -2.53 | a |
| 569 | BD-053080 | 5034 | 4.46 | -0.44 | b |
| 570 | HD141004 | 5823 | 4.10 | -0.03 | b |
| 571 | HD141714 | 5332 | 3.22 | -0.20 | b |
| 572 | HD141851 | 8246 | 3.89 | -2.00 | a |
| 573 | HD142373 | 5783 | 3.93 | -0.54 | b |
| 574 | HD142575 | 6779 | 4.23 | -0.70 | b |
| 575 | HD142908 | 7038 | 3.98 | -0.02 | b |
| 576 | HD142860 | 6309 | 4.18 | -0.16 | b |
| 577 | HD142703 | 6903 | 4.32 | -1.10 | b |
| 578 | HD143459 | 10498 | 4.00 | -0.39 | b |
| 579 | HD143761 | 5752 | 4.13 | -0.26 | b |
| 580 | MS1558-4-2232 | 4250 | 3.50 | 0.10 | a |
| 581 | HD143807 | 10727 | 3.84 | -0.01 | b |
| 582 | HD144172 | 6432 | 4.14 | -0.38 | b |
| 583 | HD144872 | 4785 | 4.76 | -0.29 | c |
| 584 | HD144585 | 5767 | 4.09 | 0.29 | b |
| 585 | HD144608 | 5363 | 2.62 | 0.03 | b |
| 586 | HD145148 | 4868 | 3.65 | 0.10 | b |
| 587 | HD145675 | 5270 | 4.31 | 0.48 | b |
| 588 | HD145250 | 4530 | 2.28 | -0.33 | c |
| 589 | HD145976 | 6927 | 4.08 | -0.02 | b |
| 590 | HD146051 | 3779 | 1.46 | -0.15 | c |
| 591 | HD147379b | 3873 | 4.68 | 0.06 | c |
| 592 | HD146624 | 9125 | 3.99 | -0.27 | b |
| 593 | HD147923 | 4787 | 4.76 | -0.28 | c |
| 594 | BD-114126 | 4702 | 4.62 | 0.00 | b |
| 595 | HD148112 | 10052 | 3.51 | 0.47 | b |
| 596 | BD-090352 | 6131 | 4.04 | -1.88 | b |
| 597 | HD148513 | 4114 | 2.16 | 0.19 | c |
| 598 | BD-112998 | 5527 | 2.97 | -1.01 | b |
| 599 | HD148816 | 5828 | 4.05 | -0.79 | b |
| 600 | HD148897 | 4278 | 0.99 | -1.20 | c |
| 601 | HD150275 | 4622 | 2.40 | -0.70 | c |
| 602 | HD148786 | 5144 | 2.70 | 0.21 | b |
| MILES ID | Star | $T_{\text{eff}}$ | log $g$ | [Fe/H] | Reference |
|-----------|------|-----------------|--------|--------|-----------|
| (a)       | (b)  | (c)             | (d)    | (e)    | (f)       |
| 603       | HD149009 | 3862            | 1.20   | 0.09   | c         |
| 604       | HD148898 | 9141            | 3.85   | 0.38   | b         |
| 605       | HD149121 | 11099           | 3.89   | 0.03   | b         |
| 606       | HD149161 | 3915            | 1.64   | -0.26  | c         |
| 607       | BD+093223 | 5200          | 2.00   | -2.31  | b         |
| 608       | HD149382 | 35500           | 5.70   | -1.30  | b         |
| 609       | HD149661 | 5281            | 4.59   | 0.13   | b         |
| 610       | HD150012 | 6651            | 3.96   | 0.13   | b         |
| 611       | HD150177 | 6190            | 4.08   | -0.58  | b         |
| 612       | HD150281 | 5164            | 4.54   | 0.14   | b         |
| 613       | HD150453 | 6589            | 4.07   | -0.24  | b         |
| 614       | HD151203 | 3570            | 0.91   | 0.03   | c         |
| 615       | HD151217 | 3878            | 1.59   | 0.05   | c         |
| 616       | HD152601 | 4661            | 2.67   | 0.10   | c         |
| 617       | HD152781 | 4969            | 3.55   | 0.08   | b         |
| 618       | HD153286 | 7534            | 3.75   | 0.49   | b         |
| 619       | HD153882 | 9999            | 3.50   | 0.61   | b         |
| 620       | HD154733 | 4227            | 2.20   | -0.09  | c         |
| 621       | HD155763 | 12500           | 3.50   | -0.11  | b         |
| 622       | HD155358 | 5888            | 4.09   | -0.63  | b         |
| 623       | HD155078 | 6508            | 4.00   | 0.03   | b         |
| 625       | HD156026 | 4381            | 4.66   | -0.28  | c         |
| 626       | HD157373 | 6552            | 4.18   | -0.43  | b         |
| 627       | HD157214 | 5621            | 4.05   | -0.41  | b         |
| 628       | HD157089 | 5792            | 4.05   | -0.57  | b         |
| 629       | HD157910 | 5227            | 2.58   | -0.07  | b         |
| 630       | HD157881 | 4923            | 4.64   | -0.01  | c         |
| 631       | HD157856 | 6523            | 4.04   | -0.07  | b         |
| 632       | HD157919 | 6826            | 3.61   | 0.29   | b         |
| 633       | BD+233130 | 5017        | 2.31   | -2.45  | b         |
| 634       | HD159332 | 6298            | 4.01   | -0.10  | b         |
| 635       | HD159307 | 6395            | 4.19   | -0.54  | b         |
| 636       | HD159482 | 5740            | 4.11   | -0.75  | b         |
| 637       | HD160933 | 5770            | 3.79   | -0.31  | b         |
| 638       | HD160762 | 17678           | 3.69   | 0.02   | b         |
| 639       | HD160693 | 5691            | 4.07   | -0.56  | b         |
| 640       | HD161074 | 3949            | 1.86   | -0.14  | c         |
| 641       | HD161149 | 7015            | 3.70   | 0.33   | b         |
| 642       | HD161096 | 4497            | 2.49   | 0.20   | c         |
| 644       | HD161227 | 7320            | 3.72   | 0.38   | b         |
| 645       | HD161695 | 11506           | 2.23   | 0.11   | b         |
| 646       | HD161797 | 5454            | 3.82   | 0.22   | b         |
| 647       | HD161817 | 7636            | 2.93   | -0.95  | a         |
| 648       | HD162211 | 4486            | 2.45   | -0.06  | c         |
| 649       | BD+203603 | 6115         | 4.10   | -2.10  | b         |
| 650       | HD164058 | 3963            | 1.51   | 0.07   | c         |
| 651       | HD163990 | 3318            | 0.48   | -0.04  | c         |
| 652       | HD163993 | 5091            | 2.87   | 0.09   | b         |
| 653       | HD164136 | 7140            | 3.87   | 0.00   | b         |
| 654       | HD164349 | 4594            | 1.74   | -0.01  | c         |
| 655       | HD164353 | 15600           | 2.55   | -0.03  | b         |
| 656       | HD164432 | 21371           | 3.81   | -0.02  | b         |
| 657       | HD165195 | 4391            | 0.75   | -2.32  | c         |
| 658       | HD164975 | 5863            | 1.22   | 0.06   | b         |
| 659       | HD165341 | 5349            | 4.58   | 0.16   | b         |
| 660       | HD165438 | 4868            | 3.43   | 0.02   | b         |
| 661       | HD165908 | 6045            | 4.19   | -0.50  | b         |
| 662       | HD166208 | 5107            | 2.73   | 0.15   | b         |
Table A1: continued.

| MILES ID | Star | T$_{\text{eff}}$ (c) | log g (d) | [Fe/H] (e) | Reference (f) |
|----------|------|----------------------|-----------|-----------|--------------|
| 663      | HD165634 | 4907                 | 2.31      | -0.14     | b            |
| 664      | HD166620 | 4968                 | 4.55      | -0.18     | b            |
| 665      | HD166161 | 5201                 | 2.33      | -1.25     | b            |
| 666      | HD166285 | 6398                 | 4.10      | -0.06     | b            |
| 667      | HD166460 | 4478                 | 2.19      | -0.05     | c            |
| 668      | HD167105 | 9000                 | 2.36      | -1.50     | b            |
| 669      | HD167006 | 3597                 | 1.12      | -0.16     | c            |
| 670      | HD167768 | 4953                 | 2.29      | -0.69     | b            |
| 671      | HD169027 | 11030                | 3.89      | -0.08     | b            |
| 672      | HD168322 | 4745                 | 2.33      | -0.51     | c            |
| 673      | HD167665 | 6125                 | 4.15      | -0.16     | b            |
| 674      | HD168720 | 3788                 | 1.45      | -0.08     | c            |
| 675      | HD168723 | 4923                 | 3.0       | -0.22     | b            |
| 676      | HD168608 | 5580                 | 1.00      | 0.03      | b            |
| 677      | HD170693 | 4396                 | 2.1       | -0.49     | c            |
| 679      | HD170737 | 5993                 | 3.36      | -0.77     | b            |
| 681      | HD171391 | 5150                 | 2.89      | 0.04      | b            |
| 682      | HD171443 | 4220                 | 2.04      | -0.10     | c            |
| 683      | HD171496 | 4933                 | 2.29      | -0.73     | c            |
| 684      | HD171999 | 5276                 | 4.35      | 0.27      | b            |
| 685      | HD172380 | 3364                 | 0.42      | -0.06     | c            |
| 686      | HD172103 | 6815                 | 4.01      | 0.03      | b            |
| 687      | HD172365 | 5886                 | 1.28      | 0.05      | b            |
| 688      | HD172958 | 11464                | 3.97      | 0.02      | b            |
| 689      | HD173524 | 11323                | 3.93      | 0.10      | b            |
| 690      | HD173740 | 3311                 | 5.01      | -0.34     | c            |
| 691      | HD172816 | 3318                 | 0.72      | -0.14     | c            |
| 692      | HD173993 | 6373                 | 4.11      | 0.00      | b            |
| 693      | HD173648 | 7914                 | 3.70      | 0.38      | b            |
| 694      | HD173650 | 11832                | 3.71      | 0.64      | b            |
| 695      | HD173667 | 6458                 | 4.04      | 0.01      | b            |
| 696      | HD175305 | 5036                 | 2.51      | -1.44     | b            |
| 697      | HD173819 | 4392                 | -0.25     | -0.67     | c            |
| 698      | HD174567 | 10256                | 3.95      | -0.07     | b            |
| 699      | HD174912 | 5936                 | 4.34      | -0.45     | b            |
| 700      | HD175225 | 5286                 | 3.70      | 0.20      | b            |
| 701      | HD174959 | 14681                | 4.00      | -0.80     | a            |
| 702      | HD174704 | 7193                 | 3.63      | 0.79      | b            |
| 703      | HD175535 | 5197                 | 2.85      | -0.07     | b            |
| 704      | HD175588 | 3484                 | 0.47      | -0.14     | c            |
| 705      | HD175865 | 3316                 | 0.36      | 0.06      | c            |
| 706      | HD175640 | 12077                | 3.94      | 0.17      | b            |
| 707      | HD178089 | 6722                 | 4.07      | -0.09     | b            |
| 708      | HD175892 | 8705                 | 4.11      | -0.29     | b            |
| 709      | HD176301 | 12667                | 4.18      | 0.18      | b            |
| 710      | HD176232 | 8743                 | 4.47      | 0.53      | b            |
| 711      | HD176437 | 11226                | 4.11      | 0.09      | b            |
| 712      | HD177463 | 4611                 | 2.30      | -0.23     | c            |
| 713      | HD180711 | 4837                 | 2.49      | -0.18     | b            |
| 714      | HD179761 | 12746                | 4.22      | 0.30      | b            |
| 715      | HD180163 | 18663                | 3.69      | 0.04      | b            |
| 716      | HD181096 | 6347                 | 4.03      | -0.17     | b            |
| 717      | HD180928 | 4024                 | 1.79      | -0.66     | c            |
| 718      | HD181470 | 9802                 | 3.91      | -0.13     | b            |
| 719      | HD182293 | 4437                 | 2.74      | -0.03     | c            |
| 721      | HD182572 | 5473                 | 3.91      | 0.34      | b            |
| 722      | HD183324 | 10325                | 4.17      | -1.24     | b            |
| 723      | CD-2415398 | 6269                | 2.93      | -1.17     | b            |
Table A1: continued.

| MILES ID | Star     | $T_{\text{eff}}$ | log $g$ | [Fe/H] | Reference |
|----------|----------|------------------|--------|--------|-----------|
| (a)      | (b)      | (c)              | (d)    | (e)    | (f)       |
| 724      | HD185144 | 5263             | 4.56   | -0.12  | b         |
| 725      | HD338389 | 6178             | 3.95   | -2.09  | b         |
| 726      | HD184499 | 5743             | 4.07   | -0.54  | b         |
| 727      | HD184786 | 3454             | 0.35   | 0.03   | c         |
| 728      | HD184406 | 4428             | 2.71   | 0.03   | c         |
| 729      | HD185351 | 5045             | 3.27   | 0.08   | b         |
| 730      | HD185657 | 4813             | 2.51   | -0.19  | c         |
| 732      | HD185859 | 26200            | 3.05   | -0.09  | b         |
| 733      | HD186408 | 5731             | 4.15   | 0.08   | b         |
| 734      | HD186427 | 5648             | 4.18   | 0.03   | b         |
| 735      | HD188119 | 4904             | 2.34   | -0.49  | b         |
| 737      | HD187879 | 21004            | 3.14   | 0.05   | b         |
| 738      | HD187691 | 6099             | 4.12   | 0.14   | b         |
| 739      | HD187921 | 5502             | 0.68   | 0.10   | b         |
| 741      | HD188650 | 5764             | 2.90   | -0.40  | a         |
| 742      | HD188510 | 5539             | 4.28   | -1.43  | b         |
| 743      | HD188512 | 5082             | 3.48   | -0.22  | b         |
| 745      | HD188947 | 4828             | 2.62   | 0.06   | b         |
| 746      | HD189005 | 5080             | 2.32   | -0.26  | b         |
| 747      | HD189558 | 5770             | 3.92   | -1.04  | b         |
| 748      | HD189849 | 7804             | 3.89   | -0.01  | b         |
| 749      | HD190360 | 5468             | 4.11   | 0.21   | b         |
| 750      | HD190404 | 5008             | 4.51   | -0.58  | b         |
| 752      | HD190178 | 6263             | 4.05   | -0.66  | b         |
| 753      | HD190390 | 6440             | 1.55   | -1.05  | a         |
| 754      | HD191026 | 5177             | 3.81   | 0.08   | b         |
| 755      | HD191046 | 4438             | 1.67   | -0.75  | c         |
| 756      | HD192907 | 10444            | 3.97   | -0.18  | b         |
| 757      | HD345957 | 5988             | 4.06   | -1.20  | b         |
| 759      | HD192640 | 8774             | 4.42   | -0.80  | b         |
| 760      | HD192909 | 3942             | 0.91   | -0.02  | c         |
| 761      | HD193281 | 8597             | 4.11   | -0.37  | b         |
| 762      | HD194508 | 6090             | 4.24   | -1.04  | b         |
| 763      | HD194943 | 6971             | 4.04   | -0.01  | b         |
| 764      | HD196502 | 9417             | 3.58   | 0.74   | b         |
| 765      | HD195633 | 6119             | 4.09   | -0.52  | b         |
| 766      | HD195838 | 6152             | 4.08   | 0.00   | b         |
| 767      | HD196544 | 8678             | 3.80   | -0.12  | b         |
| 768      | HD196755 | 5582             | 3.64   | -0.02  | b         |
| 769      | HD197177 | 4964             | 1.92   | -0.03  | b         |
| 770      | HD197572 | 5188             | 0.83   | 0.15   | b         |
| 771      | HD197461 | 7334             | 4.02   | -0.07  | b         |
| 772      | HD198149 | 4970             | 3.29   | -0.19  | b         |
| 773      | HD197989 | 4728             | 2.44   | -0.20  | c         |
| 775      | HD198183 | 15630            | 3.81   | 0.05   | b         |
| 776      | HD198001 | 9266             | 4.00   | -0.32  | b         |
| 777      | BD+044551| 6089             | 4.21   | -1.26  | b         |
| 778      | HD198478 | 16500            | 2.17   | -0.21  | b         |
| 779      | HD199191 | 4696             | 2.53   | -0.70  | c         |
| 781      | HD199799 | 3387             | 0.12   | -0.25  | c         |
| 782      | HD200527 | 3503             | 0.20   | -0.07  | c         |
| 783      | HD200580 | 6003             | 4.34   | -0.50  | b         |
| 784      | HD200905 | 3977             | 0.79   | 0.10   | c         |
| 785      | HD200779 | 4225             | 4.59   | 0.02   | c         |
| 786      | HD200790 | 6115             | 3.98   | 0.04   | b         |
| 787      | HD201078 | 6151             | 1.85   | 0.09   | b         |
| 788      | HD201091 | 4162             | 4.64   | -0.31  | c         |
| 789      | HD201601 | 7657             | 3.92   | 0.07   | a         |
| MILES ID (a) | Star ID | T\textsubscript{eff} (b) | log g (c) | [Fe/H] (d) | Reference (f) |
|-------------|---------|----------------|--------|--------|-------------|
| 790 HD201891 | 5881    | 4.18 | -1.05 | b |
| 791 HD201889 | 5762    | 4.13 | -0.74 | b |
| 792 HD202109 | 4925    | 3.39 | -0.23 | b |
| 793 HD202447 | 6277    | 4.01 | 0.26  | b |
| 794 HD202671 | 14353   | 3.25 | 0.36  | b |
| 795 HD203638 | 4553    | 2.48 | 0.12  | c |
| 796 HD204041 | 8737    | 4.45 | -0.44 | b |
| 798 HD204155 | 5718    | 3.93 | -0.69 | b |
| 799 HD204613 | 5718    | 3.88 | -0.38 | b |
| 800 HD205021 | 25500   | 3.70 | -0.10 | b |
| 801 HD204381 | 5081    | 2.76 | -0.09 | b |
| 802 HD204754 | 12610   | 4.20 | 0.30  | b |
| 803 HD204543 | 4590    | 1.17 | -1.97 | c |
| 804 HD204587 | 4111    | 4.61 | -0.11 | c |
| 805 HD205435 | 5069    | 2.86 | -0.12 | b |
| 806 HD205153 | 6005    | 4.02 | 0.07  | b |
| 807 HD205512 | 4703    | 2.57 | 0.03  | c |
| 808 HD206078 | 4741    | 2.54 | -0.59 | c |
| 809 HD206165 | 19300   | 2.65 | -0.27 | b |
| 810 HD206952 | 4643    | 2.61 | 0.15  | c |
| 811 HD206453 | 5026    | 2.34 | -0.41 | b |
| 812 HD207130 | 4741    | 2.65 | 0.08  | c |
| 813 HD206826 | 6490    | 4.09 | -0.11 | b |
| 816 HD207076 | 3022    | 0.74 | -0.12 | c |
| 817 HD207330 | 20815   | 3.69 | 0.04  | b |
| 818 HD207222 | 9230    | 4.01 | -0.36 | b |
| 821 HD208906 | 6048    | 4.27 | -0.68 | b |
| 822 HD209369 | 6632    | 4.06 | -0.04 | b |
| 823 HD209459 | 11015   | 3.99 | -0.07 | b |
| 824 HD209975 | 32983   | 3.40 | 0.06  | b |
| 825 HD210295 | 4864    | 2.30 | -1.26 | c |
| 826 HD210424 | 12771   | 4.21 | 0.22  | b |
| 827 HD210745 | 4286    | 0.65 | 0.11  | c |
| 828 HD210595 | 6639    | 4.11 | -0.47 | b |
| 829 HD210705 | 6939    | 4.16 | -0.18 | b |
| 830 HD211075 | 4318    | 1.84 | -0.42 | c |
| 831 HD212454 | 14466   | 3.33 | 0.35  | b |
| 832 HD212943 | 4634    | 2.62 | -0.31 | c |
| 833 HD213119 | 3914    | 1.42 | -0.14 | c |
| 835 HD213042 | 4505    | 4.49 | 0.12  | c |
| 837 HD214080 | 23445   | 3.28 | 0.04  | b |
| 839 HD214567 | 4997    | 2.62 | -0.23 | b |
| 840 HD214714 | 5224    | 2.03 | -0.67 | b |
| 841 HD214994 | 9373    | 3.73 | -0.14 | b |
| 843 HD215648 | 6243    | 4.03 | -0.21 | b |
| 844 HD216228 | 4745    | 2.49 | -0.03 | c |
| 845 HD216174 | 4371    | 1.82 | -0.61 | c |
| 846 HD216131 | 4999    | 2.70 | -0.07 | b |
| 847 HD216143 | 4638    | 1.38 | -2.09 | c |
| 848 HD216219 | 5637    | 3.10 | -0.36 | b |
| 849 HD216385 | 6323    | 4.06 | -0.15 | b |
| 850 HD217382 | 4105    | 1.96 | 0.09  | c |
| 851 HD216640 | 4612    | 3.11 | 0.17  | c |
| 852 HD216831 | 13207   | 3.05 | 0.05  | b |
| 854 HD217014 | 5674    | 4.14 | 0.18  | b |
| 855 HD217107 | 5523    | 4.11 | 0.33  | b |
| 856 HD217754 | 7089    | 3.80 | 0.27  | b |
| 857 HD218031 | 4713    | 2.42 | -0.17 | c |
| MILES ID | Star       | T\textsubscript{eff} (b) | log g (c) | [Fe/H] (d) | Reference (l) |
|---------|------------|---------------------------|-----------|-----------|---------------|
| 858     | HD218235   | 6463                      | 4.06      | 0.23      | b             |
| 859     | HD218329   | 3796                      | 1.46      | 0.19      | c             |
| 860     | HD218502   | 6167                      | 4.11      | -1.75     | b             |
| 861     | HD218640   | 5799                      | 3.26      | 0.36      | b             |
| 862     | HD218804   | 6493                      | 4.17      | -0.13     | b             |
| 863     | HD218857   | 5057                      | 2.43      | -1.93     | b             |
| 864     | HD219134   | 4759                      | 4.63      | 0.04      | c             |
| 866     | BD+384955  | 5270                      | 3.50      | -2.23     | b             |
| 867     | HD219449   | 4666                      | 2.52      | 0.00      | c             |
| 868     | HD219623   | 6138                      | 4.24      | 0.07      | b             |
| 869     | HD219617   | 5941                      | 4.12      | -1.36     | b             |
| 870     | HD219615   | 4890                      | 2.42      | -0.57     | b             |
| 871     | HD219734   | 3665                      | 0.99      | -0.04     | c             |
| 872     | HD219916   | 5070                      | 2.84      | -0.04     | b             |
| 874     | HD220009   | 4296                      | 1.90      | -0.80     | c             |
| 875     | HD220575   | 12241                     | 4.09      | 0.27      | b             |
| 876     | BD+592723  | 5987                      | 3.98      | -1.89     | b             |
| 877     | HD220825   | 10228                     | 3.71      | 0.78      | b             |
| 878     | HD220933   | 10515                     | 3.72      | -0.06     | b             |
| 879     | HD220954   | 4784                      | 2.61      | 0.06      | c             |
| 880     | HD221170   | 4608                      | 1.29      | -2.05     | c             |
| 881     | HD221148   | 4588                      | 3.19      | 0.34      | c             |
| 882     | HD221345   | 4662                      | 2.33      | -0.34     | c             |
| 883     | HD221377   | 6553                      | 4.20      | -0.60     | b             |
| 885     | HD221756   | 8833                      | 4.21      | -0.64     | b             |
| 886     | HD221830   | 5719                      | 4.09      | -0.40     | b             |
| 887     | HD222404   | 4758                      | 3.16      | 0.10      | c             |
| 888     | HD222368   | 6231                      | 4.14      | -0.08     | b             |
| 889     | HD222451   | 6698                      | 4.07      | 0.10      | b             |
| 891     | HD223047   | 5002                      | 1.26      | 0.04      | b             |
| 893     | HD223524   | 4560                      | 2.41      | 0.02      | c             |
| 894     | HD223640   | 12429                     | 3.93      | 0.73      | b             |
| 895     | HD224458   | 4809                      | 2.27      | -0.44     | c             |
| 896     | BD+612575  | 6222                      | 1.97      | 0.35      | a             |
| 897     | NGC288-77  | 4238                      | 1.12      | -1.32     | c             |
| 898     | HD020902   | 6690                      | 1.31      | -0.05     | b             |
| 899     | Mel22\_0296 | 5196                 | 4.25      | -0.03     | b             |
| 900     | Mel22\_2462 | 5219                 | 4.47      | -0.03     | b             |
| 901     | HD025825   | 6005                      | 4.38      | 0.13      | b             |
| 902     | HD026736   | 5772                      | 4.39      | 0.13      | b             |
| 903     | HD028453   | 5283                      | 4.47      | 0.13      | b             |
| 904     | HD027383   | 6091                      | 4.34      | 0.13      | b             |
| 905     | HD027524   | 6580                      | 4.14      | 0.13      | b             |
| 906     | HD027561   | 6682                      | 4.14      | 0.13      | b             |
| 907     | HD027962   | 8809                      | 3.80      | 0.13      | b             |
| 908     | HD028483   | 6455                      | 4.25      | 0.13      | b             |
| 909     | HD028546   | 7490                      | 3.85      | 0.13      | b             |
| 910     | HD029375   | 7240                      | 3.93      | 0.13      | b             |
| 911     | HD030034   | 7446                      | 3.91      | 0.13      | b             |
| 912     | HD030210   | 7694                      | 3.66      | 0.13      | b             |
| 913     | HD030676   | 6104                      | 4.37      | 0.13      | b             |
| 914     | HD031236   | 7262                      | 3.93      | 0.13      | b             |
| 917     | Mel22\_247 | 2170                     | 0.68      | -1.60     | c             |
| 918     | NGC2420-140 | 4421                | 1.90      | -0.31     | c             |
| 919     | Mel22\_F-108 | 4235                | 2.21      | 0.00      | c             |
| 920     | HD107276   | 7969                      | 3.99      | -0.05     | b             |
| 921     | HD107513   | 7360                      | 3.99      | -0.05     | b             |
| 922     | HD109307   | 8162                      | 3.91      | -0.05     | b             |
Table A1: continued.

| MILES ID (a) | Star (b) | $T_{\text{eff}}$ (c) | log g (d) | [Fe/H] (e) | Reference (f) |
|--------------|----------|----------------------|---------|----------|--------------|
| 923          | M3_II-25 | 4442                 | 1.02    | -1.50    | c            |
| 924          | M3_II-28 | 4306                 | 0.74    | -1.50    | c            |
| 925          | M3_III-80| 4580                 | 1.15    | -1.50    | c            |
| 926          | M5_III-83| 4174                 | 0.51    | -1.29    | c            |
| 928          | M5_II-76 | 5974                 | 2.44    | -1.11    | a            |
| 930          | M5_II-19 | 4251                 | 0.90    | -1.29    | c            |
| 933          | M4_LEE-2303| 6748                | 2.51    | -1.19    | a            |
| 934          | M13_A-171| 4266                 | 1.35    | -0.80    | c            |
| 935          | M13_B-786| 4114                 | 0.43    | -1.53    | c            |
| 936          | M92_II-114| 4726               | 1.44    | -2.31    | c            |
| 937          | M92_II-13 | 4226                | 0.38    | -2.31    | c            |
| 938          | HD170764 | 5802                 | 0.99    | 0.17     | b            |
| 939          | HD170820 | 4499                 | 1.44    | 0.03     | c            |
| 940          | NGC6791-R4| 3382               | 0.20    | 0.42     | c            |
| 941          | NGC6791-R5| 3193               | 1.12    | 0.42     | c            |
| 942          | NGC6791-R16| 3890              | 1.81    | 0.42     | c            |
| 943          | NGC6791-R19| 3904              | 1.95    | 0.42     | c            |
| 944          | M71_A9    | 4404                 | 1.41    | -0.78    | c            |
| 945          | M71_I-109 | 4759                 | 2.33    | -0.78    | c            |
| 946          | M71_I-95  | 4570                 | 1.63    | -0.78    | c            |
| 947          | M71_I-107 | 4848                 | 2.07    | -0.84    | b            |
| 948          | M71_I-75  | 4809                 | 2.52    | -0.78    | c            |
| 949          | M71_I-73  | 4800                 | 2.22    | -0.78    | c            |
| 951          | M71_I-71  | 4397                 | 1.80    | -0.78    | c            |
| 952          | M71_KC-263| 4883                 | 2.61    | -0.84    | a            |
| 953          | M71_I-87  | 4988                 | 2.19    | -0.84    | b            |
| 954          | M71_I-66  | 4250                 | 1.65    | -0.78    | c            |
| 955          | M71_I-65  | 4664                 | 1.98    | -0.78    | c            |
| 956          | M71_I-64  | 4504                 | 1.64    | -0.78    | c            |
| 958          | M71_I-21  | 4486                 | 1.40    | -0.78    | c            |
| 959          | M71_I-37  | 4576                 | 2.12    | -0.78    | c            |
| 960          | M71_I-41  | 5020                 | 2.26    | -0.84    | b            |
| 962          | M71_I-39  | 5020                 | 2.26    | -0.84    | b            |
| 964          | M71_I-53  | 4167                 | 1.51    | -0.84    | a            |
| 965          | M71_KC-169| 5083                 | 2.22    | -0.84    | b            |
| 966          | M71_A2    | 4679                 | 2.21    | -0.84    | b            |
| 968          | M71_I-78  | 3955                 | 1.48    | -0.78    | c            |
| 969          | M71_S     | 4244                 | 1.28    | -0.78    | c            |
| 971          | M71_I     | 4222                 | 1.43    | -0.78    | c            |
| 972          | NGC7789-329(491)| 4527         | 2.14    | -0.13    | a            |
| 973          | NGC7789-468(589)| 4167         | 1.75    | 0.01     | c            |
| 974          | NGC7789-342(502)| 10968       | 3.85    | -0.13    | b            |
| 975          | NGC7789-353(509)| 4538        | 2.30    | 0.01     | c            |
| 976          | NGC7789-415(550)| 3815        | 1.16    | 0.01     | c            |
| 977          | NGC7789-461(583)| 4123        | 1.75    | 0.01     | c            |
| 978          | NGC7789-501(614)| 4057        | 1.69    | 0.01     | c            |
| 979          | NGC7789-575(671)| 4547        | 2.18    | 0.01     | c            |
| 980          | NGC7789-637(723)| 4857        | 2.54    | 0.01     | c            |
| 981          | NGC7789-756(804)| 4397        | 2.07    | 0.01     | c            |
| 982          | NGC7789-859(853)| 4666        | 2.53    | 0.01     | c            |
| 983          | NGC7789-875(873)| 4861        | 2.56    | -0.13    | b            |
| 984          | NGC7789-897(881)| 4918        | 2.50    | -0.13    | b            |
| 985          | NGC7789-971(946)| 3746        | 1.22    | 0.01     | c            |
Table A2: MILES stars which were not used in the stellar population models. Column (f) gives the reference for the source of the stellar atmospheric parameters: a Cenarro et al. (2007); b Prugniel et al. (2011); c Sharma et al. (2016); d Same as a but [Fe/H] is unknown, assumed to be solar. Column (g) gives the code identifying the reason(s) why each star was discarded (see discussion in Section 2 of paper): 1 Excessive noise or corrupted spectrum; 2 Visible continuum distortions; 3 Visible emission lines; 4 Peculiar features; 5 $E(B-V) > 0.3$ from Prugniel et al. (2011); 6 Removed by the cut in $\chi^2$; 7 Removed by the cut in $\Delta$.

| MILES ID (a) | Star (b) | $T_{\text{eff}}$ (c) | log g (d) | [Fe/H] (e) | Reference (f) | Removed by (g) |
|-------------|---------|----------------|--------|------|-------------|-------------|
| 29          | HD004395 | 5444           | 3.43   | -0.27 | b           | 1, 6        |
| 44          | HD006474 | 6781           | 0.49   | 0.26  | b           | 6, 7        |
| 45          | HD006497 | 4401           | 2.55   | 0.00  | c           | 1, 6        |
| 62          | HD009408 | 4814           | 2.46   | -0.31 | b           | 1          |
| 64          | HD009919 | 6860           | 4.00   | -0.35 | b           | 1          |
| 68          | BD+720094| 6131           | 4.09   | -1.68 | b           | 7          |
| 74          | HD012014 | 4371           | 0.66   | 0.04  | b           | 1, 7        |
| 87          | HD015596 | 4811           | 2.75   | -0.71 | c           | 7          |
| 104         | HD018391 | 5750           | 1.20   | -0.13 | b           | 5, 6, 7     |
| 107         | HD019510 | 6108           | 3.91   | -2.13 | b           | 6          |
| 140         | HD281679 | 8542           | 2.50   | -1.43 | a           | 6          |
| 142         | BD+060648| 4645           | 1.38   | -1.94 | c           | 6, 7        |
| 181         | HD035620 | 4184           | 2.00   | 0.10  | c           | 7          |
| 204         | HD041117 | 20000          | 2.40   | -0.12 | b           | 3          |
| 210         | HD042474 | 3719           | 0.62   | -0.13 | c           | 3          |
| 212         | HD043042 | 6480           | 4.18   | 0.06  | b           | 2          |
| 220         | HD044889 | 4006           | 1.51   | -0.32 | c           | 7          |
| 221         | HD044691A| 7777           | 3.88   | 0.27  | b           | 7          |
| 246         | HD055496 | 4858           | 2.05   | -1.48 | b           | 4          |
| 251         | HD057060 | 33215          | 3.28   | -0.03 | b           | 3          |
| 252         | HD057061 | 34303          | 3.46   | 0.10  | b           | 6          |
| 256         | HD059612 | 8409           | 1.56   | -0.05 | b           | 1          |
| 330         | HD076813 | 5065           | 2.63   | -0.06 | b           | 6, 7        |
| 347         | HD081797 | 4171           | 1.65   | 0.01  | c           | 2, 7        |
| 365         | HD237846 | 4675           | 1.20   | -3.15 | b           | 6, 7        |
| 376         | HD088609 | 4417           | 0.91   | -2.82 | c           | 1, 7        |
| 459         | HD113285 | 2902           | 0.21   | -0.33 | c           | 6, 7        |
| 477         | HD118055 | 4391           | 0.78   | -1.86 | c           | 2          |
| 478         | HD118100 | 4277           | 4.48   | -0.14 | c           | 3          |
| 501         | HD124897 | 4245           | 1.94   | -0.70 | c           | 2          |
| 508         | HD126327 | 2908           | 0.37   | -0.33 | c           | 6, 7        |
| 624         | HD156283 | 4206           | 1.58   | 0.02  | c           | 7          |
| 643         | HD161796 | 7000           | 0.44   | -0.30 | b           | 6, 7        |
| 678         | HD169985 | 6249           | 3.84   | 0.36  | b           | 6, 7        |
| 680         | HD234677 | 4184           | 4.33   | -0.01 | c           | 3          |
| 720         | HD187216 | 3950           | 0.75   | -1.70 | b           | 4          |
| 731         | HD232078 | 3965           | 0.64   | -1.63 | c           | 4          |
| 736         | HD187111 | 4473           | 1.13   | -1.71 | c           | 7          |
| 740         | HD188041 | 9506           | 3.91   | 1.00  | b           | 1          |
| 744         | HD188727 | 5685           | 1.60   | 0.00  | a           | 4          |
| 751         | HD190603 | 19500          | 2.36   | 0.07  | b           | 3          |
| 758         | HD192577 | 4126           | 1.05   | -0.07 | c           | 6          |
| 774         | HD197964 | 4762           | 2.93   | 0.15  | b           | 7          |
| 780         | HD199478 | 11200          | 1.90   | 0.00  | d           | 3, 6        |
| 797         | HD204075 | 5397           | 1.48   | -0.14 | b           | 7          |
| 814         | HD206778 | 4196           | 0.67   | 0.04  | c           | 7          |
| 815         | HD207260 | 9911           | 1.57   | 0.27  | b           | 5, 6, 7     |
| 819         | HD207673 | 10482          | 1.87   | 0.16  | b           | 5, 6, 7     |
| 820         | HD208501 | 16477          | 2.80   | 0.05  | b           | 6, 7        |
Table A2: continued.

| MILES ID | Star   | $T_{\text{eff}}$ | log g | [Fe/H] | Reference | Removed by |
|----------|--------|------------------|-------|--------|-----------|------------|
|          |        | (c)              | (d)   | (e)    |           |            |
|          |        | (a)              |        | (f)    | (g)       |            |
| 834      | HD213307 | 7800             | 2.00  | 0.20   | b         | 6, 7       |
| 836      | HD213470 | 8943             | 1.36  | 0.11   | b         | 5, 6, 7    |
| 838      | G156-031  | 2805             | 5.13  | -0.04  | c         | 3          |
| 842      | BD+394926 | 7261             | 0.85  | -2.52  | a         | 7          |
| 853      | HD216916  | 21500            | 3.75  | -0.12  | b         | 1, 6       |
| 865      | HD219116  | 4790             | 1.79  | -0.79  | b         | 7          |
| 873      | HD219978  | 3910             | 0.19  | 0.18   | c         | 5          |
| 884      | BD+195116B | 3259            | 4.82  | -0.26  | c         | 3          |
| 890      | G171-010   | 2894             | 5.04  | 0.09   | c         | 3          |
| 892      | HD223385   | 10023            | 1.59  | 0.29   | b         | 3          |
| 915      | M79,153    | 4269             | 0.77  | -1.60  | c         | 1          |
| 916      | M79,160    | 4264             | 0.67  | -1.60  | c         | 1, 7       |
| 927      | M5 II-51   | 5718             | 1.98  | -1.29  | c         | 6, 7       |
| 929      | M5 II-53   | 9441             | 2.43  | -1.11  | a         | 1, 6       |
| 931      | M5 IV-86   | 5576             | 2.44  | -1.11  | a         | 1, 6       |
| 932      | M5 IV-87   | 5965             | 3.80  | -1.11  | b         | 1, 6       |
| 950      | M71 KC-147 | 4819             | 2.57  | -0.84  | b         | 1, 7       |
| 957      | M71 I-63   | 4706             | 1.62  | -0.78  | c         | 6, 7       |
| 961      | M71 I-99   | 4784             | 2.01  | -0.78  | c         | 6, 7       |
| 963      | M71 I-34   | 5114             | 2.35  | -0.84  | b         | 1, 7       |
| 967      | M71 I-77   | 4261             | 1.87  | -0.22  | c         | 7          |
| 970      | M71 X      | 3980             | 1.43  | -0.84  | b         | 1          |