A library of high-resolution Kurucz spectra in the range $\lambda\lambda 3000$–10 000

T. Murphy*† and A. Meiksin
Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ

Accepted 2004 March 31. Received 2004 March 31; in original form 2003 June 16

ABSTRACT
We present a library of 6410 synthetic spectra with resolution $\lambda/\Delta\lambda = 250 000$ based on the revised Kurucz 1993 model atmospheres. The library covers the wavelength range $\lambda\lambda 3000$–10 000 with 54 values of effective temperature in the range 5250–50 000 K, 11 values of log surface gravity between 0.0 and 5.0 and 19 metallicities in the range $-5.0$ to 1.0. We find that, with a few caveats, the library compares well with both the original 2 200 Kurucz spectra and also with observed spectra. The library is intended for use in population synthesis and physical parametrization of stellar spectra. We assess the suitability of the library for these tasks.

Key words: stars: atmospheres.

1 INTRODUCTION
Progress in population synthesis and automatic classification of stellar spectra has been limited by the spectral resolution of the available synthetic stellar spectra. The existing synthetic libraries are not at high enough resolution to be useful for classifying stars from recent surveys such as the SDSS (Stoughton et al. 2002) ($\lambda/\Delta\lambda \sim 1800$), or future surveys such as RAVE (Steinmetz 2002) and GAIA (Lindgren & Perryman 1996). Most classification techniques smooth the observed spectra to the resolution of the synthetic spectra. This means much of the detailed information in the observed spectra is lost, which may reduce the quality of the classifications. Population synthesis packages such as PEGASE (Fioc & Rocca-Volmerange 1997) or GISSEL (Bruzual & Charlot 1993) use a grid of stellar spectra to generate galaxy spectra. The resulting galaxy spectra are limited by the resolution of the input stellar spectra. To study the high-resolution features, it is necessary to have a grid of observed or synthetic stellar spectra which match the resolution of the observed galaxy spectra. For example, galaxy spectra synthesised from $\lambda 20$ spectra cannot be used to measure standard line indices like the Lick indices.

Perhaps the most widely used library of synthetic spectra are the flux distributions from the Kurucz ATLAS model atmospheres (Kurucz 1993a). It is important to note that while these are usually referred to as spectra, they are flux distributions predicted directly from the model atmospheres, rather than spectra generated by a spectral synthesis program. The Kurucz atmospheres have several disadvantages, which are discussed in various sources – such as Kurucz (1992). However, one of their advantages is the wide range of parameters they cover, which is important for generating a grid of stellar spectra for population synthesis. The need for higher-resolution spectra has been recognized for some time but, because of the immense computational expense involved, the synthesis of the spectra has been limited to partial wavelength ranges and specific regions of parameter space. Several groups have generated libraries of spectra from the Kurucz model atmospheres. For example, Chavez, Malagnini & Morossi (1997) provide a set of 711 Kurucz spectra at $\lambda/\Delta\lambda = 250 000$ in the wavelength region $\lambda\lambda 4850$–5400 and Castelli & Munari (2001) have generated a set of 698 Kurucz spectra at $\lambda/\Delta\lambda = 20 000$, in the wavelength region $\lambda\lambda 7650$–8750 for use with GAIA spectra. González Delgado & Leitherer (1999) have generated synthetic spectra in very small spectra regions necessary for a particular application. They created a grid of synthetic profiles of stellar H Balmer and He i lines at $\Delta\lambda = 0.3$ Å for the purposes of evolutionary synthesis.

There are also several libraries of observed spectra now available at much higher resolution. For example, the ELODIE data base (Prugniel & Soubiran 2001), consists of 709 stars observed in the wavelength range $\lambda\lambda 4100$–6800 with a resolution of $\lambda/\Delta\lambda \sim 42 000$. STELIB (Le Borgne et al. 2003) provides spectra for 249 stars observed in the wavelength range $\lambda\lambda 3200$–9500 with a resolution of $\lambda/\Delta\lambda \sim 2000$. The observed libraries are crucial for evaluating the accuracy of synthetic spectra and can also be used directly for population synthesis and classification. STELIB has been used by Kauffmann et al. (2003) with a new version of GISSEL, and ELODIE has been used to assign physical parameters to stars observed by the SDSS. However, a limitation of the observed spectral libraries is that they do not cover the full range in parameter space needed for galaxy population synthesis. Complete coverage of the parameter space is even more important for stellar spectral classification. The most successful approaches to classification have used methods from machine learning (Bailer-Jones 2001). In these methods, the distribution of spectra in the training set has a direct impact on the accuracy of the classification assigned to new spectra.

There are several efforts currently in progress to generate higher-resolution Kurucz spectra. Bertone et al. (2002) have generated a grid of 832 spectra at $\lambda/\Delta\lambda = 500 000$ over the wavelength range $\lambda\lambda 3000$–10 000, with 54 values of effective temperature in the range 5250–50 000 K, 11 values of log surface gravity between 0.0 and 5.0 and 19 values of metallicity. Bertone et al. (2002) have also used the grid of 6410 spectra presented in this paper.
\( \lambda \lambda 3500–7000. \) They intend to extend the wavelength range down to \( \lambda 850 \) at a resolution of \( \lambda / \Delta \lambda = 50,000. \) Zwitter, Castelli & Munari (2002) are in the process of generating a grid of Kurucz spectra at \( \lambda / \Delta \lambda = 20,000 \) over the wavelength range \( \lambda \lambda 2500–10 \) for use in radial velocity correction work.

We have generated a larger library of 6410 spectra from the Kurucz model atmospheres. Previously these spectra were only available either at much lower resolution (\( \lambda 20 \)) or over small wavelength ranges. Our spectra were generated from \textsc{atlas} model atmospheres, using John Lester’s Unix version of the \textsc{synth} spectral synthesis package (Lester, private communication). We have modified this package to improve the efficiency of the code, making it possible to generate the complete range of Kurucz spectra in a reasonable time.

This paper compares our higher-resolution spectra with the original \( \lambda 20 \) Kurucz spectra and the \textsc{stelib} library of observed spectra. In Section 2 we describe the main characteristics of the new library of spectra. In Section 3 we compare the spectra with the \( \lambda 20 \) Kurucz spectra from Kurucz (1993a). Finally, in Section 4 we compare the spectra with observed spectra from the \textsc{stelib} library. We will make this library of spectra available for general use on request.

2 GENERATING THE KURUCZ SPECTRA

The library presented here has been created using the updated versions of the \textsc{atlas} model atmospheres from Kurucz (1993a). These are available from Kurucz’s website (labelled `.dat”). Kurucz advises that the Kurucz (1993a) models (labelled `.dat+C’) should not be used as they have a discontinuity in the fluxes and colours as a function of \( T_{\text{eff}} \) and \( \log(g) \) that was corrected for the revised version.

The models assume plane parallel homogeneous layers in steady-state, local thermal equilibrium. A microturbulence velocity of 2 km s\(^{-1}\) and a mixing-length value of \( \ell/H_\text{p} = 1.25 \) are used. Castelli, Gratton & Kurucz (1997) give a detailed discussion of whether the mixing length theory for convection is dealt with adequately in the standard Kurucz atmospheres. They have calculated an alternative set of atmospheres in which the Kurucz ‘overshooting’ approximation is not used (NOVER models). These models have been shown to predict more accurate observable properties (e.g. colours) for some atmospheres (Heiter et al. 2002; Smalley & Kupka 1997; Smalley et al. 2002). However, since they are currently available only for some metallicity values (\(-2.5, -2.0, -1.5, -1.0, -0.5, 0.0, +0.5\) dex) we decided not to use these atmospheres for population synthesis. We have generated a small subset of the NOVER models for comparison with the \textsc{stelib} spectra.

The adopted atomic line lists for all our spectra are \textsc{lowlines} and \textsc{nltelines} from Kurucz (1994) and the adopted molecular line list is \textsc{diatomic} from Kurucz (1993b). We have included both predicted and measured lines. The inclusion of the predicted lines is necessary to reproduce accurate flux distributions. However, it does mean that care should be taken when using the high-resolution spectra, as the properties of individual lines may not be as accurate as if Kurucz’s more up-to-date linelists (which do not include predicted lines) had been used. The molecular lines have been included for spectra with \( T_{\text{eff}} \leq \) 7000 K.

The original programs making up the Kurucz package were written in \textsc{fortran} for the VAX. John Lester has written a Unix version of the original Kurucz code, and a more recent Unix version in \textsc{fortran} (Lester, private communication). However, this code could only be used to generate small sections of a spectrum at a time because it required massive quantities of disc space. The complexities in generating spectra with \textsc{synth} has restricted researchers to creating either a small number of spectra, or a large number over a very small wavelength range. We have modified the Lester code dramatically reducing the disc usage of \textsc{synth}, which makes it feasible to generate large spectral ranges on standard hardware in a relatively short period of time. We have not yet generated spectra for values of \( T_{\text{eff}} \leq 5000 \) K. These spectra require TiO lines to be included, which makes the program significantly slower and requires more disc space; we are investigating whether further optimizations may be made.

One thing to note is the subtle difference in terminology between ‘spectra’ and ‘flux distributions’, which are sometimes used interchangeably. The Kurucz \( \lambda 20 \) flux distributions were predicted directly from the Kurucz model atmospheres. The \textsc{atlas} model atmosphere program sums up the opacity in broad \( \lambda 10 \) or 20 bins creating a low-resolution spectrum. The Kurucz spectra that we have generated have been calculated from the model atmospheres, using the \textsc{synth} software. These spectra are generated at extremely high-resolution (ideally as high as the computational resources allow) and then rebinned to the required resolution. The newest versions of \textsc{atlas} will combine both the model atmosphere generation and the spectral synthesis into one process.

Of the 7216 model atmospheres available in Kurucz’s standard distribution, we have generated a grid of 6410 spectra (Fig. 1), which excludes the lowest-temperature spectra. The spectra cover the wavelength range \( \lambda \lambda 3000–10,000 \) which was chosen to be useful for comparisons with SDSS spectra. The spectra were generated at a resolution of \( \lambda / \Delta \lambda = 250,000 \).

3 COMPARISONS WITH THE \( \lambda 20 \) KURUCZ SPECTRA

In this section we compare our library of spectra with the revised version of the \( \lambda 20 \) Kurucz flux distributions. There have been several changes to the software and data between the original release of the \( \lambda 20 \) Kurucz flux distributions, and the present. Also, the flux distributions are predicted directly from the model atmosphere code, so it is not possible to compare them directly with the spectra generated by spectral synthesis. Because of this, the spectra we have generated are not expected to match the flux distributions exactly, but it is an

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{figure1.png}
\caption{The distribution of our Kurucz spectra in \( \log(T_{\text{eff}})–\log(g) \) space (\( \times \)). Also plotted is the distribution of the \textsc{stelib} spectra with \( T_{\text{eff}} > 5000 \) K (\( \oplus \)).}
\end{figure}
important check to make sure there was broad agreement between the spectra.

3.1 Direct comparisons

We compare the higher-resolution Kurucz spectra with the λ20 flux distributions. Fig. 2 shows several examples of these comparisons. For the purposes of this comparison, we re-binned the new spectra to λ20 using a simple top-hat function. We list several differences between the two sets of spectra.

(i) In all the spectra there is an extra dip in the new spectra at around λ3700. This is due to inadequate treatment of the Balmer jump. In the model atmosphere code, the way the Balmer jump is dealt with has been modified in order to remove the dip (Kurucz, private communication).

(ii) In some of the lower-temperature spectra, the shape of the Ca H/K doublet is not identical. This is largely due to the fact that, for the model atmospheres, the Stark broadening was artificially increased to make up for missing lines in computing the distribution function (Kurucz, private communication). This was changed back to generate the synthetic spectra, and also for more recent flux distributions.

(iii) In lower-temperature spectra (T$_{\text{eff}}$ ≤ 7000 K) there is a systematic difference in flux in the G-band. This is likely to be due to changes in the molecular line lists since the flux distributions were produced.

(iv) Most of the strong lines have slightly different depths. These small peaks are likely to be unresolved line cores, caused by the fact that the λ20 flux distributions are undersampled, whereas our new synthetic spectra are generated at high resolution.

Probably the most significant of these points for our applications is the difference in the G-band flux. This affects individual lines, and the U-band magnitude of the spectra. In the following sections we quantify this.

3.2 Colours

Comparing the UBVRI magnitudes is important for checking that the broadband properties of the spectra are reproduced. We have used the Johnson–Cousins bandpasses, as defined by Bessell (1990). Fig. 3 shows the offset in mag calculated for the new spectra and the λ20 flux distributions. The rms errors for the colours for the two sets of spectra are: ΔU = 0.05 mag, ΔB = 0.01 mag, ΔV = 0.01 mag, ΔR = 0.01 mag and ΔI = 0.01 mag. The B, V, R and I magnitudes are in good agreement. However, the differences are greater for the U magnitudes at lower temperatures (T$_{\text{eff}}$ ≤ 7000 K). For higher-temperature spectra the U magnitudes are also in good agreement. The U-band discrepancy is probably a consequence of the differences in the spectra noted in Section 3.1.

The question is how important these magnitude offsets are for the applications we are interested in. A difference in measured colour is largely degenerate with a difference in T$_{\text{eff}}$. For example, Lejeune, Cuisinier & Buser (1997) find that the colour versus temperature relations for Kurucz spectra do not match those derived empirically. To fix the problem, they developed a method for adjusting the shape of the continuum (in other words change the magnitudes) for spectra of a certain T$_{\text{eff}}$. However, an alternative approach is to leave the shape of the spectrum unchanged and reassign a T$_{\text{eff}}$ to the spectrum. For example, a solar metallicity spectrum with T$_{\text{eff}}$ = 7500 and log(g) = 1.0 has a U magnitude offset of 0.05. This difference in colour between our new spectrum and the Kurucz flux distribution corresponds to a change of T$_{\text{eff}}$ by less than 30 K. Since quoted errors for temperatures on observed spectra are typically around 40–100 K (see for example Katz et al. 1998 or Alonso, Arribas & Martínez-Roger 1999), the spectra agree to within usual measurement errors.

4 COMPARISONS WITH OBSERVED SPECTRA

Having shown that the new spectra agree reasonably well with the λ20 flux distributions, the next step is to evaluate them against observed spectra. This serves two purposes. First, there are some differences between the two sets of Kurucz spectra, especially in the blue. However, if these differences are smaller than the differences between one of the Kurucz spectra and an observed spectrum with the same physical parameters, then they may be neglected. Secondly, we want to evaluate what kind of applications the synthetic spectra can be used for. Our aim is to demonstrate that our new Kurucz spectra are as suitable for use in population synthesis as the commonly used λ20 Kurucz flux distributions, but with the advantage of higher resolution. There are already various comparisons of Kurucz spectra with observed spectra in the literature. For example, the colour–T$_{\text{eff}}$ correlation for the spectra has been analysed by Lejeune et al. (1997) and the λ20 spectra have been compared with observed spectra by Straizys, Liubertas & Valiauga (1997) and Straizys, Lazauskaite & Valiauga (2002). Here, we make our own comparisons to focus on properties such as the Lick indices, which are relevant to the specific applications we are interested in.

We have compared the spectra to those in the STELIB library (Le Borgne et al. 2003), which consists of 250 spectra in the visible range (λλ3200–9500) with a spectral resolution of Δλ ≤ 3 Å and covering a wide range in parameter space. As well as a direct comparison of the SEDs, we compare the measured colours and Lick indices to confirm that the spectra meet our requirements.

Many of the STELIB stars do not have values for all three physical parameters (T$_{\text{eff}}$, log(g) and [Fe/H]), have a large section of the spectrum missing, or do not lie close to a point on our grid of spectra. Hence we have selected a subset of 125 of the spectra that have tabulated values for T$_{\text{eff}}$, log(g) and [Fe/H] in Le Borgne et al. (2003), T$_{\text{eff}}$ > 5000 K, and which have a good χ$^2$ match to the corresponding Kurucz spectrum. The values for most of the physical parameters were obtained from the Cayrel de Strobel et al. (1997) and Cayrel de Strobel, Soubran & Ralite (2001) catalogues. However, some were obtained from the ELODIE data base (Prugniel & Soubran 2001) and several were calculated using the TEMET method (Katz et al. 1998). We corrected the spectra for interstellar reddening using the values of A$_v$ from Le Borgne et al. (2003) and the IDL ASTROLIB routine ccm_dered.pro. The STELIB spectra have not been corrected for atmospheric absorption, so they have strong absorption features (most noticeably in the Oxygen A-band around λ7600) that are not present in the synthetic spectra.

4.1 Colours

We have calculated colours for all of the STELIB spectra and their closest Kurucz matches. Since the wavelength range of the STELIB spectra is λλ3200–9500, we have calculated a modified U-band magnitude (denoted U$^*$), which is truncated at λ3200 for both the STELIB and Kurucz spectra. Fig. 4 shows the magnitude offsets between the STELIB spectra and their Kurucz matches. The rms error between the two sets of spectra are: ΔU$^*$ = 0.14 mag, ΔB = 0.05 mag, ΔV = 0.02 mag, ΔR = 0.03 mag and ΔI = 0.04 mag. For comparison, we also calculated the magnitude offsets for the
Figure 2. Comparison between a sample of the \( \lambda \)20 Kurucz flux distributions (bold line) and the newly generated Kurucz spectra (thin line) (box-car smoothed to \( \Delta \lambda = 20 \) Å). These spectra cover a range of physical parameters: the title of each plot gives the values for \( T_{\text{eff}} \), \( \log(g) \) and [Fe/H]. The x-axis is the wavelength in Å and the y-axis is flux, \( F(\lambda) \), in arbitrary units. Underneath each pair of spectra is \( \Delta F = F(\lambda)_{\text{new}} - F(\lambda)_{\text{old}} \).
Figure 3. Magnitude offsets between our Kurucz spectra and the $\lambda 20$ flux distributions. The x-axis is $\log_{10}(T_{\text{eff}})$ and the y-axis shows the difference (in mag) between the Kurucz spectra we have generated and the $\lambda 20$ flux distributions.

Figure 4. Magnitude offsets between the STELIB spectra and the closest Kurucz spectrum match from the grid.

STELIB spectra and their closest Kurucz matches, using the $\lambda 20$ flux distributions. The rms error between these two sets of spectra are: $\Delta U^* = 0.11$ mag, $\Delta B = 0.05$ mag, $\Delta V = 0.02$ mag, $\Delta R = 0.03$ mag and $\Delta I = 0.04$ mag. This demonstrates that, with the exception of $U^*$, the scatter in the magnitudes is no worse for our new spectra than for the $\lambda 20$ spectra that are in standard use.

Some differences are expected due to the mismatch between the STELIB temperatures and those of the closest Kurucz match – many of the spectra have a difference in temperature of about 100 K, corresponding to a difference of a few hundredths in mag. However, the important point for our work is that our new spectra are as well matched to the observed spectra as the $\lambda 20$ spectra that are often used for population synthesis. Fig. 5 shows various colour comparisons. There is some scatter in each of the plots and a slight systematic offset in $R-I$. Again however, this is no worse than when comparing the $\lambda 20$ spectra with the STELIB spectra.
4.2 Line indices

We have calculated Lick indices for each of the 125 STELIB spectra in our sample, and for the matching Kurucz spectra. There are two types of index, atomic \((I_a)\) and molecular \((I_m)\) which we have calculated from the standard formulae:

\[
I_a = \int_{\lambda_{c1}}^{\lambda_{c2}} \left[ 1 - \frac{S(\lambda)}{C(\lambda)} \right] \, d\lambda
\]

\[
I_m = -2.5 \log_{10} \int_{\lambda_{c1}}^{\lambda_{c2}} \frac{S(\lambda)}{C(\lambda)} \, d\lambda / (\lambda_{c2} - \lambda_{c1}).
\]

where \(\lambda_{c1}\) and \(\lambda_{c2}\) are the limits of the central bandpass defining the index (in Å), \(S(\lambda)\) is the object spectrum and \(C(\lambda)\) is the linearly interpolated pseudo-continuum, defined by

\[
C(\lambda) \equiv S_{b} \frac{\lambda_{b} - \lambda}{\lambda_{b} - \lambda_{b1}} + S_{t} \frac{\lambda - \lambda_{b}}{\lambda_{t} - \lambda_{b}}.
\]

Here,

\[
S_{b} = \int_{\lambda_{b1}}^{\lambda_{b2}} S(\lambda) \, d\lambda / \lambda_{b2} - \lambda_{b1}, \quad \lambda_{0} \equiv (\lambda_{b1} + \lambda_{b2})/2
\]

\[
S_{t} = \int_{\lambda_{t1}}^{\lambda_{t2}} S(\lambda) \, d\lambda / \lambda_{t2} - \lambda_{t1}, \quad \lambda_{t} \equiv (\lambda_{t1} + \lambda_{t2})/2
\]

and \(\lambda_{b1}, \lambda_{b2}, \lambda_{t1}\) and \(\lambda_{t2}\) are the limits of the blue and red continuum bands. The bandpass definitions for the Lick indices and the red and blue pseudo-continua are those defined in Worthey et al. (1994). These are given in Table 1.

A method for random error estimation in line-strength indices is outlined in detail by Cardiel et al. (1998). The resulting equations are based on a full analysis of the error propagation throughout the calculation process. The resulting random errors are given by:

\[
\sigma^2[I_a] = \sum_{i=1}^{N_{\text{pixels}}} \left[ \frac{C^2(\lambda_i) \sigma^2(\lambda_i) + S_i^2(\lambda_i) \sigma^2_{\lambda_i}(\lambda_i)}{C^4(\lambda_i)} \int d\lambda \right]
\]

\[
+ \sum_{i=1}^{N_{\text{pixels}}} \sum_{j \neq i} S_i(\lambda_i) S_j(\lambda_j) \frac{C^2(\lambda_i) C^2(\lambda_j)}{C^4(\lambda_i) C^4(\lambda_j)} \left( \Lambda_1 \sigma_{I_a}^2 + \Lambda_4 \sigma_{\lambda_i}^2 \right) d\lambda_i d\lambda_j
\]

for the atomic indices and:

\[
\sigma^2[I_m] = 2.5 \log_{10} \frac{1}{10^{-0.4 N_{\text{pixels}}}} \frac{1}{\lambda_{c2} - \lambda_{c1}} \sigma[I_a]
\]

for the molecular indices, where

\[
\Lambda_1 = \frac{(\lambda_{c1} - \lambda_{c2})(\lambda_{c1} - \lambda_{c2})}{(\lambda_{c1} - \lambda_{c2})^2}
\]

\[
\Lambda_4 = \frac{(\lambda_{c1} - \lambda_{c2})(\lambda_{c1} - \lambda_{c2})}{(\lambda_{c1} - \lambda_{c2})^2}
\]

\[
\sigma_{\lambda_i}^2 = \frac{1}{\lambda_{c2} - \lambda_{c1}} \sum_{i=1}^{N_{\text{pixels}}} \sigma^2(\lambda_i) d\lambda_i^2
\]

\[
\sigma_{\lambda_i}^2 = \frac{1}{\lambda_{c2} - \lambda_{c1}} \sum_{i=1}^{N_{\text{pixels}}} \sigma^2(\lambda_i) d\lambda_i^2
\]

These are given in Table 1.

Figure 5. Top left: \(U^* - B\) versus \(B - V\) for STELIB spectra (+) and their Kurucz matches (o). Top right: \(U^* - B\) colours for STELIB spectra (x-axis) and their Kurucz matches (y-axis). The solid line is the line ‘\(x = y\)’ for comparison. Bottom left: comparison of \(B - V\) colours. Bottom right: comparison of \(R - I\) colours.

These spectra. The average absolute offsets (i.e. calculated the two TiO indices since TiO lines are switched off in STELIB spectra and the Kurucz spectra. We have not keep it inside the summation signs.

Note that Cardiel et al. (1998) assume the size of each pixel $d_\lambda$ (in their notation) is fixed, and so take it out of all the summations. However, in general (and in our case), $d_\lambda$ is not fixed, and so we keep it inside the summation signs.

Fig. 6 shows the correlation between the Lick indices calculated from the STELIB spectra and the Kurucz spectra. We have not calculated the two TiO indices since TiO lines are switched off in these spectra. The average absolute offsets (i.e. $\sum |I_k - I_{k,l}|/n$) for the correlations are given in Table 2. It should be noted that the Kurucz spectrum paired with a given STELIB spectrum is not necessarily the best possible spectrum that could be synthesized to match the STELIB spectrum, but simply the spectrum from our grid with the closest match in physical parameters. This means it does not take into account any particular properties of the STELIB spectrum that could in principle be modelled and which may affect the line indices. However, the comparison does give an indication of the level of mismatch to be expected when comparing observed stellar spectra with a grid of synthetic spectra like ours. Such mismatches are an inevitable consequence of any automated comparisons between a grid of model spectra and the vast number of spectra being made available from large surveys like the SDSS.

We have calculated Lick indices and their associated errors for a set of 9473 SDSS galaxies from the Early Data Release (Stoughton et al. 2002). This allows us to compare the scatter between the Lick index values for the STELIB and Kurucz spectra, with the expected accuracy of the indices measured from observed galaxy spectra.

We have found that the random error (as calculated by equations 6 and 7) associated with each index measured in the SDSS spectra, is of the same order of magnitude as the average offset between the Kurucz and STELIB index measurement. This suggests that the accuracies measured from galaxy spectra synthesized from the Kurucz spectra will have at least comparable accuracy with those measured with SDSS, and so our grid of stellar spectra is well matched to the SDSS galaxies.

### 5 DISCUSSION

We have generated a grid of theoretical spectra from the Kurucz model atmospheres. Since the intended use of these spectra is in population synthesis and stellar classification, we have made several comparisons to check the validity of using the spectra for these purposes. The broadband properties of the spectra compare well with observed spectra, as do the line index measurements. The comparisons do not guarantee the accuracy of the Kurucz spectra as models...
Figure 6. Each plot shows the correlation between the Lick index calculated on the STELIB spectrum (x-axis) and the closest matching Kurucz spectrum from our grid (y-axis). The solid line is the line ‘$x = y$’ for comparison. We have not included the TiO indices for reasons discussed in the text. The rms error for each index is given in Table 1.
of observed stellar spectra. Rather, they demonstrate that our new, high-resolution Kurucz spectra are as good for use in population synthesis as the commonly used library of λ2.0 spectra. The advantage of these spectra over the previously available Kurucz spectra is that they allow the modelling of spectral line features such as the Lick indices.

When using these spectra at high resolutions, it should be recognized that the spectra were generated using line lists that include ‘predicted’ lines. This is necessary to reproduce the broadband colours of the spectra accurately. However, it does mean that many of the individual lines present at high resolutions do not have measured properties. Also, the line lists that we used (such as LOWLINES) are known to have problems with the values for specific lines. As this mostly involves weak lines, it should not present any difficulties for population synthesis at the resolution of the SDSS. More accurate properties for these lines could be obtained using alternative values, for example from the Vienna Atomic Line Data base (VALD) (Kupka et al. 2000).

Also, the λ2.0 Kurucz flux distributions are often used with the corrections of Lejeune et al. (1997) and Lejeune, Cuisinier & Buser (1998) applied. The corrections are an attempt to calibrate the spectra by comparing the synthetic model colours with empirical stellar colours. We investigated applying the same corrections to our high-resolution spectra, but found that artefacts were introduced when using this technique directly. The Lejeune corrections mainly affect the lower-temperature spectra, which we have not included in this library. For most of our spectra, the corrections are negligibly small.

We intend to extend the library to the lower-temperature models in which TiO lines become important and also generate spectra for the NOVER models as these are more accurate. We are in the process of building a large library for population synthesis – a higher-resolution version of that done by Lejeune et al. (1997) – which will also incorporate the NextGen models (Hauschildt, Allard & Baron 1999a; Hauschildt et al. 1999b).

ACKNOWLEDGMENTS

TM thanks the University of Edinburgh and the University of Sydney for scholarships. We would like to thank John Lester for making his code available and for the extensive help he provided in generating the spectra. We would also like to thank Ivan Baldry, Friedrich Kupka, Barry Smalley, Robert Kurucz and Ian Sheret for helpful discussions and email exchanges about various aspects of the spectra and James Curran for advice on computational issues.

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