Spectrum syntheses of high-resolution integrated light spectra of Galactic globular clusters

Charli M. Sakari,1†‡ Matthew Shetrone,2 Kim Venn,1 Andrew McWilliam3 and Aaron Dotter4
1Department of Physics and Astronomy, University of Victoria, Victoria, BC V8W 3P2, Canada
2McDonald Observatory, University of Texas at Austin, HC75 Box 1337-MCD, Fort Davis, TX 79734, USA
3The Observatories of the Carnegie Institute of Washington, 813 Santa Barbara Street, Pasadena, CA 91101-1292, USA
4Research School of Astronomy and Astrophysics, The Australian National University, Weston, ACT 2611, Australia

ABSTRACT
Spectrum syntheses for three elements (Mg, Na and Eu) in high-resolution integrated light spectra of the Galactic globular clusters 47 Tuc, M3, M13, NGC 7006 and M15 are presented, along with calibration syntheses of the solar and Arcturus spectra. Iron abundances in the target clusters are also derived from integrated light equivalent width analyses. Line profiles in the spectra of these five globular clusters are well fitted after careful consideration of the atomic and molecular spectral features, providing levels of precision that are better than equivalent width analyses of the same integrated light spectra, and that are comparable to the precision in individual stellar analyses. The integrated light abundances from the 5528 and 5711 Å Mg I lines, the 6154 and 6160 Å Na I lines, and the 6645 Å Eu II line fall within the observed ranges from individual stars; however, these integrated light abundances do not always agree with the average literature abundances. Tests with the second parameter clusters M3, M13 and NGC 7006 show that assuming an incorrect horizontal branch morphology is likely to have only a small (<0.06 dex) effect on these Mg, Na and Eu abundances. These tests therefore show that integrated light spectrum syntheses can be applied to unresolved globular clusters over a wide range of metallicities and horizontal branch morphologies. Such high precision in integrated light spectrum syntheses is valuable for interpreting the chemical abundances of globular cluster systems around other galaxies.

Key words: techniques: spectroscopic – globular clusters: individual: 47 Tuc – globular clusters: individual: M3 – globular clusters: individual: M13 – globular clusters: individual: NGC 7006 – globular clusters: individual: M15.

1 INTRODUCTION
Detailed chemical abundances from high-resolution spectroscopy of individual stars in globular clusters (GCs) associated with the Milky Way and its nearby satellite galaxies have provided valuable information about stellar evolution and nucleosynthesis (e.g. Gratton, Sneden & Carretta 2004), the chemical evolution of low- and high-mass galaxies (e.g. Tolstoy, Hill & Tosi 2009) and the assembly history of the Milky Way (e.g. Freeman & Bland-Hawthorn 2002). In particular, chemical tagging has enabled the identification of potentially accreted stellar streams and GCs (e.g. Cohen 2004; Sbordone et al. 2005; Chou et al. 2010; Sakari et al. 2011), which shows that hierarchical merging has played an important role in the formation of the Milky Way Galaxy. Observations of extragalactic GC systems suggest that most galaxies have experienced complicated assembly histories that may include a significant component of accretion from dwarf galaxies (see Harris 2000 and Brodie & Strader 2006 for reviews on the observed properties of GC systems). Certain models suggest that most GCs form in small dark matter haloes at high redshift and are accreted by larger galaxies at later times (Bekki et al. 2008; Muratov & Gnedin 2010). Detailed chemical abundances of extragalactic GC systems, particularly

* Based on observations obtained with the Hobby–Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München and Georg-August-Universität Göttingen.
† E-mail: sakaricm@uvic.ca
‡ Vanier Canada Graduate Scholar.

© 2013 The Authors
Published by Oxford University Press on behalf of the Royal Astronomical Society

doi:10.1093/mnras/stt1026
those associated with galaxy types (e.g. massive ellipticals versus spirals) and environments (e.g. located within galaxy clusters) that are not found in the Local Group, can provide information about the assembly histories of their host galaxies.

Individual stars are too faint for detailed spectral analyses beyond the Local Group. Distant extragalactic GCs, however, appear as bright, point-like sources and can be observed at much greater distances than individual stars. Therefore, an alternative way to determine the flux-weighted average chemistry of a GC is from an integrated light spectrum (ILS) of the entire population. Information on the chemical abundance ratios for a system of GCs can then be used to study the chemical evolution and early assembly history of the host galaxy. Integrated light (IL) spectroscopy has historically been done at low to medium resolution. Lower resolution ILS analysis methods have been tested and calibrated on Galactic GCs within the last few decades (e.g. Schiavon et al. 2002; Lee & Worthey 2005) – such methods have proven capable of determining the ages, metallicities and α-abundances of Galactic GCs. However, detailed abundances (of, e.g., iron-peak or neutron capture elements) require moving to higher resolution. By providing additional elements and higher precision, high-resolution observations provide information about, for example, the contributions from different types of supernovae or asymptotic giant branch (AGB) stars.

The high-resolution IL abundance analysis program ILABUNDS (presented in McWilliam & Bernstein 2008, hereafter MB08) has been tested on several Galactic GCs. The majority of ILABUNDS analyses thus far have been equivalent width (EW) analyses, which are sufficient for elements with multiple, fairly strong lines since with a large number of lines the error in the mean abundance will be less sensitive to individual measurement errors. EW techniques have successfully reproduced the literature abundances (from individual stars) of α, iron-peak and neutron capture elements in several Galactic GCs (MB08; Cameron 2009) and produced reasonable abundances for inner halo M31 GCs, Large Magellanic Cloud GCs and GCs associated with other Local Group dwarf galaxies (Colucci et al. 2009, 2011; Colucci & Bernstein 2011; Colucci et al. 2012). However, many elements do not have enough (or any) strong lines available for an EW analysis. The features in ILS are also often weak and/or blended, which makes an EW analysis particularly difficult. There are many elements with detectable spectral lines in high-resolution spectra, e.g. Cu, Zn, Ba and Eu, which are valuable for galaxy and GC formation and chemical evolution theories (e.g. Matteucci et al. 1993; Mishenina et al. 2002; Travaglio et al. 2004) but which are unsuitable for an EW analysis.

With individual stellar analyses, the preferred method for determining abundances of such elements is to synthesize the entire spectral region around the line of interest. This technique is different from an EW analysis, because the line profile, width and depth can be fitted simultaneously, while the effects of nearby lines are taken into account. When a line is too weak or a spectrum is too noisy, upper limits can be obtained with spectrum synthesis, which can still provide valuable constraints. Colucci et al. (2009, 2012) have synthesized high-resolution ILS to obtain abundances of Na, Mg, Al, Sr, Ba, La and Eu, among other elements, with random errors that are typically ~0.15–0.3 dex. These errors are quite large given the spectral resolution; lower uncertainties would be more useful for chemical comparisons between clusters or galaxies, or for comparisons with chemical evolution models. Tests on Galactic GCs can better determine the accuracy (through comparisons with literature abundances) and precision (through stringent tests on high-S/N spectra) of ILS syntheses.

In order to understand and quantify the accuracy and precision of an ILS synthesis method, this paper presents tests on the five Galactic GCs 47 Tuc, M3, M13, NGC 7006 and M15 in four different 10 Å regions around the 5528 and 5711 Å Mg I lines, the 6154 and 6160 Å Na I lines, and the 6645 Å Eu II line. These elements have been selected because they are important for galaxy/GC formation theories. In addition, the lines are easily detectable in the majority of the spectra, providing abundances rather than upper limits. Other than the Eu II line, these lines and features also avoid the complications of significant hyperfine structure (HFS) or isotopic corrections.

The target clusters were selected to cover a range of metallicities and horizontal branch (HB) morphologies, as discussed in Section 2.1. Sections 2.2 and 2.3 describe the observations of these nearby targets, and the subsequent data reductions, while Section 3 describes the abundance analysis method used to infer the chemical abundances. The syntheses are finally presented in Section 4, along with detailed discussions of the errors. The important findings of this paper are discussed in Section 5. Finally, the results are summarized in Section 6.

### 2 OBSERVATIONS AND DATA REDUCTION

#### 2.1 Target selection

The targets were selected to span a range of metallicities (from [Fe/H] = −0.7 to −2.4) and HB morphologies (from red to very blue), though all appear to be standard Galactic GCs (i.e. old and α-enhanced). In particular, M3/M13/NGC 7006 form a ‘second parameter’ triad, i.e. the three GCs have similar ages and metallicities, yet different HB morphologies. Basic information about the target clusters is provided in Table 1. Positions and integrated V magnitudes are from Harris (1996; 2010 edition); the [Fe/H], [α/Fe] and age estimates come from isochrone fits by Dotter et al.

| Cluster | RA (J2000) | Dec. (J2000) | Vint | [Fe/H] | [α/Fe] | Age | HB index |
|---------|------------|-------------|------|--------|--------|-----|----------|
| 47 Tuc (NGC 104) | 00°24'05.67 | −72°04'52.6 | 3.95 | −0.70 | 0.2 | 12.75 ± 0.50 | −0.99 |
| M3 (NGC 5272) | 13°42'11.62 | +28°22'38.2 | 6.19 | −1.60 | 0.2 | 12.50 ± 0.50 | 0.08 |
| M13 (NGC 6205) | 16°41'41.24 | +36°27'35.5 | 5.78 | −1.60 | 0.2 | 13.00 ± 0.50 | 0.97 |
| NGC 7006 | 21°01'29.38 | +16°11'14.4 | 10.56 | −1.50 | 0.2 | 12.25 ± 0.75 | −0.28 |
| M15 (NGC 7078) | 21°29'58.33 | +12°10'01.2 | 6.20 | −2.40 | 0.2 | 13.25 ± 1.00 | 0.67 |

References: positions and integrated magnitudes are from Harris (1996; 2010 edition). The [Fe/H], [α/Fe] and age estimates are from isochrone fitting (Dotter et al. 2010, 2011). The HB index, (B − R)/(B + V + R), comes from Mackey & van den Bergh (2005).
2.2 Observations

The 47 Tuc spectrum was kindly provided by R. Bernstein and A. McWilliam. It is the same spectrum analysed in MB08; details on the observations and data reduction can be found there. Additional normalizations with low-order polynomials were performed and the apertures were combined, as described below.

The other spectra were observed with the High Resolution Spectrograph (HRS; Tull 1998) on the Hobby–Eberly Telescope (HET; Ramsey et al. 1998; Shetrone et al. 2007) at McDonald Observatory in Fort Davis, Texas, in 2011 and 2012. A slit width of 1 arcsec was used, leading to an instrumental spectral resolution of $R \approx 30,000$. Given the velocity dispersions of the targets (see below), a higher spectral resolution is unnecessary. The 600 gr mm$^{-1}$ cross-disperser was used, with a central wavelength of 6302.9 Å. The spectral coverage is therefore ~5320–6290 Å on the blue chip and ~6360–7340 Å on the red chip. This wavelength range was chosen for future unresolved targets in order to minimize the effects of improperly modelled HBs, since blue HB stars should contribute less to the IR at red wavelengths.

ILS observations of distant, point-like targets are relatively simple. Nearby GCs, however, are much more difficult to observe for IL studies, given their large sizes on the sky and the fact that their stars are resolved. It is essential to observe these difficult targets, however, because the ILS methods can be calibrated through comparisons with abundances from individual stars. To overcome these observational difficulties, the ILS of M3, M13, NGC 7006 and M15 were obtained by scanning the HRS fibres across the cluster cores. A number of specific pointings on the cluster were selected, and the fibres were moved to each position. The large 3 arcsec fibre was used in order to maximize spatial coverage on the clusters. HRS provides two additional 3 arcsec fibres located 10 arcsec from the centre of the object fibre. In typical observations these extra fibres are intended to serve as sky fibres; however, because of the spatial extent of the Galactic GCs, these sky fibres served as additional object fibres during the observations. Separate sky observations with all three fibres were therefore taken after each GC observation. These pointing patterns are shown in Fig. 1, along with the clusters’ core and half-light radii.

For M3, M13 and NGC 7006, the entire core of each cluster was observed, though the clusters were too large to observe the entire area within the half-light radius in a reasonable amount of time. Note that M15 was mapped differently than NGC 7006, M3 or M13; its wedge-shaped map represents a slice of the cluster out to the half-light radius, assuming that the cluster is spherically symmetric. Any differences in the spectra as a result of the different mappings will be negligible because the input photometry has been selected to reflect the spatial coverage of the ILS (see Section 3.1.1).

The total exposure times and S/N ratios in blue (5500 Å) and red (7000 Å) regions are shown in Table 2. Generally, the exposure times were calculated to allow an observation of a single HB star to reach S/N = 70, though NGC 7006 did not receive sufficient time to meet this goal.

2.3 Data reduction

The data reduction was performed in the Image Reduction and Analysis Facility (IRAF) program according to the standard HRS data reduction methods, with several exceptions. A separate bias frame removal was not completed, as the process can add noise to the spectra. To remove cosmic rays the aperture extraction was performed with variance weighting, where IRAF considers the gain and read noise of the CCD and identifies and removes any pixels that deviate significantly from the noise. This variance weighting procedure occasionally affects the shape of the continuum; thus, the shape of the non-weighted extraction was maintained.

Separate sky observations were obtained after all ILS observations. Again, all three fibres (object and sky) were used in each exposure; the spectra from the three fibres were averaged together to remove noise and cosmic rays. Because the sky spectra were still fairly noisy, the spectra were replaced with continuum fits and the emission lines were added back in (using the sky line identifications from the UVES Quality Control sky spectrum website). The IRAF task skywweak determined the necessary scaling factor between a target object spectrum and its sky spectrum, and the sky spectrum was multiplied by that factor before it was subtracted from the object spectrum. Telluric standards were also observed during each night, allowing separate removal of the telluric absorption lines.

Because ILS may have many undetectable, blended, weak features that can obscure/distort the continuum level, the spectra must be carefully normalized. To remove the blaze function of the spectrograph and the blackbody function of the cluster, an extremely metal-poor (EMP) giant was observed with the same instrumental setup. An EMP star should have very few spectral lines, and finding the continuum should therefore be quite simple. Furthermore, an EMP giant should have a similar effective temperature as the average temperature of the cluster. Information on the observed EMP star, CS29502–092, is given in Table 3. The EMP star’s continuum was fitted with the IRAF task continuum, and the target spectra were divided by these continuum fits. Additional low-order polynomial fits were required to fully normalize the target spectra.

The normalized GC spectra were then cross-correlated with a reference spectrum (using the IRAF task fxcor) to determine the radial velocity and velocity dispersion. Arcturus was used as the template spectrum for the cross-correlation; this very high resolution ($R = 150,000$) spectrum was observed with the Fourier transform spectrometer on the McMath Telescope (Hinkle et al. 2003), and was obtained from the Arcturus Atlas. The IRAF task fxcor correlates the target spectra with the Arcturus template spectrum and identifies the values with the highest correlation; the peak of the correlation occurs at the observed radial velocity of the cluster, and the width determines the velocity dispersion (as discussed below). The heliocentric velocities were measured from each observation, and were averaged together to produce the final, averaged heliocentric velocities (shown in Table 2).

1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

2 In addition, the scattered light subtraction removes some of the bias level; see the online HRS Data Reduction Tips (http://hydra.as.utexas.edu/?a=help&h=29#HRS).

3 http://www.eso.org/observing/dfo/quality/UVES/pipeline/sky_spectrum.html

4 ftp://ftp.noao.edu/catalogs/arcturusatlas/
Figure 1. Fibre pointings for the HET observations of the target clusters. The small circles show the positions of the 3 arcsec fibres (both sky and object), while the larger circles show the core and half-light radii (from Harris 1996; 2010 edition). The centres of the clusters are shown at arbitrary positions. Each observation scans the three fibres across the cluster; for an individual GC, each pointing lasts for the same amount of time, and the pointings are not overlapped.

Table 2. GC observations.

| Cluster    | Observation dates | Exposure time (s) | S/N$^a$ (5500 Å) | S/N$^a$ (7000 Å) | $v_{\text{helio, obs}}$ (km s$^{-1}$) | $v_{\text{helio, lit}}$ (km s$^{-1}$) | $\sigma_{\text{obs}}$ (km s$^{-1}$) | $\sigma_{\text{lit}}$ (km s$^{-1}$) |
|------------|-------------------|-------------------|-------------------|-------------------|--------------------------------------|--------------------------------------|-----------------------------------|-----------------------------------|
| 47 Tuc$^b$ | 2000 July 18, 19   | 11 030            | 120               | 180               | −146.0 ± 1.1                        | −147.6                              | 5.66 ± 0.15                       | 5.5                               |
| M3         | 2012 March 25, April 16, 17, 18 | 9940             | 180               | 230               | −247.5 ± 1.3                        | −244.2                              | 7.23 ± 0.33                       | 7.1                               |
| M13        | 2012 April 17, 20, 22 | 11 569           | 130               | 250               | −380.4 ± 0.7                        | −384.1                              | 4.49 ± 0.60                       | −                                 |
| NGC 7006   | 2011 September 24, 2012 May 29, June 19 | 8903            | 65                | 130               | −106.6 ± 0.2                        | −107.0                              | 12.54 ± 0.60                      | 13.5                              |
| M15        | 2011 September 27  | 3280              | 95                | 220               | −                                  | −                                  | 12.54 ± 0.60                      | 13.5                              |

References: literature values are from the Harris Catalog (Harris 1996; 2010 edition).

$^a$S/N ratios (per pixel) are measured in IRAF.

$^b$47 Tuc was observed with the Las Campanas 2.5 m Du Pont Telescope by R. Bernstein and A. McWilliam; see MB08 for more details.

$^c$This velocity dispersion has been determined in the same way as the other GCs, for consistency.
Table 3. Properties of the observed EMP star.

| Star          | RA (J2000) | Dec. (J2000) | V    | \(T_{\text{eff}}\) (K) | Observation dates | Exposure times (s) | S/N\(^a\) (5500 Å) | S/N\(^b\) (7000 Å) | \(v_{\text{helio}}\) (km s\(^{-1}\)) |
|----------------|------------|--------------|------|------------------------|-------------------|--------------------|----------------------|----------------------|----------------------------------|
| CS29502−092   | 22\(^{h}\)22\(^{m}\)36\(^{s}\)0 | −01\(^{d}\)38\(^{m}\)27\(^{s}\)5 | 11.87 | 5001                  | 2011 November 16 | 690                | 167                  | 341                  | −67.0 ± 0.4                     |

References: the position and magnitude are from the SIMBAD data base (http://simbad.u-strasbg.fr/simbad). The stellar temperature is an average from the Stellar Abundances for Galactic Archaeology (SAGA) data base (Suda et al. 2008).

\(^a\)S/N ratios (per pixel) are measured in IRAF.

\(^b\)The radial velocity was determined in the same way as the GC targets.

Figure 2. The ILS of the five Galactic GCs studied in this work. The 47 Tuc spectrum is from MB08, while the other four are HET spectra. Lines of interest are noted; the lines identified in black are lines that are typically used in standard RGB stellar analyses, while those in purple are used with hotter stars. The differences in line strengths are due to population, composition and velocity dispersion differences between the five GCs.

Each of the individual reduced and normalized spectra was shifted to the rest frame, using the radial velocity from \(fxcor\). The rest-frame spectra were then combined with average sigma-clipping rejection routines. The individual observations were weighted by flux during the averaging. The blue ends of the individual apertures often suffered from lower S/N, especially at blue wavelengths. These noisy regions were removed from the spectrum before the individual apertures were combined. Examples of the final spectra are shown in Fig. 2, along with notable spectral features.

After the individual observations were combined, the final spectra were again cross-correlated with Arcturus to determine the cluster velocity dispersions. The width of the cross-correlation peak in \(fxcor\) depends on the width of the spectral lines. In individual stars the line width is often dominated by the instrumental broadening, though rotation, microturbulence, etc. can also affect the line width. In an ILS, the velocity dispersion of the target is often the most significant source of broadening. The full width at half-maximum (FWHM) of the cross-correlation peak of an ILS is therefore related to the velocity dispersion, \(\sigma\), of the cluster, as described by Alpaslan (2009). Since the instrumental broadening is often significant in the target GCs,\(^5\) the observed velocity dispersion is found by subtracting (in quadrature) the instrumental broadening. The broadening of the target spectrum is taken into account in the calibration curve, though there may be additional sources of broadening that are unaccounted for. Thus, the derived velocity dispersions may be upper limits. This is not crucial for this analysis, since only the total width of the lines is important. These velocity dispersions for the target GCs are reported in Table 2, and are in good agreement with the literature values. Line blends in the ILS may lead to overestimates of the velocity dispersion; however, this does not seem to be significant for these GCs.

2.4 Calibration spectra

As shown in Section 4, the success of spectrum synthesis relies upon a complete and accurate input line list. To test the accuracy of these input line lists, spectrum syntheses of the solar and Arcturus spectra have been performed. The solar spectrum (\(R = 300000\); Kurucz 2005) comes from the Kurucz 2005 solar flux atlas.\(^6\) Solar atmospheric parameters of \(T_{\text{eff}} = 5777\) K, \(\log g = 4.44\) dex, \(\chi = 0.85\) km s\(^{-1}\) and \([\text{M/H}] = 0.0\) were adopted (Yong, Carney & Teixera de Almeida 2005).

The Arcturus spectrum is the same as the one used for the cross-correlation with the target ILS (see Section 2.3). Arcturus atmospheric parameters of \(T_{\text{eff}} = 4300\) K, \(\log g = 1.50\) dex, \(\chi = 1.56\) km s\(^{-1}\) and \([\text{M/H}] = −0.6\) (Yong et al. 2005) were adopted. The Arcturus temperature and surface gravity are in excellent agreement with Fulbright, McWilliam & Rich (2006) and Ramírez & Allende Prieto (2011), though the microturbulence values and metallicities differ slightly between the three studies. Both Fulbright et al. (2006) and Ramírez & Allende Prieto (2011) find higher

---

\(^5\) Recall that \(R = 30000\), which means that the FWHM from instrumental broadening alone should be 10 km s\(^{-1}\). This instrumental broadening is likely to vary across the CCD – however, these variations are likely to be insignificant in ILS given the width of the lines.

\(^6\) http://kurucz.harvard.edu/sun.html
metallicities and microturbulence values, with $\xi = 1.67$ km s$^{-1}$ and [Fe/H] = $-0.50$, and $\xi = 1.74$ km s$^{-1}$ and [Fe/H] = $-0.52$, respectively. The Yong et al. microturbulence and metallicity are adopted here, because their values agree best with the Fe I and Fe II abundances derived in this work (Section 3.1.3).

### 3 Detailed Abundances with ILABUNDS

The chemical abundances in the target GCs were determined with the program ILABUNDS (MB08). ILABUNDS is a modification of the 1997 version of the local thermodynamic equilibrium (LTE) line analysis and spectrum synthesis code MOOG$^7$ (Sneden 1973). The EW version of ILABUNDS was described and presented in MB08; here, a spectrum synthesis version of ILABUNDS (recently developed by A. McWilliam) is employed.

For spectrum syntheses of individual stars, MOOG requires an input model atmosphere and line list. ILABUNDS operates similarly, except that a model atmosphere must be provided for each star in the cluster, and the line list must be fairly complete. The input model atmospheres for ILABUNDS are discussed in Section 3.1, while the input line list is discussed in Section 3.2. With these inputs, the spectrum synthesis code calculates a synthetic ILS for each population box (Section 3.1.2) and combines the spectra together, weighted by flux. The final synthetic spectrum is broadened by the instrumental broadening and velocity dispersion (see Section 2.3), and is compared to the observed spectrum.

#### 3.1 Model atmospheres

For each star observed in the ILS, the atmospheric parameters (effective temperature $T_{\text{eff}}$, surface gravity log $g$, microturbulence $\xi$ and metallicity [Fe/H]) must be known in order to determine a cluster's IL chemical abundances. The stellar temperature, gravity and microturbulence values are estimated from observed photometry (Section 3.1.1), which is grouped into colour–magnitude diagram (CMD) boxes to simplify the process (Section 3.1.2). The metallicities are found through a standard ILS EW analysis (Section 3.1.3). Once the atmospheric parameters of a CMD box are known, a
information on this data can be found in MB08. For M3, M13, Gilliland 2000) were used to estimate the stellar parameters – more
anytic Globular Cluster Survey (e.g. Sarajedini et al. 2007; Anderson et al. 2008; Dotter et al. 2011) provided the estimates for the stellar
coordinates (particularly for M15; see Fig. 1). Field star contamination
the observed values were adopted. An empirical relationship be-
the atmospheric parameters. The (\(\xi\)) provided values for
the surface gravity and the microturbulence (also described
of McCall (2004) and the (\(\xi\)) values from
the ILS. Although the photometry was selected to only
include stars within the maximum radii covered by the HET, the
non-circular coverage of the ILS introduces some population dif-
fences (particularly for M15; see Fig. 1). Field star contamination
may also affect the input photometry and the observed spectrum.
The presence of even one additional bright star can affect the ob-
served ILS and the subsequent analysis (for example, the bright

3.1.1 Input photometry

For unresolved targets the atmospheric parameters of the stars in
a cluster must be modelled with isochrones, and observational di-
agnostics must be developed in order to ensure that the population
is correctly modelled (see, e.g., Colucci et al. 2009, 2011). With
nearby targets, the uncertainties from modelling the stellar popula-
tions can be removed with the use of resolved photometry, which
provides the colour and magnitude of each star in the observed
region. These observable quantities are then converted to physical
quantities via empirical relations.

For 47 Tuc, the Hubble Space Telescope (HST) B, V data from
R. Schiavon (Guhathakurta et al. 1992; Howell, Guhathakurta &
Gilliland 2000) were used to estimate the stellar parameters – more
information on this data can be found in MB08. For M3, M13,

\[\begin{array}{cccccccccc}
V_{\text{obs}} & (V-I)_{\text{obs}} & T_{\text{eff}} & \log g & \xi & R_{\odot} & f(V) & N \\
\hline
\text{RGB} & 12.502 & 1.564 & 3995 & 0.33 & 1.87 & 100.95 & 0.0141 & 1 \\
 & 12.675 & 1.450 & 4125 & 0.51 & 1.83 & 81.63 & 0.0361 & 3 \\
 & 12.754 & 1.377 & 4218 & 0.62 & 1.81 & 71.90 & 0.0224 & 2 \\
 & 12.981 & 1.334 & 4266 & 0.75 & 1.78 & 61.81 & 0.0544 & 6 \\
 & 13.332 & 1.218 & 4437 & 1.03 & 1.73 & 45.60 & 0.0394 & 6 \\
 & 13.683 & 1.164 & 4531 & 1.22 & 1.69 & 36.34 & 0.0332 & 7 \\
 & 14.270 & 1.081 & 4676 & 1.54 & 1.62 & 24.94 & 0.0761 & 28 \\
 & 14.748 & 1.014 & 4686 & 1.75 & 1.57 & 19.86 & 0.0284 & 16 \\
 & 15.398 & 0.952 & 4810 & 2.07 & 1.50 & 13.63 & 0.0712 & 74 \\
 & 16.446 & 0.879 & 4975 & 2.57 & 1.40 & 7.64 & 0.0695 & 197 \\
 & 17.470 & 0.824 & 5114 & 3.04 & 1.30 & 4.34 & 0.0419 & 296 \\

\text{SGB} & 18.185 & 0.769 & 5265 & 3.40 & 1.22 & 2.96 & 0.0252 & 338 \\
 & 18.512 & 0.619 & 6166 & 3.85 & 1.13 & 1.76 & 0.0530 & 960 \\

\text{MS} & 18.959 & 0.568 & 6403 & 4.09 & 1.07 & 1.32 & 0.0630 & 1720 \\
 & 19.475 & 0.588 & 6336 & 4.28 & 1.03 & 1.07 & 0.0707 & 3120 \\
 & 20.147 & 0.651 & 6075 & 4.47 & 0.99 & 0.86 & 0.0552 & 4557 \\
 & 20.992 & 0.773 & 5586 & 4.64 & 0.96 & 0.70 & 0.0323 & 5928 \\
 & 22.113 & 0.999 & 4716 & 4.70 & 0.94 & 0.66 & 0.0067 & 3549 \\

\text{AGB/HB} & 13.697 & 1.052 & 4757 & 1.36 & 1.65 & 30.79 & 0.0363 & 8 \\
 & 14.471 & 0.948 & 4820 & 1.70 & 1.58 & 20.75 & 0.0302 & 16 \\
 & 15.084 & 0.861 & 5018 & 2.05 & 1.51 & 13.96 & 0.0129 & 10 \\
 & 15.468 & 0.733 & 5374 & 2.36 & 1.44 & 9.78 & 0.0170 & 19 \\
 & 15.615 & 0.599 & 5855 & 2.59 & 1.39 & 7.43 & 0.0144 & 18 \\
 & 15.718 & 0.521 & 6438 & 2.82 & 1.34 & 5.70 & 0.0080 & 11 \\
 & 15.654 & 0.436 & 6773 & 2.90 & 1.33 & 5.24 & 0.0069 & 9 \\
 & 15.610 & 0.292 & 7360 & 3.04 & 1.30 & 4.46 & 0.0097 & 12 \\
 & 15.481 & 0.179 & 7886 & 3.11 & 1.28 & 4.13 & 0.0267 & 30 \\
 & 15.529 & 0.103 & 8372 & 3.21 & 1.26 & 3.65 & 0.0111 & 13 \\
 & 15.834 & 0.028 & 9168 & 3.45 & 1.21 & 2.79 & 0.0163 & 25 \\
 & 15.953 & 0.021 & 10 189 & 3.58 & 1.18 & 2.39 & 0.0045 & 8 \\
 & 17.501 & 0.144 & 15 471 & 4.50 & 0.99 & 0.83 & 0.0001 & 1 \\
 & 18.145 & 0.355 & 7309 & 4.02 & 1.09 & 1.44 & 0.0042 & 57 \\
 & 17.356 & 0.146 & 8264 & 3.92 & 1.11 & 1.62 & 0.0030 & 20 \\

The average \(V\) and \((V-I)\) colours of each box are shown, along with the average effective temperature,
surface gravity, microturbulence, radius, fractional \(V\)-band flux and number of stars assigned to each
box. The different evolutionary stages of the boxes are also shown, where RGB stands for red giant
branch, SGB for subgiant branch, MS for main sequence, AGB for asymptotic giant branch, HB for
horizontal branch and BS for blue stragglers. Note that the 50 per cent light level for M3 is \(V_{1/2} =
15.65\), which reaches the middle of the HB.

\[8\]http://kurucz.harvard.edu/grids.html

NGC 7006 and M15, the \(V, I\) HST photometry from the ACS Galactic
Globular Cluster Survey (e.g. Sarajedini et al. 2007; Anderson et al. 2008; Dotter et al. 2011) provided the estimates for the stellar
atmospheric parameters. The \(m - M\) and \(E(B-V)\) values from
Harris (1996; 2010 edition), the \(E(V-I)\) extinction corrections
of McCall (2004) and the \((V-I)\) colour–temperature conversions
from Ramirez & Melendez (2005) then provided the temperatures and
surface gravities of the stars, as described in MB08. For stars that
fell outside the Ramirez & Melendez (2005) calibration space,
the atmospheric parameters of the Kurucz models that best matched
the observed values were adopted. An empirical relationship be-
tween the surface gravity and the microturbulence (also described
in MB08) provided values for \(\xi\).

The input photometry does not exactly match the populations
observed in the ILS. Although the photometry was selected to only
include stars within the maximum radii covered by the HET, the
non-circular coverage of the ILS introduces some population dif-
fences (particularly for M15; see Fig. 1). Field star contamination
may also affect the input photometry and the observed spectrum.
The presence of even one additional bright star can affect the ob-
served ILS and the subsequent analysis (for example, the bright

\[364\] C. M. Sakari et al.
blue star in NGC 7006’s CMD). The effects of stochastic sampling of the brightest stars in unresolved targets have been investigated by Colucci et al. (2011), who used Monte Carlo sampling to populate their stellar populations. They found, for an old, metal-poor GC, that the maximum difference in [Fe/H] is only ~0.08 dex when randomly repopulating the entire GC. Resolved Galactic GCs, that the maximum difference in [Fe/H] is only 

| CMD box | \(V_{0,\text{avg}}\) | \((V - I)_{0,\text{avg}}\) | \(T_{\text{eff}}\) (K) | \(\log g\) | \(\xi\) (km s\(^{-1}\)) | \(R\) (R\(_{\odot}\)) | \(f(V)\) | \(N\) |
|---------|----------------|-----------------|----------------|--------|----------------|----------------|--------|-----|
| RGB     | 11.739         | 1.494           | 4083           | 0.400  | 1.86           | 93.39          | 0.0158 | 1   |
|         | 11.907         | 1.494           | 4070           | 0.458  | 1.85           | 87.35          | 0.0136 | 1   |
|         | 12.059         | 1.373           | 4221           | 0.649  | 1.81           | 70.16          | 0.0236 | 2   |
|         | 12.474         | 1.257           | 4377           | 0.933  | 1.75           | 50.57          | 0.0561 | 7   |
|         | 12.740         | 1.192           | 4477           | 1.110  | 1.71           | 41.23          | 0.0565 | 9   |
|         | 13.035         | 1.155           | 4541           | 1.269  | 1.67           | 34.36          | 0.0526 | 11  |
|         | 13.601         | 1.061           | 4717           | 1.600  | 1.60           | 23.46          | 0.0556 | 20  |
|         | 14.123         | 1.003           | 4707           | 1.803  | 1.56           | 18.58          | 0.0350 | 20  |
|         | 14.681         | 0.952           | 4809           | 2.081  | 1.50           | 13.48          | 0.0808 | 78  |
|         | 15.469         | 0.890           | 4948           | 2.467  | 1.42           | 8.65           | 0.0506 | 101 |
|         | 16.134         | 0.852           | 5040           | 2.776  | 1.35           | 6.06           | 0.0369 | 135 |
|         | 16.839         | 0.816           | 5133           | 3.100  | 1.29           | 4.17           | 0.0486 | 346 |
| SGB     | 17.525         | 0.779           | 5247           | 3.424  | 1.22           | 2.87           | 0.0196 | 257 |
|         | 17.809         | 0.662           | 5987           | 3.808  | 1.13           | 1.85           | 0.0357 | 608 |
| MS      | 18.213         | 0.585           | 6329           | 4.074  | 1.08           | 1.36           | 0.0677 | 1676|
|         | 18.738         | 0.580           | 6369           | 4.295  | 1.03           | 1.05           | 0.0805 | 3249|
|         | 19.441         | 0.635           | 6146           | 4.507  | 0.99           | 0.83           | 0.0812 | 6352|
|         | 20.367         | 0.762           | 5633           | 4.710  | 0.94           | 0.65           | 0.0478 | 8903|
|         | 21.594         | 1.007           | 4699           | 4.778  | 0.93           | 0.60           | 0.0158 | 9561|
| AGB     | 13.473         | 0.969           | 4776           | 1.581  | 1.61           | 23.99          | 0.0223 | 7   |
|         | 14.022         | 0.841           | 5069           | 1.947  | 1.53           | 15.74          | 0.0134 | 7   |
|         | 14.646         | 0.817           | 5133           | 2.224  | 1.47           | 11.43          | 0.0044 | 4   |
| HB      | 14.851         | 0.194           | 7816           | 3.139  | 1.28           | 3.99           | 0.0153 | 17  |
|         | 14.879         | 0.054           | 8836           | 3.322  | 1.24           | 3.23           | 0.0261 | 32  |
|         | 15.389         | -0.013          | 9951           | 3.649  | 1.17           | 2.22           | 0.0247 | 46  |
|         | 16.169         | -0.105          | 13 400         | 4.157  | 1.06           | 1.24           | 0.0122 | 53  |
|         | 17.645         | -0.214          | 20 818         | 4.733  | 0.94           | 0.64           | 0.0013 | 10  |
|         | 18.333         | -0.247          | 24 467         | 5.000  | 0.78           | 0.27           | 0.0024 | 67  |
| BS      | 16.465         | 0.193           | 7980           | 3.809  | 1.13           | 1.85           | 0.0019 | 10  |
|         | 17.656         | 0.341           | 7408           | 4.144  | 1.06           | 1.25           | 0.0022 | 34  |

The 50 per cent light level for M13 is \(V_{1/2} = 15.45\), which is slightly below the reddest HB stars.

The CMD boxes for M3, M13, NGC 7006 and M15 are shown in Fig. 3, while Tables 4–7 list the characteristics of these population boxes (see MB08 for a figure and list of the 47 Tuc boxes). The stars are boxed in approximately the same way as 47 Tuc, i.e. the number of red giant branch (RGB) and main-sequence boxes is approximately the same, and the coarseness of the boxes increases down the RGB. The number of boxes on the HB differs between the clusters as a result of the different HB morphologies. A forthcoming paper (Sakari et al., in preparation) shows that redefining the boxes has a negligible effect on the output abundances. The approximate evolutionary stages for each box are also shown in Tables 4–7, while the 50 per cent \(V\) magnitude light levels are indicated by dashed lines in Fig. 3. This shows that the brightest red giants, AGB stars and HB stars truly do dominate the \(V\)-band flux.

The number of stars drops slightly in the lower main-sequence boxes. This may be due to a combination of photometric incompleteness and mass segregation. Increasing the number of stars in the faintest two boxes has an insignificant effect on the abundances, suggesting that this effect can be neglected.

### 3.1.3 Metallicities

The iron abundances were determined through an IL EW analysis, as described in MB08. The EWs were measured with a modified version of the automated program DAOSPEC\(^9\) (Stetson & Pancino)

\(^9\) DAOSPEC has been written by P. B. Stetson for the Dominion Astrophysical Observatory of the Herzberg Institute of Astrophysics, National Research Council, Canada.

---

---
for all lines.\(^\text{10}\) In individual stars, the FWHM is often dominated by \(R\) (providing their EWs. One major advantage of DAOSPEC over hand lines in a defined region and fits Gaussian profiles to the lines, iteratively fits a continuum to the input spectrum, detects the spectral to our knowledge, this is its first application to ILS. The program

\[10\text{ Though of course this fixed FWHM, } \Delta \lambda, \text{ is allowed to scale appropriately with wavelength, given the constant resolving power of the spectrum, } R = \lambda / \Delta \lambda.\]

The success of DAOSPEC seems highly dependent on the choice of input parameters, at least for ILS. DAOSPEC has the option to determine its own FWHM. However, because ILS contain so many weak and/or blended features, the FWHM was fixed to the input parameter. This input FWHM is the sum (in quadrature) of the broadening from the velocity dispersion, the spectrograph and the intrinsic broadening of Arcturus (see Section 2.3), and is given in pixels. This FWHM was then allowed to scale with wavelength. Another important input is the order of the polynomial fit to the continuum. For individual stars, Stetson & Pancino (2008) found that higher order continuum fits produced the best results. Again, however, ILS suffer from contributions from a variety of stars, severe blends and line blanketing; high-order fits could therefore remove real features from the spectra, leading to underestimates of the line strengths. As described in Section 2.2, the HET spectra presented here have been carefully and conservatively normalized – thus the continuum was unchanged from the input. Occasionally valuable lines were mismeasured by DAOSPEC; these lines were remeasured with Gaussian fits in IRAF’s splot task.

Previous tests have shown that with the correct input parameters, DAOSPEC is capable of reproducing splot-measured EWs (in IRAF) for individual stars (Stetson & Pancino 2008; Sakari et al. 2011). DAOSPEC is also capable of reproducing splot EWs in the ILS of 47 Tuc. Fig. 4(a) shows that for Fe lines the agreement between DAOSPEC and splot EWs is excellent, with an average offset of only 1.76 mÅ, though the scatter about the average is significant (±9.93 mÅ). This scatter is likely caused by blends in the ILS, which can be difficult to detect by eye. DAOSPEC also reproduces the EWs of MB08, which

### Table 6. NGC 7006’s CMD boxes.

| Region | \(V_{0, \text{avg}}\) | \((V - I)_{0, \text{avg}}\) | \(T_{\text{eff}}\) (K) | \(\log g\) | \(\xi\) (km s\(^{-1}\)) | \(R\) (\(R_\odot\)) | \(f(V)\) | \(N\) |
|--------|----------------|----------------|-----------------|---|----------------|----------------|---|---|
| RGB    | 15.694         | 1.539          | 4022            | 0.371 | 1.87           | 96.61         | 0.0197 | 1  |
|        | 15.800         | 1.504          | 4058            | 0.445 | 1.85           | 88.69         | 0.0357 | 2  |
|        | 15.941         | 1.300          | 4333            | 0.726 | 1.79           | 64.21         | 0.0157 | 1  |
|        | 16.215         | 1.327          | 4271            | 0.793 | 1.78           | 59.40         | 0.0122 | 1  |
|        | 16.455         | 1.247          | 4389            | 0.975 | 1.74           | 48.20         | 0.0195 | 2  |
|        | 16.645         | 1.196          | 4469            | 1.107 | 1.71           | 41.40         | 0.0327 | 4  |
|        | 16.855         | 1.194          | 4465            | 1.188 | 1.69           | 37.69         | 0.0472 | 7  |
|        | 17.400         | 1.096          | 4644            | 1.517 | 1.62           | 25.82         | 0.0568 | 14 |
|        | 17.896         | 1.049          | 4735            | 1.768 | 1.57           | 19.33         | 0.0460 | 18 |
|        | 18.517         | 0.987          | 4738            | 2.018 | 1.52           | 14.50         | 0.0895 | 62 |
|        | 19.211         | 0.930          | 4856            | 2.357 | 1.44           | 9.81          | 0.0465 | 61 |
|        | 20.276         | 0.876          | 4981            | 2.845 | 1.34           | 5.59          | 0.0871 | 328 |
| SGB    | 21.312         | 0.808          | 5156            | 3.339 | 1.23           | 3.17          | 0.0196 | 177 |
|        | 21.607         | 0.663          | 5978            | 3.765 | 1.14           | 1.94          | 0.0664 | 792 |
| MS     | 22.181         | 0.627          | 6151            | 4.048 | 1.08           | 1.40          | 0.0748 | 1516 |
|        | 22.774         | 0.660          | 6022            | 4.243 | 1.04           | 1.12          | 0.0491 | 1722 |
|        | 23.392         | 0.722          | 5774            | 4.409 | 1.01           | 0.92          | 0.0237 | 1467 |
|        | 23.998         | 0.812          | 5439            | 4.530 | 0.98           | 0.80          | 0.0070 | 759 |
|        | 24.733         | 0.955          | 4804            | 4.534 | 0.98           | 0.80          | 0.0021 | 454 |
| AGB    | 16.429         | 1.101          | 4668            | 1.141 | 1.70           | 39.81         | 0.0299 | 3  |
|        | 17.233         | 1.008          | 4697            | 1.481 | 1.63           | 26.91         | 0.0281 | 6  |
|        | 17.694         | 0.941          | 4833            | 1.739 | 1.57           | 19.99         | 0.0372 | 12 |
| HB     | 18.496         | 0.823          | 5115            | 2.197 | 1.48           | 11.81         | 0.0265 | 18 |
|        | 18.718         | 0.663          | 5612            | 2.489 | 1.42           | 8.43          | 0.0266 | 22 |
|        | 18.747         | 0.493          | 6542            | 2.809 | 1.35           | 5.83          | 0.0244 | 21 |
|        | 18.638         | 0.244          | 7564            | 3.040 | 1.30           | 4.47          | 0.0363 | 28 |
|        | 18.713         | 0.093          | 8451            | 3.240 | 1.26           | 3.55          | 0.0308 | 26 |
| BS     | 21.184         | 0.407          | 7063            | 3.912 | 1.11           | 1.63          | 0.0039 | 33 |
|        | 20.583         | 0.209          | 7923            | 3.883 | 1.12           | 1.69          | 0.0053 | 26 |

\(^{10}\text{The 50 per cent light level is } V_{1/2} = 18.75, \text{i.e. in the middle of the HB.}\)
Table 7. M15’s CMD boxes.

|      | V0,avg | (V − I0,avg) | T_eff (K) | log g | ξ (km s⁻¹) | R (R☉) | f(V) | N |
|------|--------|--------------|-----------|-------|-----------|--------|------|---|
| RGB  | 12.452 | 1.361 | 4349 | 0.446 | 1.85 | 88.58 | 0.0107 | 1 |
|      | 12.599 | 1.271 | 4464 | 0.594 | 1.82 | 74.73 | 0.0373 | 4 |
|      | 12.830 | 1.228 | 4513 | 0.724 | 1.79 | 64.33 | 0.0151 | 2 |
|      | 13.061 | 1.157 | 4617 | 0.884 | 1.76 | 53.51 | 0.0967 | 16 |
|      | 13.569 | 1.082 | 4710 | 1.196 | 1.56 | 18.73 | 0.0706 | 66 |
|      | 15.503 | 0.880 | 4987 | 2.064 | 1.51 | 13.75 | 0.0487 | 77 |
|      | 16.136 | 0.843 | 5073 | 2.356 | 1.44 | 9.83 | 0.0383 | 108 |
|      | 16.814 | 0.800 | 5180 | 2.673 | 1.38 | 6.82 | 0.0518 | 274 |

Table 8. The Fe line list.a

| Wavelength (Å) | Element | E.P. (eV) | log gf | EW (mÅ) | 47 Tuc | M3 | M13 | NGC 7006 | M15 |
|----------------|---------|-----------|--------|---------|--------|----|-----|----------|-----|
| 5324.191       | Fe I    | 3.211     | −0.103 |        | −      | −  | −   |          | −   |
| 5339.937       | Fe I    | 3.266     | −0.72  |        | −      | −  | −   |          | −   |
| 5367.476       | Fe I    | 4.415     | 0.443  | 142.3   | 114.0  | 70.0 | 68.0 | 78.0     | 22.9 |
| 5369.974       | Fe I    | 4.371     | 0.536  | 144.0   | 147.0  | 72.5 | 73.2 | 75.1     | −   |
| 5371.501       | Fe I    | 0.958     | −1.644 | −       | −      | −   | −   | 108.6    | −   |

SGB 18.069 0.702 5460 3.285 1.25 3.37 0.0344 576
18.366 0.556 5985 3.588 1.18 2.38 0.0427 939
MS 18.947 0.520 6612 4.009 1.09 1.46 0.0863 3261
19.649 0.554 6495 4.252 1.04 1.11 0.0621 4473
20.399 0.633 6164 4.451 1.00 0.88 0.0414 5994
21.285 0.770 5617 4.627 0.96 0.72 0.0278 17
17.448 0.921 4898 1.796 1.56 18.73 0.0706 66
15.503 0.880 4987 2.064 1.51 13.75 0.0487 77
16.136 0.843 5073 2.356 1.44 9.83 0.0383 108
16.814 0.800 5180 2.673 1.38 6.82 0.0518 274
17.448 0.766 5270 2.963 1.31 4.88 0.0342 323
18.069 0.702 5460 3.285 1.25 3.37 0.0344 576
18.366 0.556 5985 3.588 1.18 2.38 0.0427 939

The 50 per cent light level for M15 is V1/2 = 15.84, which runs through the red HB stars.

Table 8. The Fe line list.a

| Wavelength (Å) | Element | E.P. (eV) | log gf | EW (mÅ) | 47 Tuc | M3 | M13 | NGC 7006 | M15 |
|----------------|---------|-----------|--------|---------|--------|----|-----|----------|-----|
| 5324.191       | Fe I    | 3.211     | −0.103 | −       | −      | −  | −   |          | −   |
| 5339.937       | Fe I    | 3.266     | −0.72  | −       | −      | −  | −   |          | −   |
| 5367.476       | Fe I    | 4.415     | 0.443  | 142.3   | 114.0  | 70.0 | 68.0 | 78.0     | 22.9 |
| 5369.974       | Fe I    | 4.371     | 0.536  | 144.0   | 147.0  | 72.5 | 73.2 | 75.1     | −   |
| 5371.501       | Fe I    | 0.958     | −1.644 | −       | −      | −   | −   | 108.6    | −   |

EWs were measured in DAOSPEC; all strong lines were checked and refined in splot. The lines that were not measured in the solar spectrum were those stronger than EW > 150 mÅ.

Table 8 is published in its entirety in the electronic edition of MNRAS. A portion is shown here for guidance regarding its form and content.

were measured with the program GETJOB (McWilliam et al. 1995a). The offset between the data sets remains insignificant (0.37 mÅ, with the DAOSPEC EWs slightly higher), and the scatter is smaller (±6.69 mÅ). Note that MB08 did not combine their apertures; the spectral lines in the overlapping regions were measured twice, and both measurements were included in their analysis. For this EW comparison, the two EWs were averaged together for all lines in the overlapping regions. In individual stars, DAOSPEC often underestimates the EWs of the strongest lines (e.g. Sakari et al. 2011) – thus, the EWs of these lines have been verified or corrected in splot. DAOSPEC is therefore capable of accurately reproducing the EWs of the lines in the 47 Tuc ILS. Since 47 Tuc has a higher velocity dispersion than most of the targets in this work (except for M15; see Table 2), DAOSPEC should also be able to accurately measure the EWs for all the target GCs. However, care must be taken with the strongest lines to ensure that they are properly measured, and attention must be paid to lines in regions with uncertain continuum normalization.

3.1.3.2 Fe abundances. The Fe I and Fe II EWs for the target GCs were input into ILABUNDS, along with the model atmospheres derived
from the HST photometry. The [Fe/H] values for each line were computed differentially (i.e. relative to the derived solar abundance for that line), in order to reduce uncertainties from, e.g., atomic data. If the solar lines were stronger than EW $\geq$ 200 mÅ, a value of $\log \epsilon_{Fe} = 7.50$ (Asplund et al. 2009) was instead adopted. The average [Fe/H] and [Fe ii/H] ratios for Arcturus and the target GCs are shown in Table 9. Also shown are the uncertainties in the average Fe abundances, as determined from the line-to-line scatter, $\sigma$, divided by $\sqrt{N}$, where $N$ is the number of lines. Since only a single line is available for M15's Fe ii abundance, the Cayrel (1988) formula was used to determine the error in the Fe ii line's EW, as described in Sakari et al. (2011). The adopted uncertainty in abundance was then found by rerunning ILABUNDS with the new EWs.

As stated earlier, the Arcturus values agree well with Yong et al. (2005). The GC [Fe/H] values in Table 9 agree quite well with the literature values quoted in Harris (1996; 2010 edition), which are also shown in Table 9. The 47 Tuc IL [Fe ii/H] values are slightly different from the ILS values from MB08 (which are also shown in Table 9), though the 47 Tuc IL [Fe ii/H] ratios are in excellent agreement with MB08. Given that the EWs (Fig. 4b) and CMD boxes are nearly identical, and since both [Fe ii/H] ratios have been computed differentially, it is puzzling that the [Fe ii/H] values are not in agreement. The two log $\epsilon_{Fe}$ values are actually in agreement (log $\epsilon_{Fe} = 6.73$ compared to MB08's 6.77) – this suggests that there are differences in how the differential ratios are computed.

For the remainder of this paper, all quoted [X/Fe] values are computed with the IL Fe abundances derived here.

3.1.4 Hot stars

Stars hotter than $\sim$8000 K are expected to show chemical abundance variations as a result of radiative levitation which may bring the hottest stars up to solar composition (e.g. Behr, Cohen & McCarthy 2000; Behr 2003; Lovisi et al. 2012). To test this result, syntheses of M13 were completed with solar composition hot stars. These tests are discussed in more detail in a forthcoming paper; here it is simply noted that these abundance variations have a negligible effect on the syntheses of the lines studied here.

Hot stars have also been observed to have large rotational velocities (up to $\sim$60 km s$^{-1}$; Behr 2003). Syntheses were also performed on M13, assuming that all stars hotter than 8000 K have solar composition and rotational velocities of $\sin i = 60$ km s$^{-1}$. The effects are again negligible, since the increased broadening weakens the line strengths in HB stars. The changes in composition and the high rotation of HB stars are therefore ignored in this analysis.

3.2 Input line lists

To demonstrate the necessity of having a complete, calibrated line list, spectrum syntheses were performed with three different line lists.

**Minimal list:** this list uses only lines found in standard RGB EW analyses. The ILS-specific line lists from MB08 and Colucci et al. (2009) were supplemented with additional RGB lines [from the line lists assembled in Sakari et al. (2011) and Venn et al. (2012)].

**VALD list:** this list consists of RGB lines from the Vienna Atomic Line Database11 (VALD; Kupka et al. 2000). These are lines that VALD has determined would appear (to at least 2 per cent) in a tip of the RGB star at 47 Tuc's metallicity. None of the atomic data were changed from the VALD values.

11 http://www.astro.uu.se/vald/php/vald.php
Figure 5. Syntheses of the Arcturus spectral regions around the 5528 Å Mg I (left) and 6645 Å Eu II (right) lines. The cyan lines show syntheses of only atomic lines (i.e., no molecular lines were included), with isotopic and HFS components included for the Eu II line in (b). It is evident that atomic lines do not account for all the lines in the regions. The Mg I region contains mainly MgH lines, while the Eu II region contains CN lines. The blue lines in the left-hand image indicate Mg isotopic ratios of 48: 13: 39 for $^{24}$Mg:$^{25}$Mg:$^{26}$Mg (Yong et al. 2006), while the magenta lines indicate Mg isotopic ratios of 83: 10: 7 (Yong et al. 2003). The orange, blue and magenta lines in the right-hand image show $^{12}$C/$^{13}$C ratios of 50, 9 and 4, respectively.

Figure 6. Spectrum syntheses of the 5528 Å Mg I line on the 47 Tuc ILS with the minimal, VALD and final line lists. Uncertainties in continuum location and line profile fitting are both considered. The red lines show the average abundance, while the green/blue lines show the $\pm 1\sigma$ abundances, respectively. The shaded grey regions indicate areas with possible HFS components, while the hatched light purple regions indicate uncertain molecular features. Both types of regions have been ignored for continuum fits.
**Final list:** The final line list consists of lines from the minimal list, with supplements from VALD for the coolest RGB stars, warmer RGB stars and hot stars, all at 47 Tuc’s metallicity. Lines that should appear in the solar spectrum were also included. As shown below, the atomic data from VALD are not capable of reproducing the strengths or profiles of all the lines in the solar and Arcturus spectra. Thus, atomic data (i.e. log $gf$ values, damping parameters and wavelengths) were checked in both the Kurucz\(^\text{12}\) and National Institute of Standards and Technology (NIST)\(^\text{13}\) data bases. These atomic data were then adjusted so that the solar and Arcturus spectra were accurately reproduced in the syntheses. The final line list also contains molecular lines from the Kurucz data base, as described in Section 3.2.2.

### 3.2.1 Hyperfine structure

Hyperfine structure (HFS) occasionally affects lines in the synthesized spectral regions. The HFS components are not included at this time (except for the case of the Eu II line in Section 4.3) though their presence is noted. All regions with possible HFS components were ignored when determining continuum levels. In the future, these components can also be incorporated into the syntheses.

### 3.2.2 Molecular lines

As discussed above, spectral lines from several important molecules (e.g. CH, CN and MgH) are also included in the final list when the lines were detected in the Arcturus Atlas (Hinkle et al. 2003). The MOOG 1997 default values for the molecular equilibrium calculations were employed, with the exception of the MgH dissociation energy, for which the MOOG 2010 value was adopted.

Syntheses of these molecular features require input C and N abundances, and $^{12}\text{C}/^{13}\text{C}$ and $^{24}\text{Mg}/^{25}\text{Mg}/^{26}\text{Mg}$ ratios. For each cluster, ‘integrated’ C and N abundances are derived to best fit the molecular lines – each integrated abundance is adopted for the whole cluster, and star-to-star variations are not considered. The observed isotopic ratios from individual stars can vary significantly, even within a single cluster. The $^{12}\text{C}/^{13}\text{C}$ ratio has been observed to vary from $>50$ down to $\sim 4$ (Lambert & Ries 1981; Gilroy & Brown 1991; Gratton et al. 2000). In M13, NGC 6752 and M71, Yong et al. (2003) and Yong, Aoki & Lambert (2006) found $^{24}\text{Mg}/^{25}\text{Mg}/^{26}\text{Mg}$ ratios ranging from 48: 13: to 83: 10: 7. Fig. 5 shows the effects of varying the isotopic ratios, as well as the effects of neglecting all molecular lines, in the regions around the 5528 Å Mg I and the 6645 Å Eu II line (the regions with molecular lines, according to the Arcturus

---

\(^{12}\text{http://kurucz.harvard.edu/linelists.html}\)

\(^{13}\text{http://www.nist.gov/index.html}\)
Spectrum syntheses of high resolution ILS

Here $^{12}$C/$^{13}$C ratios of 4, 9 and 50 are considered, as well as $^{24}$Mg/$^{25}$Mg/$^{26}$Mg ratios of 48: 13: 39 and 83: 10: 7. In these regions, the isotopic ratios do not significantly affect the continuum levels or the specific lines that are being synthesized. Hence, different isotopic ratios are not investigated in the ILS syntheses.

It should also be noted that none of the molecular lines have been calibrated to the solar and Arcturus spectra (i.e. none of the atomic data, etc., were changed from the Kurucz values). Any regions with mismatching/uncertain molecular features (whether from isotopic ratios or atomic data) are identified in the syntheses with the final line list.

3.2.3 Damping

Damping (e.g. from pressure broadening) can affect the abundances derived from strong lines. For consistency, damping is included for the strongest lines (in the Arcturus spectrum). The damping is implemented in ILABUNDS in a similar way as the 2010 version of MOOG, i.e. the damping parameters from Barklem, Piskunov & O’Mara (2000) and Barklem & Aspelund-Johansson (2005) were converted to C6 parameters. When damping data were not available from the Barklem sources (or when they did not provide satisfactory fits to the solar/Arcturus spectra), values from the VALD or Kurucz data bases were included.

4 SPECTRUM SYNTHESIS RESULTS

Any rigorous spectrum synthesis method should yield abundances with random errors that are less than or equal to the standard error from an EW analysis, whether for individual stars or an ILS (though an EW analysis may still be the preferable choice when the line profiles are uncertain, or if the S/N is quite low). An EW analysis of Fe I lines from an $R \approx 30000$ and S/N $\sim 100$ spectrum of an RGB star results in a line-to-line scatter of $\sim \pm 0.1$ dex (e.g. Sakari et al. 2011). Since there are many Fe I lines, and each line is considered to be an independent measurement, the average Fe I abundance has a random error of $\sim 0.1/\sqrt{N}$ dex (though systematic uncertainties may be larger, as discussed by McWilliam et al. 1995a). However, for a single line, this random measurement error in the elemental abundance cannot be determined directly. Therefore, $\pm 0.1$ dex is adopted as the minimum uncertainty in the abundance of any single spectral line in an $R = 30000$ and S/N $= 100$ spectrum. Since the GC ILS have the same qualities, the goal of this analysis is to reduce the spectrum synthesis abundance uncertainties to this minimum.

Sections 4.1, 4.2 and 4.3 show the IL syntheses of Mg, Na and Eu lines in the ILS of the five Galactic GCs. Each section begins with

Figure 8. Spectrum syntheses of the 5528 Å Mg I line in the solar (top) and Arcturus (bottom) spectra. Lines are as in Fig. 6. Note that only the best fits are shown, as the differences in the $\pm 1\sigma$ syntheses are generally too small to see.
syntheses of the 47 Tuc ILS, using the three different line lists (see Section 3.2). For each case, the errors due to continuum placement and profile fitting are discussed in detail, and it is shown that neither the minimal nor VALD line lists are sufficient for reducing the errors to a satisfactory level. Each section then presents syntheses on the other Galactic GCs, using only the final line list.

4.1 Mg: the 5528 and 5711 Å lines

Magnesium is an important element in any abundance analysis. As an $\alpha$-element, Mg can trace the chemical contributions from massive stars, particularly Type II supernovae. Additionally, its nucleosynthetic history is simpler than many other elements that form entirely through core burning in massive stars. In GCs, however, Mg has been observed to vary among stars in a single cluster (e.g. Shetrone 1996; Gratton et al. 2004), which means that an ILS abundance may not reflect the ‘primordial’ $\alpha$-abundance of the cluster. The effects of star-to-star chemical variations will be investigated more in the future – the current work is limited to a single ILS Mg abundance per cluster.

4.1.1 Mg in 47 Tuc: the minimal and VALD line lists

This section first presents spectrum syntheses of the 47 Tuc ILS Mg I lines using only the lines in the minimal and VALD line lists. This is to show that a complete line list that has been calibrated to the Sun and Arcturus is necessary, and affects the precision of the results. The next section (Section 4.1.2) presents results with the Sun and Arcturus is necessary, and affects the precision of the

4.1.1.1 5528 Å

The 5528 Å feature is typically strong in metal-rich ([Fe/H] $\gtrsim$ −1.0) stars. In the 47 Tuc spectrum, the EW of this line is $\sim$230 mA, making the line too strong for an abundance analysis, since the uncertainties in damping, stellar structure and non-LTE (NLTE) corrections become too large. However, this 5528 Å feature is not as strong in the more metal-poor clusters (such as M3, M13, NGC 7006 and M15), and the spectral region must therefore be calibrated.

Fig. 6 shows syntheses of the 5528 Å line in 47 Tuc with the two basic line lists. The top panel shows the syntheses with lines only from the minimal list, while the middle panel shows the syntheses with the VALD line list. In addition to the Mg I line, only two other lines are in the minimal list (an Fe I line at 5522.45 Å and an Sc II line at 5526.82 Å). The scarcity of lines makes it very difficult to distinguish weak lines from noise. This leads to large uncertainties in continuum placement, as shown by the large vertical offsets. This uncertainty leads to Mg abundance errors that are $\sim$0.20 dex, which is insufficient for distinguishing between an Mg-enhanced and non-Mg-enhanced cluster.

The VALD line list (which includes more lines) helps significantly with continuum identification. Different continuum shifts are still necessary in order to fit the different features, and it is still difficult to distinguish weak features from noise. In this case, the best-fitting synthesis leads to Mg abundance errors that are $\pm$0.15 dex – this uncertainty is lower than before, but is still large.

4.1.1.2 5711 Å

The only RGB line from the minimal list that appears in this spectral region is the 5711 Å Mg I line itself. Without any additional lines in the region, it is difficult to locate the continuum level in the region, as illustrated by the synthesis of 47 Tuc in

Table 10. Solar, Arcturus and GC abundances.

|            | Sun  | Arcturus | 47 Tuc | M3       | M13       | NGC 7006 | M15       |
|------------|------|----------|--------|----------|-----------|----------|-----------|
| Mg 5528 Å  | 7.75 ± 0.05 | 0.55 ± 0.18 | 0.39 ± 0.13 | 0.12 ± 0.11 | 0.13 ± 0.11 | 0.10 ± 0.14 | −0.15 ± 0.21 |
| Mg 5711 Å  | 7.58 ± 0.04 | 0.59 ± 0.06 | 0.44 ± 0.14 | 0.20 ± 0.07 | 0.14 ± 0.08 | 0.13 ± 0.20 | <0.55     |
| Mg Total   | −     | 0.57 ± 0.13 | 0.42 ± 0.14 | 0.16 ± 0.11 | 0.14 ± 0.10 | 0.12 ± 0.17 | −         |
| MB08       | −     | 0.22 ± 0.56 |         |          |           |          |           |
| Literature Avg | 7.60 ± 0.04 | 0.46 ± 0.09b | 0.40 ± 0.03 | 0.23 ± 0.03 | 0.11 ± 0.03 | 0.34 ± 0.02 | 0.35 ± 0.05 |
| Lit. Range | −     | [0, +0.6] | [−0.1, +0.6] | [−0.2, +0.5] | [0.3, +0.4] | [−0.4, +0.8] |           |
| Na 6154 Å  | 6.28 ± 0.02 | 0.20 ± 0.03 | 0.38 ± 0.15 | 0.27 ± 0.13 | 0.45 ± 0.10 | 0.66 ± 0.14 | 0.90 ± 0.40 |
| Na 6160 Å  | 6.33 ± 0.03 | 0.20 ± 0.04 | 0.37 ± 0.08 | 0.17 ± 0.13 | 0.20 ± 0.20 | 0.26 ± 0.13 | <1.05     |
| Na Total   | −     | 0.20 ± 0.04 | 0.38 ± 0.12 | 0.22 ± 0.13 | 0.33 ± 0.16 | 0.41 ± 0.14 | −         |
| MB08       | −     | 0.45 ± 0.10 |         |          |           |          |           |
| Literature Avg | 6.24 ± 0.04 | 0.18 ± 0.05b | 0.45 ± 0.01 | 0.02 ± 0.06 | 0.27 ± 0.06 | 0.32 ± 0.06 | 0.39 ± 0.06 |
| Lit. Range | −     | [−0.3, +1.0] | [−0.3, +0.3] | [−0.3, +0.6] | [0, +0.4] | [−0.6, +2.0] |           |
| Eu 6645 Å  | 0.45 ± 0.02 | 0.28 ± 0.05 | 0.27 ± 0.14 | 0.75 ± 0.11 | 0.76 ± 0.10 | 0.72 ± 0.15 | 1.31 ± 0.20 |
| MB08       | 0.45 |         | 0.04 |         |          |          |           |
| Literature Avg | 0.52 ± 0.04 | 0.26 ± 0.04 | 0.14 ± 0.03 | 0.51 ± 0.02 | 0.49 ± 0.03 | 0.36 ± 0.02 | 0.63 ± 0.03 |
| Lit. Range | −     | [−0.4, +0.4] | [0.4, +0.8] | [0.3, +1.0] | [0.3, +0.4] | [0.2, +2.2] |           |

The [X/Fe] ratios use Fe I for neutral species, and Fe II for singly ionized species. The mean literature values are straight, unweighted averages from all available sources. The quoted $\pm 1\sigma$ errors in the literature averages do not reflect the observed range in the abundances. The literature ranges show the approximate extremes that have been observed in the clusters. Flux-weighted averages may be more appropriate for comparisons with IL abundances; however, these averages require a reasonably complete sample that reflects the scanned population.

References: literature solar values are from Asplund et al. (2009). Arcturus literature values are an average of the values from Yong et al. (2005), Fulbright, McWilliam & Rich (2007), Ramírez & Allende Prieto (2011) and McWilliam et al. (in preparation, for Eu), after shifting to a common [Fe/H] = −0.6. The GC literature data are from observations of individual stars, and are from Pritzl et al. (2005), with supplements from Brown & Wallerstein (1992), Sneden et al. (1997, 2004), Kraft et al. (1998), Carretta et al. (2004, 2009), Jasniwickz et al. (2004), Cohen & Melendez (2005), Alves-Brito et al. (2005), Preston et al. (2006), Wylie et al. (2006), Koch & McWilliam (2008), Worley et al. (2009), Soebeck et al. (2011), Gratton et al. (2013). The 47 Tuc values from MB08 are also shown.

b Values were adjusted to [Fe/H] = −0.6.
In particular, it is unclear whether the peak bluewards of the 5711 Å line is the true continuum, noise, an improperly removed cosmic ray, etc. It is also unclear whether the width or depth of the line should be fitted. Considering all these factors, the uncertainty in the best-fitting abundance ends up being $\pm 0.25$.

As before, the increased number of lines in the VALD line list helps to isolate the continuum level. However, many of the synthesized lines in the region do not match the observed ones – some are stronger, others are weaker and some are missing altogether. With the VALD lines, the error in the best-fitting abundance becomes $\pm 0.17$. This level of uncertainty is better, but is still less than expected for a spectrum synthesis on such a high-S/N spectrum ($\sim 100$).

Thus, the minimal and VALD line lists are insufficient for the ILS syntheses of the regions around these two MgI lines, primarily because the continuum level cannot be clearly identified. These lists may be missing spectral lines (which are blended together in the ILS) – furthermore, the lines that are in the lists do not all fit the observed lines properly. This suggests that the line lists must be tested and calibrated on well-studied stars, such as the Sun and Arcturus.

### 4.1.2 Mg in 47 Tuc: the final line list

This section presents syntheses of the MgI lines in the solar, Arcturus and 47 Tuc spectra with the complete, calibrated final line lists. The regions with possible HFS components are highlighted in purple, while the regions with particularly uncertain molecular lines are highlighted with grey, hatched rectangles. These regions (and any with missing lines) were ignored in the final synthesis fits.

#### 4.1.2.1 5528 Å

The syntheses of the 5528 Å line are shown in Figs 6 and 8, while the final abundances are tabulated in Table 10. The addition of the MgH features in the final line list helps improve the continuum identification, particularly for the blended features in 47 Tuc. Despite the strength of the line, the synthesis of the 5528 Å line fits the solar spectrum quite well (see the top panel of Fig. 8). The best-fitting value is slightly higher than the Asplund et al. (2009) value, but is likely due to the strength of the line and the uncertain atomic data. The Arcturus abundance agrees well with the average literature value in Table 10.

In the 47 Tuc spectrum, the complete, calibrated line list leads to a synthetic spectrum that is an excellent fit to the observed spectrum, as shown in Fig. 8. This is due to two reasons: first, most of the lines in the region now fit better than before they were calibrated, and secondly, the best continuum regions are evident in the solar and Arcturus spectra, and can be used to fit the 47 Tuc continuum. However, the 47 Tuc syntheses indicate a best-fitting $[\text{Mg}/\text{Fe}]$ ratio that is higher than the MB08 value of $[\text{Mg}/\text{Fe}] = 0.22$ (which was determined from the EW of the 7387 Å MgI line, and which was
not calculated differentially). Adjusting the MB08 solar abundance leads to a higher [Mg/Fe] ratio in 47 Tuc, as shown below.

4.1.2.2 5711 Å. The syntheses of the 5711 Å Mg I line are shown in Figs 7 and 9. These fits show that there are missing lines in the syntheses of this region of the solar and Arcturus spectra, even with a complete, calibrated line list. Several lines in the region also require HFS components, e.g. the V I and Sc I lines. Despite the missing features, the strong lines are generally matched well in both the individual and 47 Tuc spectra, with the exception of the feature at 5709 Å. This feature is a blend of Ti I, Fe I, Ni I and Ti II features, where the Fe I and Ni II features dominate the line strength. It is unclear why the lines match in the solar spectrum, but not in the Arcturus or 47 Tuc spectra. Regardless, these features can be disregarded in the analyses.

The derived abundances are again tabulated in Table 10, along with comparison literature abundances. The solar abundance is in excellent agreement with the Asplund et al. (2009) value. The Arcturus [Mg/Fe] ratio is slightly higher than the average literature value, but the values agree within the errors. The 47 Tuc [Mg/Fe] ratio is again considerably higher than the MB08 value ([Mg/Fe] = 0.22), but is in excellent agreement with the values from the 5528 Å line and with the recalculated MB08 value (see below).

Taken together, the two Mg I lines provide a total [Mg I/Fe I] = 0.46 ± 0.14 for 47 Tuc. This qualitatively agrees with the literature stellar abundances assembled by Pritzl, Venn & Irwin (2005), i.e. 47 Tuc is Mg-enhanced, as expected for a Galactic GC at its metallicity, and the ILS value is in good agreement with the literature average. Ultimately, the calibrated final line list has reduced uncertainties in the Mg abundance ratios from the minimal and VALD lists from ~0.2 and ~0.18 to ~0.14. Thus, spectrum synthesis techniques with the carefully calibrated final line list are able to provide improved and precise abundances.

4.1.2.3 7387 Å. To compare the above Mg I IL abundances with MB08, the 7387 Å line was synthesized in the solar, Arcturus and 47 Tuc spectra using the VALD RGB line list only (Fig. 10). This region was not calibrated because it falls outside the observed spectral region of the HET clusters, and will not be used in this analysis. Many of the lines in the region do not fit well, precisely because they have not been calibrated. Molecular lines and HFS components were also not included, although the Arcturus Atlas (Hinkle et al. 2003) shows that there are CN lines in the region.

The solar synthesis in Fig. 10 shows that a solar abundance of log \( \epsilon_{\text{Mg}} = 7.30 \pm 0.02 \) is required to fit the observed feature; this

**Figure 10.** Spectrum syntheses of the 7388 Å Mg I line in the solar (top), Arcturus (middle) and 47 Tuc (bottom) spectra. The HFS regions are not shown, though there are several in this wavelength range. Molecular lines are also not included. Lines are as in Fig. 6.
value is significantly lower than the Asplund et al. (2009) Mg abundance. The line profile also cannot be fitted perfectly, as there seem to be extra components in the red wing of the Mg I line. The Arcturus synthesis fit is better, but the Mg abundance ($\log \epsilon_{\text{Mg}} = 7.15 \pm 0.03$) is lower than the other Mg lines; a differential comparison with the lower solar abundance leads to a normal $[\text{Mg I}/\text{Fe I}] = 0.50 \pm 0.04$. This suggests that the atomic data are systematically offset for this line, and illustrates the importance of using differential abundances and of checking all important lines in the solar and Arcturus spectra.

Syntheses of the 47 Tuc ILS yield $\log \epsilon_{\text{Mg}} = 7.21 \pm 0.20$ or $[\text{Mg I}/\text{Fe I}] = 0.72 \pm 0.20$. The large uncertainty in the abundance reflects the uncertainty in the continuum level, the uncertain line profile and the low S/N at the line centre. With the solar Mg abundance from the 7387 Å line, the MB08 value (which comes from an EW analysis of this line) can be recalculated differentially to $[\text{Mg I}/\text{Fe I}] = 0.56$ – this value now agrees with the 7388, 5528 and 5711 Å syntheses. Thus, the value quoted in MB08 is systematically lower than it should be, as a result of the lower solar abundance.

### 4.1.3 Mg in the other GCs

The Mg I abundances for M3, M13, NGC 7006 and M15, as determined from the final line list, are shown in Table 10 and Figs 11 and 12.

The fits to the Mg I lines are quite good for M3 and M13, but are much more uncertain for NGC 7006 (owing to its lower S/N) and M15 (as a result of its weaker lines). The 5528 Å line is easily detectable in all spectra, and there are enough additional lines to help isolate the continuum. The 5711 Å region, however, is much more difficult for M15, as is evident in Fig. 12; this line only provides an upper limit for the Mg abundance in M15. The final derived abundances are shown in Table 10.

The average Mg I ILS abundance ratios for M3, M13 and NGC 7006 are in excellent agreement with each other. With the exception of M13, all the ILS values are slightly lower than the average literature abundances, especially M15. These differences between the ILS abundances and the ‘average’ literature abundances are due to the known star-to-star Mg variations within the clusters. For example, the M15 Mg abundance quoted in Pritzl et al. (2005) is an average of 18 bright RGB stars observed by Sneden et al. (1997); the latter analysis showed that M15 has strong star-to-star Mg variations, in the range $-0.4 \lesssim [\text{Mg/Fe}] \lesssim +0.8$, with $[\text{Mg/Fe}]$ decreasing for stars higher up the RGB. Since ILS are dominated by the brightest stars, the M15 ILS is most likely dominated by the most Mg-poor giants, which decreases the IL Mg abundance. The derived ILS $[\text{Mg/Fe}]$ ratio for M15 does fall at the lower end of the observed abundance range. M3 and M13 also show signs of Mg variations (Sneden et al. 2004; Cohen & Melendez 2005) which most likely accounts for their slightly low average $[\text{Mg/Fe}]$.

![Figure 11. Spectrum syntheses of the 5528 Å Mg I line in M3, M13, NGC 7006 and M15. Lines are as in Fig. 6.](https://academic.oup.com/mnras/article-abstract/434/1/358/997300)
abundances in comparison to Milky Way field stars. However, even though these clusters also have star-to-star variations, their abundances do agree with the literature averages. This shows that caution must be taken when comparing ILS abundances to ‘average’ literature abundances from a limited sample of stars, as discussed in Section 5.2. Regardless, these comparisons with the literature abundances do show that spectrum syntheses of the 5528 and 5711 Å lines are capable of producing Galactic GC Mg I abundances that fall within the observed ranges from individual stars, provided that the lines are sufficiently strong and that the S/N is sufficiently high.

4.2 Na I 6154/6160 Å lines

Sodium has always been an interesting element for GC studies because, like magnesium, it varies strongly between stars in a single cluster. These variations are anticorrelated with O, and indicate abundance changes up the RGB and/or the presence of multiple stellar populations in GCs (e.g. Kraft et al. 1992; Gratton et al. 2004; Carretta et al. 2009). The Na/O anticorrelation has been detected in all unambiguous Galactic GCs, and seems to be a common signature of the GC formation process. Thus, Na is another significant element in GC studies.

Sodium lines are known to suffer from strong NLTE effects. To minimize NLTE effects, Lind et al. (2011) suggest that analyses at solar metallicity should use the 6154/6160 Å doublet, while analyses of more metal-poor stars ([Fe/H] ≲ −1.0) should use the 5682/5688 Å lines. However, literature results use both sets of lines, often without any NLTE corrections. Here the results for the 6154/6160 doublet are presented for all the GCs. The NLTE effects make it difficult to fit the solar 5682/5688 Å lines (in agreement with, e.g., Baumüller, Butler & Gehren 1998), which prevents a differential analysis from being done. Without a differential analysis the atomic data can lead to systematic offsets between lines. Further calibration work must therefore be done to synthesize the 5682/5688 Å doublet in ILS.

Mashonkina, Shimanskii & Sakhibullin (2000) also note that for all Na lines the strengths of NLTE corrections depend on the temperature and surface gravity of the stars, in addition to the stellar metallicity, and that Na abundances of giants cannot be accurately determined to within 0.1 dex without NLTE corrections. This could be particularly problematic for ILS, whose spectral lines contain contributions from stars over a wide range of $T_{\text{eff}}$ and log g. Despite these concerns, NLTE corrections are neglected in this analysis. However, as NLTE corrections are not generally applied to the comparison literature data, differential comparisons should be reasonably robust.

---

**Figure 12.** Spectrum syntheses of the 5711 Å Mg I line in M3, M13, NGC 7006 and M15. Lines are as in Fig. 6.
4.2.1 Na in 47 Tuc: the minimal and VALD line lists

Fig. 13 shows spectrum syntheses of the 6154/6160 Å doublet in 47 Tuc, using the minimal and VALD lists. The synthesis with the minimal line list (the top synthesis in Fig. 13) only has a few strong lines available for continuum identification. Furthermore, the features are strongly blended in the 47 Tuc spectrum, and there are a few obvious continuum locations. With only these strong lines, the errors in the best-fitting abundances are ±0.30 and ±0.13 for 6154 and 6160 Å, respectively. The VALD lines (the middle spectrum in Fig. 13) help slightly, bringing the abundance errors to ±0.25 and ±0.12, respectively.

With so many strong lines and blends in the region, it is easy to see how fitting becomes very difficult in ILS. In particular, it is difficult to isolate continuum regions and to know which regions should match the synthetic spectra, and which could be different as a result of improper atomic data, missing atomic or molecular lines, or HFS. Without solar and Arcturus calibrations to identify the best areas for continuum fitting, such a region is quite difficult to fit in ILS.

4.2.2 Na in 47 Tuc: the final line list

Figs 13 and 14 show syntheses of the 6154 and 6160 Å NaI lines in the solar, Arcturus and 47 Tuc spectra with the final line list. HFS contamination seems to be minimal in this region. The solar and Arcturus syntheses show that there are clearly lines missing from the line list, though they are mostly weak. The solar and Arcturus spectra also show that the syntheses cannot perfectly reproduce the shape of the 6154 Å NaI line – there seems to be a missing component slightly redwards of the line centre. Thus, the syntheses of the 47 Tuc spectrum focused primarily on fitting the depth of the line rather than the width.

The best-fitting abundances to the 6154/6160 Å Na I lines are shown in Table 10. The solar values are in reasonable agreement with the Asplund et al. (2009) value. The Arcturus value is also in excellent agreement with the average literature value, after shifting to a common [Fe/H]. The 47 Tuc value is also in excellent agreement with the MB08 value, which was derived from the same lines. The IL abundance also agrees well with the average literature abundance in Table 10. As a Galactic GC, 47 Tuc is one of the many Galactic GCs that have shown star-to-star variations in Na, as mentioned earlier (e.g. Carretta et al. 2009). However, in this case the Na abundance is not overly high, suggesting that the IL is not dominated by Na-enhanced stars.

For the 6154 Å sodium line, the final line list has reduced the errors from 0.30 (from the minimal line list) and 0.25 (from the VALD line list) to 0.15. In the case of the 6160 Å line the improvements are similarly excellent, with decreases from 0.13 and 0.13 to 0.07. Again, the final line list provides...
a significant improvement to the precision of the derived ILS abundances.

4.2.3 Na in the other GCs

The Na 6154/6160 Å syntheses on M3, M13, NGC 7006 and M15 are shown in Fig. 15, while the abundances are given in Table 10. The comparison literature abundances are also shown in Table 10. These literature abundances were determined with both the 6154/6160 and 5682/5688 Å lines (and occasionally also the Na D lines). In the case of M3, M13 and NGC 7006, the literature abundances have not had NLTE corrections, while some of the M15 stars did have NLTE corrections. The M3/M13 literature abundances are from 36 and 60 stars from the base of the RGB, up to the tip of the RGB, while the NGC 7006 literature abundances are only from six tip of the RGB stars. M15’s literature abundances are mainly from more evolved stars (e.g. RGB, HB and AGB stars).

While M13 and NGC 7006’s ILS abundances are in good agreement with the literature averages, the IL Na abundance in M3 is quite a bit higher than the average literature value. The 6160 Å line is not well resolved in the M15 ILS, and hence provides only an upper limit. The 6154 Å line in M15, however, provides a larger Na abundance than the literature average. Again, these discrepancies with the literature averages are results of the intercluster Na variations, which vary in the range $-0.6 \lesssim [\text{Na/Fe}] \lesssim 2$ (Sneden et al. 1997; Preston et al. 2006).

4.3 Eu II 6645 Å line

The weak 6645 Å Eu II feature is commonly synthesized in spectroscopic analyses, since it provides important constraints on contributions from the $r$- (rapid) neutron capture process.14

4.3.1 Eu in 47 Tuc: the minimal and VALD line lists

The 47 Tuc syntheses with the minimal and VALD lists are shown in Fig. 16. There appear to be fewer lines in this region, making it easier to identify the continuum level. Altogether, the errors in the abundances are ±0.17 and ±0.15 for the minimal list and the VALD RGB list, respectively.

4.3.2 Eu in 47 Tuc: the final line list

With the final line list, syntheses of the Eu II line in the solar, Arcturus and 47 Tuc spectra are shown in Figs 16 and 18. HFS and

14 At solar metallicity 97 per cent of Eu comes from the $r$-process (Burris et al. 2000).
isotopic components for the Eu \( \text{II} \) line are included, using the data from Lawler et al. (2001) – these corrections alter the shape of the line slightly, but have a negligible effect on its EW. There are several other lines with HFS components in the region of the Eu \( \text{II} \) line which are not included.

As discussed earlier, CN molecular lines are present throughout the region around the 6645 Å Eu \( \text{II} \) line. For the solar syntheses the C and N abundances from Asplund et al. (2009) are used, while scaled-solar C and N abundances are adopted for Arcturus. For 47 Tuc it is less clear which C and N abundances to use. The effects of dredge-up in RGB stars (e.g. C depletion and N enhancement; Lambert & Ries 1981) are likely to influence the IL abundance. In addition, all the stars in 47 Tuc show a well-established CN bimodality, from the RGB (e.g. Briley 1997) down to the main sequence (e.g. Briley et al. 2004). To determine the extent to which the input C and N abundances affect the ILS results, spectrum syntheses were performed with the extreme values determined from individual stars, i.e. \([\text{C}/\text{Fe}] \approx -0.8\) and \([\text{N}/\text{Fe}] \approx 0.0\) versus \([\text{C}/\text{Fe}] \approx +0.4\) and \([\text{N}/\text{Fe}] \approx +2.0\) (Briley et al. 2004).

The 47 Tuc spectrum syntheses with different carbon abundances are presented in Fig. 17. All syntheses were vertically shifted to fit the continuum regions, and the Eu \( \text{II} \) abundances were re-derived to best fit the line profile. The differences in the strengths of the CN lines are quite striking – in general the CN-weak case (in blue, i.e. the higher carbon abundance) has stronger spectral lines than the CN-strong case (in cyan). The unfortunate presence of a blended CN line redwards of the Eu \( \text{II} \) line makes the Eu abundance particularly sensitive to the input C abundance. In order to force the CN-weak syntheses to best match the observed line profile, an Eu \( \text{II} \) abundance that is \( \sim 0.2 \) dex lower than the CN-strong case must be adopted. However, if the carbon abundance is treated as a free parameter, and is determined by fitting the CN lines in the region (the magenta line in Fig. 17), the systematic errors in abundance can be reduced.

The final line list spectrum synthesis abundances are shown in Table 10, along with the literature averages. The solar value is slightly lower than the Asplund et al. (2009) value. The Arcturus abundance again agrees with the average literature value. The 47 Tuc ILS \([\text{Eu}/\text{Fe}]\) value is higher than MB08’s \([\text{Eu}/\text{Fe}] = 0.04\), which is based on an EW analysis with the same spectrum; measurements of this weak line may be more difficult than originally realized. The syntheses presented here show that the width of the synthesized line is greater than the observed feature (see Fig. 18), indicating that noise may have distorted the shape of the Eu \( \text{II} \) line. In this case, the spectrum syntheses, with a fixed FWHM broadening parameter, will do a better job of fitting the true line profile.

The IL Eu abundance in 47 Tuc is slightly higher than the average literature value, though the values do agree within the errors. The average literature \([\text{Eu}/\text{Fe}]\) abundance in Pritzl et al. (2005) is based on
the abundances of five giants, eight subgiants and three turnoff stars, whose abundances are in the range $-0.39 \lesssim \text{[Eu/Fe]} \lesssim +0.44$. The ILS abundance falls at the upper end of this observed range, suggesting that the Eu-enhanced stars are dominating the ILS Eu II line strength.

Thus, the precision of the abundance from the weak Eu II line has significantly improved with the use of the final line list, with the error decreasing to 0.10 from 0.18 and 0.15 for the minimal and VALD lists, respectively. The spectrum synthesis technique has also improved the accuracy of the derived abundance, as compared to the EW analysis.

4.3.3 Eu in the other GCs

The syntheses of the Eu II line in the ILS of the other GCs are shown in Fig. 19, and the abundances are given in Table 10. The input carbon abundances are less important for these GCs, since the CN lines are weaker. Table 10 shows that these clusters are all enhanced in Eu, and that these enhancements are considerably greater than the literature averages. However, these literature averages do not reflect the Eu variations that exist within the clusters. Roederer (2011) has shown that large Eu dispersions are present in many Galactic GCs, including M3 (0.4 < \text{[Eu/Fe]} < 0.8), M13 (0.2 < \text{[Eu/Fe]} < 1.0) and M15 (0.2 < \text{[Eu/Fe]} < 2.2). NGC 7006 does not show a significant dispersion in Eu (0.30 < \text{[Eu/Fe]} < +0.44) but these abundances are based on observations of only six giants (Kraft et al. 1998). All of the IL synthesis-based abundances fall at the upper end of the literature ranges, again suggesting that the ILS-derived abundance is dominated by the most Eu-rich stars in the GCs.

5 DISCUSSION

Section 4 presented spectrum syntheses of high-resolution ILS of the five Galactic GCs 47 Tuc, M3, M13, NGC 7006 and M15, clusters which cover a wide range in metallicity (from [Fe/H] ≈ −0.7 to −2.4) and HB morphology. This section presents a discussion of the important findings from these syntheses.

5.1 The nature of ILS syntheses

The results from Section 4 clearly show that determining abundances from spectrum syntheses of ILS is more difficult than with individual, resolved stars. The severe blends in an ILS make fitting individual lines and identifying the continuum level difficult. Comparisons between the individual solar/Arcturus spectra and the 47 Tuc ILS clearly show that 47 Tuc does not have ‘traditional’ continuum regions (i.e. regions that are free of any spectral lines) – even the most featureless regions in the 47 Tuc spectrum are blends of continuum and weak absorption features. This is
Figure 17. Syntheses of the region around the Eu II line in 47 Tuc with the CN molecules, and assuming a carbon isotopic ratio of $^{12}$C/$^{13}$C = 9. The cyan line assumes [C/Fe] = −0.8 and [N/Fe] = 0.0, typical of the C-enhanced stars in 47 Tuc, while the blue synthesis represents the C-deficient abundances, [C/Fe] = 0.4 and [N/Fe] = 2.0 (Briley et al. 2004). The syntheses have been vertically shifted to fit the continuum, and the Eu abundances were then altered to best fit the Eu II 6645 Å line. The Eu abundances differ by nearly 0.2 dex as a result of the differing input carbon abundances. The magenta line shows the synthesis with the best-fitting carbon abundance, as determined by fitting all the CN lines in the region; this case yields an Eu abundance similar to the CN-strong case.

5.2 Comparisons with literature abundances

As is clear from the abundances presented in Section 4, caution must be taken when comparing ILS abundances to average literature values. The ILS abundances do not represent average cluster abundances. The stellar contributions to an ILS are flux-weighted, meaning that the brightest RGB, AGB and post-AGB stars contribute the most light to the observed spectrum (and therefore have more influence on a line’s shape and strength). Furthermore, the contributions to individual line strengths can also depend on line properties (e.g. ionization state, excitation potential, etc.; see fig. 9 in MB08). For elements that are not expected to vary significantly between stars in a given cluster (e.g. Fe), these effects will be unimportant (assuming that the population is properly modelled). For elements that are expected to vary (such as Mg, Na and Eu), the observed line strengths will also depend on the abundance spreads in the stars that dominated the light. The literature averages will also depend on the number and types of stars observed. It is important to consider these effects when comparing with literature abundances. Flux-weighted literature averages may help with comparisons with ILS abundances, but this requires a reasonably complete sample of stars that are selected only from the observed regions.

For elements with star-to-star variations within a GC, such as Mg, Na and Eu, it is therefore more instructive to consider the observed literature ranges, especially those observed among the brightest evolved stars that dominate the IL. These ranges will reflect any star-to-star abundance variations, whether due to effects that may occur up the RGB (e.g. mixing; Korn et al. 2007) or as a result of separate populations throughout the cluster. With this caveat in mind, the ILABUNDS spectrum synthesis method presented here provides accurate abundances that fall within the ranges of literature abundances from individual stars.

5.3 The chemical signatures of multiple populations

As standard Galactic GCs, 47 Tuc, M3, M13, NGC 7006 and M15 all show signs of multiple populations (under the definition of multiple populations as ‘synonymous with multiple generations of stars that can be distinguished either from their spectra or from multiple sequences in the CMD’; Gratton, Carretta & Bragaglia 2012). These multiple populations are often distinguished through star-to-star C,
N, O, Na, Mg and Al abundance variations (e.g. Carretta et al. 2009). These abundance variations are known to affect certain features in lower resolution ILS [e.g. Coelho, Percival & Salaris (2011) find that the Ca 4227, G4300, CN₁, CN₂ and NaD Lick indices are all affected by the second-generation abundance differences]. The high-resolution IL Na and Mg abundances presented here are therefore likely affected by these multiple populations within the GCs.

The abundance trends from the syntheses are generally qualitatively similar among the GCs. With the exception of M15, the GCs are all found to be Mg-enhanced in their IL, as compared to the Sun. Similarly, all GCs were found to be Na-enhanced. The magnitudes of these enhancements vary between the clusters. For example, 47 Tuc has the highest IL Mg enhancement and a moderate IL Na enhancement, while M15 shows Mg depletion and a much stronger Na enhancement. These findings qualitatively agree with the Na and Mg star-to-star variations in Galactic GCs, and suggest that in the observed regions, stars from different populations may be dominating the IL in these clusters (e.g. ‘normal’ stars may dominate the 47 Tuc light, while more ‘second-generation’ Na-rich/Mg-poor stars may dominate the M15 IL). This is likely a stochastic effect, and the IL abundances will likely depend on the area observed in the ILS. More theoretical work with multiple populations must be done in order to understand exactly how these effects will alter the IL abundances.

5.4 The effects of HB morphology
Metallicity variations alone cannot explain differences in HB morphologies in Galactic GCs (e.g. Sandage & Wildey 1967). Thus, there must be at least a second parameter governing HB morphology, such as age, although other factors are expected to contribute to differences in HB morphology (Dotter et al. 2010; Gratton et al. 2010). Because the physical causes behind HB morphology are not well understood, HB stars cannot be accurately modelled for all cluster types a priori. This means that for a given GC, the temperatures and surface gravities of the synthesized HB stars may not be accurate. In addition, uncertain physical processes (e.g. radiative levitation; Michaud, Richer & Richard 2008) can lead to abundance anomalies in hot HB stars (e.g. Fe; Lovisi et al. 2012), which complicates their contributions to the ILS. Although HB stars do not contribute much of the optical light in Galactic GCs (Schiavon et al. 2002) and although HB morphology does not have a drastic effect on the integrated optical colours of GCs (Smith & Strader 2007), certain spectral lines may be affected (i.e. those affected by hot stars, e.g. the Balmer lines, Schiavon et al. 2004; or partially ionized lines, MB08). Colucci et al. (2009) found that manually adding in blue

Figure 18. Spectrum syntheses of the 6645 Å Eu II line on the solar and Arcturus spectra with the final line list. Lines are as in Fig. 8.
Figure 19. Spectrum syntheses of the 6645 Å Eu II line on the M3, M13, NGC 7006 and M15 ILS. Lines are as in Fig. 8.

Figure 20. Syntheses of the Na I 6154/6160 Å doublet in the 47 Tuc spectrum. The magenta line shows the best-fitting abundance from Section 4.2.2. The grey line shows the same synthesis, before it has been broadened by the velocity dispersion and instrumental broadening. It is clear that the magenta line never fully reaches the continuum level of the grey synthesis, due to blending of the weak features.
HB stars did not significantly change the age and Fe estimates for M31 GCs, but the effects on spectrum syntheses have not yet been investigated.

The ILS and HST observations of the second parameter triad M3, M13 and NGC 7006 provide a unique opportunity to test the effects of HB morphology on synthetic spectra. If these Galactic clusters were unresolved, their HB morphologies would not be known a priori – the adopted models might synthesize HBs that are bluer or redder than the real HB. With resolved photometry, the HB morphology of one of these second parameter clusters, M3, is deliberately mismodelled (using the HB photometry from the other second parameter clusters). The effects of an improperly modelled HB on the spectrum syntheses of Mg, Na and Eu can then be tested directly. The effects of a purely red HB can also be investigated, by putting all the HB stars into the reddest HB box. In all cases, the total number of HB stars is preserved.

The resulting abundance changes are shown in Table 11. The abundance differences are quite small, in all cases; in particular, the abundance differences between the syntheses with M3’s HB and NGC 7006’s HB are insignificant. The largest abundance differences occur for the synthesis of the 5528 Å Mg I line with the purely red HB, though the other lines show much smaller abundance differences with the reddest HB. In general, the differences with an HB that is too blue are also insignificant (with $\Delta \log \epsilon < 0.03$). Though the resulting abundance changes are small, the effects are not isolated to the lines of interest. A different HB morphology affects lines throughout the spectrum, as shown in Fig. 21. All lines in the region around the 5711 Å line, including the Fe lines, are affected by the HB morphology, which can affect the continuum placement. In this spectral region, variations are <1 per cent, which causes a negligible error in abundance. However, this test shows that some spectral lines and regions are more sensitive to the HB morphology than others, even at red wavelengths, since the blue HB stars add continuum flux. At bluer wavelengths the blue HB stars are likely to have an even stronger effect.

### Table 11. Abundance changes with various HB morphologies.

| Line       | M3’s HB | NGC 7006’s HB | Purely Red HB |
|------------|---------|---------------|--------------|
| Mg 5528    | $-0.03$ | $0.0$         | $-0.06$      |
| Mg 5711    | $-0.02$ | $0.0$         | $-0.02$      |
| Na 6154    | $-0.03$ | $0.0$         | $-0.02$      |
| Eu 6645    | $-0.03$ | $0.0$         | $-0.12$      |

The differences in abundance are with respect to the original synthesis, with M3’s true HB stars. Three cases are considered: M3 with M3’s HB, M3 with NGC 7006’s HB and M3 with a purely red HB. Lines throughout the region are affected by the HB morphology, which could influence continuum placement and line profile fitting.

### 6 CONCLUSIONS

This work has introduced a high-resolution ILS synthesis technique, and has applied the method to five Galactic GCs over a wide range of metallicities and HB morphologies. Previous high-resolution ILS analyses were either only EW analyses (e.g. MB08) or adopted different spectrum syntheses methods (e.g. Colucci et al. 2009). The spectrum synthesis method introduced here is fully consistent with the MB08 EW technique, and is capable of reproducing the integrated abundances of 47 Tuc, as derived from an EW analysis.

In particular, this work has produced the following key findings.

(i) Spectrum syntheses of GC ILS can yield abundances with $\sim 0.1$ dex precision, comparable to the accuracy obtained with high-quality spectral analyses of individual stars. To achieve this level of precision, attention must be given to the completeness of the input line list, which needs to be calibrated, e.g. to the solar and Arcturus spectra. Molecular features do affect spectral lines of

![Figure 21. Spectrum syntheses of the 5711 Å Mg I line in the M3 ILS, with different HB morphologies. The green line shows M3’s original intermediate HB morphology. The blue line shows M3’s synthesis with M13’s blue HB, the orange line shows M3’s synthesis with NGC 7006’s redder HB and the red line shows M3 with a purely red HB.](https://academic.oup.com/mnras/article-abstract/434/1/358/997300)
interest and the continuum determinations, and need to be included in
the syntheses.

(ii) The abundances determined here from the ILS of 47 Tuc, M3, M13, NGC 7006 and M15 fall within the abundance ranges in
the literature from individual cluster member stars.

(iii) The IL abundances may not represent the average cluster abundances in the literature, due to star-to-star abundance variations
within each GC. The signatures of star-to-star abundance variations
in Mg, Na and Eu seem to be evident in the IL abundances of all
the target GCs.

(iv) HB morphology has only a negligible effect on the final Mg, Na
and Eu abundances from syntheses of the four spectral regions
investigated here. Composition changes in the hottest stars, e.g.
from radiative levitation, and rotational variations have a negligible
effect on the abundances from these lines.

This work shows that high-resolution ILS analyses can be used to
determine precise elemental abundances in GCs, at least for certain
lines of Mg, Na and Eu, when the spectral line list is carefully considered. This method works over the observed range of metallicities
and HB morphologies found in the target Galactic GCs.

ACKNOWLEDGEMENTS

The authors thank the referee for helpful comments and suggestions.
The authors also thank R. Bernstein for the use of her 47 Tuc spectrum. CMS acknowledges funding from the Natural Sciences & Engineering Research Council (NSERC), Canada, via the Vanier CGS programme. KAV acknowledges funding through the NSERC Discovery Grants programme. The Hobby–Eberly Telescope (HET) is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München and Georg-August-Universität Göttingen. The HET is named in honour of its principal benefactors, William P. Hobby and Robert E. Eberly. The authors wish to
thank the night operations staff of the HET for their assistance and expertise with these unusual observations.

REFERENCES

Alpaslan M., 2009, preprint (arXiv:0912.4755)
Alves-Brito A. et al., 2005, A&A, 435, 657
Anderson J. et al., 2008, AJ, 135, 2055
Asplund M., Grevesse N., Sauval J. A., Scott P., 2009,ARA&A, 47, 481
Barklem P. S., Asplund-Johansson J., 2005, A&A, 435, 373
Barklem P. S., Piskunov N., O’Mara B. J., 2000, A&AS, 142, 467
Baumüller D., Butler K., Gehren T., 1998, A&A, 338, 637
Behr B. B., 2003, ApJS, 149, 67
Behr B. B., Cohen J. G., McCarthy J. K., 2000, ApJ, 531, L37
Bekki K., Yahagi H., Nagashima M., Forbes D. A., 2008, MNRAS, 387,
1131
Briley M. M., 1997, AJ, 114, 1051
Briley M. M., Harbeck D., Smith G. H., Grebel E., 2004, AJ, 127, 1588
Brodie J. P., Strader, J. 2006, ARA&A, 44, 193
Brown J. A., Wallerstein G., 1992, AJ, 104, 1818
Burris D. L., Pilachowski C. A., Armandroff T. E., Sneden C., Cowan J. J.,
Roe H., 2000, ApJ, 544, 302
Kraft R. P., Sneden C., Langer G. E., Prosser C. F., 1992, AJ, 104, 645
Kraft R. P., Sneden C., Smith G. H., Shetrone M. D., Fulbright J., 1998, AJ,
115, 1500
Kupka F., Ryabchikova T. A., Piskunov N. E., Stempels H. C., Weiss W. W.,
2000, Balt. Astron., 9, 590
Kurucz R. L., 2005, Mem. Soc. Astron. Ital., 8, 189
Lambert D. L., Ries L. M., 1981, ApJ, 248, 228
Lee H.-C., Worthey G., 2005, ApJS, 160, 176
Lind K., Asplund M., Barklem P. S., Belyaev A. K., 2011, A&A, 528, 30
Lovisi L., Mucciarelli A., Lanzoni B., Ferraro F. R., Gratton R., Dalessandro
E., Contreras Ramos R., 2012, ApJ, 754, 91
Mackey A. D., van den Bergh S., 2005, MNRAS, 360, 631
Mashonkina L. I., Shimanski˘ı V. V ., Sakhibullin N. A., 2000, Astron. Rep.,
54, 55
Mart´ınez-Delgado D., 2010, ApJ, 720, L10
Matteucci F., Raiteri C. M., Busso M., Gallino R., Gratton R., 1993, A&A,
272, 421
McCall M. L., 2004, AJ, 128, 2144
McWilliam A., Bernstein R., 2008, ApJ, 684, 326 (MB08)
McWilliam A., Preston G. W., Sneden C., Shectman S., 1995a, AJ, 109,
2736
Mishenina T. V., Kovtyukh V. V., Soubiran C., Travaglio C., Busso M., 2002,
A&A, 396, 189
C. M. Sakari et al.

Muratov A. L., Gnedin O. Y., 2010, ApJ, 718, 1266
Preston G. W., Sneden C., Thompson I. B., Shectman S. A., Burley G. S., 2006, AJ, 132, 85
Pritzl B. J., Venn K. A., Irwin M., 2005, AJ, 130, 2140
Ramírez I., Allende Prieto C., 2011, ApJ, 743, 135
Ramírez I., Melendez J., 2005, ApJ, 626, 465
Ramsey L. W. et al., 1998, Proc. SPIE, 3352, 34
Roederer I. U., 2011, ApJ, 732, L17
Sakari C. M., Venn K. A., Irwin M., Aoki W., Arimoto N., Dotter A., 2011, ApJ, 740, 106
Sandage A., Wildey R., 1967, ApJ, 150, 469
Sarajedini A. et al., 2007, AJ, 133, 1658
Sbordone L., Bonifacio P., Marconi G., Buonanno R., Zaggia S., 2005, A&A, 437, 905
Schiavon R. P., Faber S. M., Castilho B. V., Rose J. A., 2002, ApJ, 580, 850
Schiavon R. P., Rose J. A., Courteau S., MacArthur L. A., 2004, ApJ, 608, L33
Shetrone M. D., 1996, AJ, 112, 1517
Shetrone M. D. et al., 2007, PASP, 119, 556
Smith G. H., Strader J., 2007, AN, 328, 107
Sneden C., 1973, ApJ, 184, 839
Sneden C., Kraft R. P., Shetrone M. D., Smith G. H., Langer G. E., Prosser C. F., 1997, AJ, 114, 1964
Sneden C., Kraft R. P., Guhathakurta P., Peterson R. C., Fulbright J., 2004, AJ, 127, 2162
Sobeck J. S. et al., 2011, AJ, 141, 175
Stetson P. B., Pancino E., 2008, PASP, 120, 1332
Suda T. et al., 2008, PASJ, 60, 1159
Tolstoy E., Hill V., Tosi M., 2009, ARA&A, 47, 371
Travaglio C., Gallino R., Arnone E., Cowan J., Jordan F., Sneden C., 2004, ApJ, 601, 864
Tull R. G., 1998, Proc. SPIE, 3355, 387
Venn K. A. et al., 2012, ApJ, 751, 102
Worley C. C., Cottrell P. L., Freeman K. C., Wylie-de-Boer E. C., 2009, MNRAS, 400, 1039
Wylie E. C., Cottrell P. L., Sneden C. A., Lattanzio J. C., 2006, ApJ, 649, 248
Yong D., Grundahl F., Lambert D. L., Nissen P. E., Shetrone M. D., 2003, A&A, 402, 985
Yong D., Carney B. W., Teixera de Almeida M. L., 2005, AJ, 130, 597
Yong D., Aoki W., Lambert D. L., 2006, ApJ, 638, 1018

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 8. The Fe line list (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt1026/-/DC1).

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the paper.

This paper has been typeset from a TeX/LaTeX file prepared by the author.