The ability of intermediate-band Strömgren photometry to correctly identify dwarf, subgiant, and giant stars and provide stellar metallicities and surface gravities

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ABSTRACT

Context. Several large scale photometric and spectroscopic surveys are being undertaken to provide a more detailed picture of the Milky Way. Given the necessity of generalisation in the determination of, e.g., stellar parameters when tens and hundreds of thousands of stars are considered it remains important to provide independent, detailed studies to verify the methods used in the surveys.

Aims. Our first aim is to critically evaluate available calibrations for deriving [M/H] from Strömgren photometry. Secondly, we develop the standard sequences for dwarf stars to reflect their inherent metallicity dependence. Finally, we test how well metallicities derived from urchiz photometry reproduce metallicities derived from the well-tested system of Strömgren photometry.

Methods. We evaluate available metallicity calibrations based on Strömgren uvby photometry for dwarf stars using a catalogue of stars with both uvby photometry and spectroscopically determined iron abundances ([Fe/H]). The catalogue was created for this project. Using this catalogue we also evaluate available calibrations that determine log g. A larger catalogue, in which metallicity is determined directly from uvby photometry, is used to trace metallicity-dependent standard sequences for dwarf stars. We also perform comparisons, for both dwarf and giant stars, of metallicities derived from urchiz photometry with metallicities derived from Strömgren photometry.

Results. We provide a homogenised catalogue of 451 dwarf stars with 0.3 < (b − y)\(\odot\) < 1.0. All stars in the catalogue have uvby photometry and [Fe/H] determined from spectra with high resolution and high signal-to-noise ratios (S/N). Using this catalogue, we test how well various photometric metallicity calibrations reproduce the spectroscopically determined [Fe/H]. Using the preferred metallicity calibration for dwarf stars, we derive new standard sequences in the c1,0 versus (b − y)\(\odot\) plane and in the c1,0 versus (v − y)\(\odot\) plane for dwarf stars with 0.40 < (b − y)\(\odot\) < 0.95 and 1.10 < (v − y)\(\odot\) < 2.38.

Conclusions. We recommend the calibrations by Ramirez & Meléndez (2005) for deriving metallicities from Strömgren photometry and find that intermediate band photometry, such as Strömgren photometry, more accurately than broad band photometry reproduces spectroscopically determined [Fe/H]. Strömgren photometry is also better at differentiating between dwarf and giant stars. We conclude that additional investigations of the differences between metallicities derived from urchiz photometry and intermediate-band photometry, such as Strömgren photometry, are required.

Key words. Stars: abundances, Stars: fundamental parameters (classification, colours, luminosities, metallicities), Stars: late-type

1. Introduction

The photometric system introduced by Bengt Strömgren (Strömgren 1963, 1964) provides a means of reliably estimating stellar parameters for stars with a wide range of spectral classes. For instance, metallicities can be determined for many types of stars. In particular, the system can accurately identify stars at different evolutionary stages (see discussion in, e.g., Strömgren 1963). This makes it possible to determine the distances of stars with no parallax measurements. If reddening is not known, the system must, however, be complemented with no parallax measurements. If reddening is not known, the system must, however, be complemented with

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\(^*\) Appendices A and B are only available in electronic form at the http://www.aanda.org. The table in Appendix B will be available through CDS.
Schuster et al. 2004, 2006). Recent attempts to use Strömgren photometry to study the properties of the Milky Way stellar disks away from the solar neighbourhood are few. Interesting examples being von Hippel & Bothun (1993) and Jønch-Sørensen (1995).

Advancements in technology have meant that we now also have access to larger CCD areas on telescopes equipped with large uvby-filters, enabling an efficient study of stellar properties across larger areas of the sky.

We have published two studies based on Strömgren photometry of the red giant branches of dwarf spheroidal galaxies in the Local Group using the Wide Field Camera (WFC) on the Isaac Newton Telescope on La Palma (Faria et al. 2007, Adén et al. 2009). This camera is equipped with large filters that allow an, almost, unvignetted field of view of half by half a degree. However, far more can be achieved with this dataset. It provides the largest database of Strömgren photometry for Milky Way disk stars without any kinematic or colour biases. The stars are situated at distances between 0.5 and 4 kpc away from the Sun and in the directions of the four dwarf spheroidal galaxies Draco, Sextans, Hercules, and Ursa Major II. We intend to apply this unique dataset to explore the properties of the Milky Way disk(s) in some detail.

As part of a series of papers on the properties of the Milky Way disks using Strömgren photometry, we have undertaken a critical evaluation of the available calibrations for metallicity and log g determinations for dwarf and sub-giant stars. We have also determined new standard sequences (compare, e.g. Olsen 1984) to improve the identification of dwarf and giant stars in the distant disk and halo. We also provide a basic comparison of metallicities derived using Strömgren photometry and metallicities derived for dwarf and giant stars from SDSS ugriz photometry using the calibration in Ivezić et al. (2008).

The paper is organised as follows. Section 2 provides a short introduction to the Strömgren photometric system and background to the work presented here. Sect. 3 details the catalogues we compile to test the metallicity calibrations available for dwarf stars, which is described in Sect. 4 where we also compare the Strömgren metallicities with those derived by the SDSS project (DR7 Abazajian et al. 2009). Section 5 considers the system’s ability to distinguish between giant and dwarf stars of similar colour. We also provide new, metallicity-dependent stellar sequences for dwarf stars in this section. These new sequences are compared to model predictions (e.g., isochrones) in Sect. 6. Section 7 summarises our findings and provides a few suggestions for future work.

2. A short introduction to the Strömgren photometric system

The Strömgren system consists of the four medium-width filters u, v, b, and y (hereafter collectively denoted as uvby), where the y magnitude is calibrated to be the same as the V magnitude in the UBV system (e.g. Johnson & Morgan 1953, see also Olsen 1984 and Fig. 1). The filters are centred on 350, 410, 470, and 550 nm and their half-widths are 38, 20, 10, and 20 nm, respectively (e.g., Golay 1974, page 180). In addition, the system relies on the three colour indices (differences) that are constructed in the following way (compare, e.g., Strömgren 1963):

\[ (b - y) \]
\[ m_1 \equiv (v - b) - (b - y) \]
\[ c_1 \equiv (u - v) - (v - b). \]

\[ a) \]

These indices are designed to measure important properties of the stars and were first introduced by Bengt Strömgren in a series of papers, including Strömgren (1963) and Strömgren (1964). Work on the system continued by establishing standard stars (e.g., Crawford & Barnes 1970, Gronbech et al. 1976, Olsen 1983, Perry et al. 1987, Olsen 1993). However, as discussed in Claussen et al. (1997), the establishment of standard fields akin to those available for UVBRI photometry (Landolt 1992) have only very recently been attempted. An additional problem is that the primary standards are too bright for most available combinations of cameras with uvby filters and telescopes. Although Claussen et al. (1997), Cousins (1987), and Schuster & Nissen (1988) provide secondary fainter standards, the situation for both standard fields and secondary standards that can be used with large telescopes remains unsatisfactory.

There are two main sets of established standard stars for the uvby system, those of Bond (1980) and Olsen (1993). There are some non-negligible differences between the two sets and Olsen (1993) provides a detailed discussion of this subject. He concludes that the main difference concerns the c1 index and is caused mainly by the u-filter. Hence, if we wish to compare results based on the two sets of standards we need to apply corrections (compare, e.g., Fig. 15 in Faria et al. 2007). We adopt observations calibrated to the system established by Olsen (1993).

The system was originally designed to study earlier types of stars (A2 to G2, Strömgren 1963). Later work has, however, shown that the system and its properties can be extended to later types of stars. Particularly important extensions of the application of the system have been presented by Bond (1970) (for metal-poor giants), Gustafsson & Ardeberg (1978) (for red horizontal branch stars), Olsen (1984) (for G and K dwarf stars), Schuster & Nissen (1989b) (for metal-poor stars), Anthony-Twarog & Twarog (1994) (for giants), and Twarog et al. (2007) (for G and K dwarf stars). The theoretical foundations of these extension can be found in, e.g., Bell & Gustafsson (1978) and Gustafsson & Bell (1979), and more recently Onehag et al. (2009). Applications to yellow super-giants have also been successful (see, e.g., Arellano Ferro & Mendoza 1993).
stars are strong enough to depend mainly on microturbulence ($\xi_t$) and less on metallicity. It was later shown that $\xi_t$ is not a free parameter and hence the dependence still prevails (see, e.g., discussion in Gustafsson & Nissen 1972). Because of the properties of the $m_1$ index it can be used to derive metallicities for a variety of late-type stars (e.g., F to K and V to III). Recent examples of metallicity calibrations include for giants Hilker (2000) and Calamida et al. (2007), and for dwarf stars Olsen (1984), Schuster & Nissen (1989b), and Holmberg et al. (2007) (see Sect. 4 for a more complete list). The calibrations for giant stars include only linear terms in the different indices and none include $c_1$. For dwarf stars, the relations are more complex and less straightforward, including dependencies also, e.g., on the $c_1$ index and quadratic terms. The reliability of the metallicity calibrations for dwarf stars is one of the main topics of this paper.

Finally, the $c_1$ index is designed to measure the Balmer discontinuity (Strömgren 1963). For early-type stars, B and A, the $c_1$ index is a measure of the temperature but for later type stars (F and G stars) it provides a measure of the surface gravity. Hence, for stars with spectral class later than roughly A, already by design this system is able to identify different types of stars in a reliable way. This was, in fact, the main advantage of the system as it was used in early applications. Note that the identification works equally well if the reddening is known or if all stars can be assumed to suffer from the same amount of reddening. For stars with spectral type later than A, it was possible, by measuring $(b - y)$ and $c_1$ and comparing to standard sequences, to determine an absolute magnitude for the star once it had been classified (e.g., Strömgren 1963). It thus became important to develop standard sequences in the $c_1$ vs. $(b - y)$ diagram so that stars could be reliably classified according to spectral class and evolutionary stage. We return to the issue of standard sequences for late-type dwarf stars later in this paper.

The ability to classify stars at different evolutionary stages using the $uvby$ system has been elaborated upon. For metal-poor stars, Schuster et al. (2004) developed a finely tuned classification scheme to identify main sequence, turn-off, blue stragglers, red giant, horizontal branch and asymptotic branch stars (see Fig. 2). Adén et al. (2009) used this classification scheme to successfully trace the faint ($V \sim 21.1$) horizontal branch of the Hercules dwarf spheroidal galaxy.

The scheme developed in Schuster et al. (2004) extends only to about $(b - y) = 0.4$ for dwarf stars and about 0.6 for giants. However, the ability of the $uvby$ system to distinguish different evolutionary stages (for all metallicities) improves as we move to redder colours. A simple illustration of this is given in Fig. 2. In this figure, we reproduce the classification scheme of Schuster et al. (2004) and overlay two sets of isochrones by VandenBerg et al. (2006), which use the temperature-colour transformation by Clem et al. (2004) (but see Faria et al. 2007, for a critical discussion of the reliability of the intermediate metallicity isochrones based on this temperature-colour transformation).

Finally, $uvby$ photometry is often complemented with observations in additional filters. In particular, many studies have been

Fig. 2. Illustration of the $uvby$ system's ability to identify stars at different evolutionary stages. The classification scheme by Schuster et al. (2004) is indicated by dotted lines. Evolutionary stages are identified in panel a. as: 1. SL-BHB: sub-luminous – blue horizontal branch transition, 2. BHB: blue horizontal branch, 3. HB: horizontal branch, 4. RHB-AGB: red horizontal branch – asymptotic giant branch transition, 5. BS: blue-straggler stars, 6. BS-TO: blue-straggler – turn-off transition, 7. Turn-off: turn-off stars, 8. Main sequence, 9. sub-giants, 10. red giants, and, 11. SL: sub-luminous stars. Two isochrones by VandenBerg et al. (2006) using the temperature-colour transformation by Clem et al. (2004) are shown as full lines (age = 1Gyr and 10Gyrs). The metallicities of the isochrones are indicated in the panels. The region occupied by metal-poor red giants in the Draco dwarf spheroidal galaxy (Faria et al. 2007) is indicated by a hashed area in panel b.

and for giant stars by Alonso et al. (1999), Ramírez & Meléndez (2005b) provide calibrations for both giant and dwarf stars.

In contrast, the $m_1$ index is designed specifically to measure the amount of blanketing in a region around 410 nm (e.g., Crawford 1975) or as originally stated by Strömgren (1963) as “a colour difference that is a measure of the total intensity of the metal lines in the $v$-band”. It is thus sensitive to the total amount of metals present in the stellar atmosphere. However, it was soon recognised that these metallicity lines in population I
performed using the $\beta$ index (e.g., Schuster et al. 1994). For late-
type stars, this index provides a temperature estimate that is es-
tentially independent of reddening. However, the two filters in-
cluded in this index are both narrow or very narrow, hence for
large-scale studies of fainter stars observing times become pro-
hibitively long. Here we are therefore not concerned with the $\beta$
index.

Other studies have also developed systems that use addi-
tionally information, e.g., Ca II H and K photometry (see, e.g.,
Anthony-Twarog & Twarog 1998). For the same reasons given
for the $\beta$ index, we do not address these systems but rather con-
sider only $uvby$, where, in terms of observing time, $u$ is by far
the most expensive filter.

3. Two catalogues

Before testing available metallicity and log $g$ calibrations and
deriving new standard relations we will first detail how we se-
lected the stars used to perform these tasks. Below we describe
the construction of two catalogues for dwarf stars, one with
$uvby$ photometry only and one with both $uvby$ photometry and iron
abundances determined from high-resolution spectroscopy.

3.1. Reddening

For both catalogues we need to decide whether the photometry
for the stars should be dereddened or not and which reddening
map to use. We only consider stars that have parallaxes in the
Hipparcos catalogue (Perryman et al. 1997; van Leeuwen 2007)
and use the same method to deredden the photometry in the two
catalogues. In brief, we assume that the dust in the Galactic disk
can be modelled as a thin exponential disk with a scale-height of
125 pc (following, e.g., Bonifacio et al. 2000; Beers et al. 2002).
Since most of the stars are nearby, they are inside this dust disk.
We reduce the extinction accordingly using

$$E(B - V)_{\text{star}} = \left[1 - \exp\left(-d \sin b / h\right)\right] \cdot E(B - V)_{\text{LOS}},$$

where $E(B - V)_{\text{LOS}}$ is the full colour-excess along the line of
sight (LOS) taken from the dust maps by Schlegel et al. (1998).
$d$ is the distance (here we use the parallaxes from the new reduc-
tion of the Hipparcos catalogue of van Leeuwen 2007), $b$ is the
galactic latitude, and $h$ is the scale-height of the thin dust disk
(taken to be 125 pc, see above).

Following, for instance, Nordström et al. (2004) we assume
that stars with $E(B - V) < 0.02$ are un-reddened and do not
apply any dereddening to the photometry for these stars. We dis-
cuss the implications of this in Sect. 4.1.

Several studies have noted that the dust maps of
Schlegel et al. (1998) overpredict $E(B - V)$ when $E(B - V) > 0.15$ (see, e.g., Arce & Goodman 1999; Beers et al. 2002
Yasuda et al. 2007). Our catalogues are dominated by nearby
stars with low $E(B - V)$. For the spectroscopic catalogue dis-
cussed in Sect. 3.3 and used to test the metallicity calibration in
Sect. 4.1 only two stars have $E(B - V) > 0.15$. In the photomet-
cric catalogue used to trace dwarf-star sequences in Sect. 5 there
are 38 of 3645 stars that have $E(B - V) > 0.15$. Since so few
stars are affected by a possible overprediction of the reddening
we chose not to apply any corrections to the reddening values
found from the map by Schlegel et al. (1998).

To deredden the $uvby$ photometry we use the relation for $A_y/E(B - V)$ from Table 6 (Col. 8) in Appendix B of
Schlegel et al. (1998). For individual magnitudes, this amount
to $x_0 = x - E(B - V) \cdot k_x$, where $x$ is any of $uvby$ and $k_x = 5.231$,
4.552, 4.049, and 3.277 for $uvby$, respectively, and the subscript
0 corresponds to the dereddened photometry.

3.2. The photometric catalogue

The three studies by Olsen (1993), Olsen (1994a), and Olsen
(1994b) represent one of the largest homogeneous catalogues of
high quality $uvby$ photometry for nearby dwarf stars that also in-
cludes spectral classification of the stars. The stars were classi-
fied into three main groups: sub-giant stars (or the BAF group),
giant stars (or the GKIII group), and dwarf stars (or the GKV
group). For our final catalogue, we only include stars classified
as dwarf stars by Olsen (the GKV group). Whenever a star has
an entry in more than one of the three studies we adopt the most
recent set of measurements.

Dereddening was performed as described in Sect. 3.1. The
majority of the stars in Olsen (1993), Olsen (1994a), and
Olsen (1994b) have parallaxes from Hipparcos (ESA 1997).
Perryman et al. 1997; van Leeuwen 2007). Stars that have no
parallax from Hipparcos were simply discarded from the pho-
tometric catalogue. Known binary stars were excluded using the
SIMBAD database. The resulting catalogue consists of 3645
dwarf stars. Figure 3a shows the distribution of the stars in the
HR-diagram.

3.3. The spectroscopic catalogue

To test the available metallicity and log $g$ calibrations for dwarf
stars, we need a homogeneous catalogue of stars, which have both
$uvby$ photometry and spectroscopically determined [Fe/H] and
log $g$. The [Fe/H] should preferably have been derived using
parallaxes, but ionisation equilibrium might also be acceptable
(compare discussion in Bensby et al. 2005).

Because we place special emphasis on the redder dwarf stars,
we started our search by looking in the General Catalogue of
Photometric Data (Mermilliod et al. 1997) for stars with $(b -}$

\footnote{We adopt the usual notation where $[Fe/H] = \log(N_{\text{Fe}}/N_{\text{H}})_{\odot} - 
\log(N_{\text{Fe}}/N_{\text{H}})_{\odot}$ and use $[Fe/H]$ exclusively for iron abundances de-
termined from high-resolution spectroscopy. Metallicities determined
from photometric calibrations will be either called just that or denoted
[M/H].}
Fig. 4. a) HR diagram for the photometric catalogue of dwarf stars (see Sect. 3.2). b) HR-diagram for the dwarf stars in the spectroscopic catalogue (see Sect. 3.3).

Table 1. Coefficients for Eq. (2).

| Study                  | Ref. | # of stars | # of stars with \((b−y)_{0} > 0.6\) | \(a\)  | \(b\)  | \(c\)  | \(d\)  | \(σ\)  |
|------------------------|------|------------|-------------------------------------|-------|-------|-------|-------|-------|
| Favata et al. (1997)   | 2    | 46         | 1                                   | 1.0608| -0.9662| -0.7918| 7.1781| 0.07  |
| Feltzing & Gustafsson  | 3    | 23         | 2                                   | 0.7903| -0.8958| -0.1252| 3.9841| 0.05  |
| Chen et al. (2000)     | 4    | 28         | 1                                   | 1.1759| -2.0582| -0.0767| 8.2072| 0.06  |
| Thorén & Feltzing      | 5    | 12         | 4                                   | 0.9918| 0.0163 | -0.2020| 0.8187| 0.08  |
| Santos et al. (2001)   | 6    | 61         | 1                                   | 1.0050| -0.9088| -0.0586| 3.6431| 0.04  |
| Heiter & Luck (2003)   | 7    | 75         | 0                                   | 0.8985| 0.7027 | -0.1373| -2.0303| 0.05  |
| Yong & Lambert (2003)  | 8    | 6          | 2                                   | 1.1258| 2.0080 | -0.2534| -6.3255| 0.05  |
| Mishenina et al. (2004)| 9    | 93         | 1                                   | 1.1434| -1.8958| -0.0888| 7.5583| 0.06  |
| Santos et al. (2004)   | 10   | 141        | 1                                   | 1.0098| -1.2361| -0.0838| 5.0008| 0.04  |
| Bonfils et al. (2005)  | 11   | 19         | 0                                   | 0.8761| -0.5454| -0.0422| 2.2801| 0.07  |
| Luck & Heiter (2005)   | 12   | 65         | 6                                   | 0.9736| 0.7346 | -0.0249| -2.6251| 0.06  |
| Santos et al. (2005)   | 13   | 64         | 7                                   | 1.0495| -1.1400| -0.0204| 4.3450| 0.04  |
| Woolf & Wallerstein (2005)| 14  | 8          | 6                                   | 1.0192| 0.0846 | -0.4226| 1.5298| 0.04  |
| Sousa et al. (2006)    | 15   | 57         | 1                                   | 0.9360| -0.9590| -0.0805| 3.9268| 0.02  |

Column 1 lists the study that is being moved onto the Valenti & Fischer (2005) system and Col. 2 the reference number used in Table B.1. Column 3 lists the number of stars in common with Valenti & Fischer (2005). These are used to obtain the coefficients. Column 4 lists the number of stars redder than \((b − y)_{0} = 0.6\). Columns 5 to 8 list the coefficients used in Eq. (2), and Col. 9 lists the \(σ\) for the difference between [Fe/H] in the study listed in Col. 1 and the [Fe/H] derived once the data have been put on to the Valenti & Fischer (2005) system. The difference is calculated in the sense [Fe/H]_{original} minus [Fe/H]_{corrected}.

Upon further inspection, it was found that 44 entries in this list were duplications. We decided to keep the most recent photometric measurements when more than one set of measurements were available for a given star.

In total, we found 190 probable dwarf stars with \((b − y) > 0.6\). Eleven additional stars were excluded (5 stars were marked as binaries in one of the four papers and 6 stars had been observed to be variables during those observing campaigns). Finally, we used the SIMBAD database to identify any additional binaries, variables, or unclassified stars. In total, 37 additional stars were excluded by this check: 5 because they had no identification at all in SIMBAD, being possible miss-identifications.
28 stars because they were identified as variable, spectroscopic binaries, carbon stars, T Tauri stars or peculiar; and 4 stars were giants.

For the remaining 98 dwarf stars with \((b - y) > 0.6\), we searched the literature for metallicity determinations using the SIMBAD and VizeR databases (Ochsenbein et al. 2000). Fifty-seven of the stars had no previous metallicity determinations at all. Thirteen stars had only metallicities derived from photometry. We were thus left with 28 stars with \((b - y) > 0.6\) and [Fe/H] derived from high-resolution spectroscopy.

The 28 red dwarf stars were found in 15 studies using high-resolution spectroscopy to determine [Fe/H]: Valenti & Fischer (2005), Favata et al. (1997), Feltzing & Gustafsson (1998), Chen et al. (2000), Thorén & Feltzing (2000), Santos et al. (2001), Heiter & Luck (2003), Yong & Lambert (2003), Santos et al. (2004), Mishenina et al. (2004), Woelfl & Wallerstein (2005), Santos et al. (2005), Luck & Heiter (2005), Bonifils et al. (2005), and Sousa et al. (2006). Several of these 15 studies also include large numbers of dwarf stars bluer than \((b - y) = 0.6\). This is especially true for Valenti & Fischer (2005), which includes [Fe/H] for 1040 stars. Our aim is to use this compilation to the test available calibrations for, mainly, F- and G-type dwarf stars. We therefore decided that Valenti & Fischer (2005) should be the baseline for our compilation.

Following Twarog et al. (2007), the [Fe/H] determined in the 15 spectroscopic studies (referred to as the 'original studies' below) were moved onto the system of Valenti & Fischer (2005) in the following way. For each study, we took all stars (i.e., including stars with \((b - y) < 0.6\)) in common between the study and Valenti & Fischer (2005) and performed a least-squares fit to determine the coefficients of the equation that transforms [Fe/H] onto the metallicity-scale by Valenti & Fischer (2005) given by

\[
[Fe/H]_{\text{VF05}} = a[Fe/H] + b \log T_{\text{eff}} + c \log g + d,
\]

where [Fe/H] is the iron abundance, \(T_{\text{eff}}\) is the effective temperature, \(\log g\) is the surface gravity derived in the original study, that is being moved onto the metallicity-scale by Valenti & Fischer (2005). [Fe/H]_{\text{VF05}} is the [Fe/H] derived in Valenti & Fischer (2005). The coefficients, \(a, b, c,\) and \(d\), together with the number of stars in common between Valenti & Fischer (2005) and the original study are listed in Table I.

These transformations were then used to move all entries in the 15 studies onto the common metallicity scale. We then used the General Catalogue of Photometric Data (Mermilliod et al. 1997) to find uvby photometry for these stars from the catalogues by Olsen and Schuster and collaborators. In total, 451 stars had [Fe/H] derived from high-resolution spectroscopy and uvby photometry. As before, if a star had more than one set of uvby measurements the most recent was kept. The spectroscopic catalogue can be found in Table B.1.

Also for this catalogue we dereddened the photometry as described in Sect 5.1. We recall that, the photometry for stars with \(E(B-V) < 0.02\) were not corrected. The implications of this are discussed in Sect 4.3. Fifty stars in the catalogue have \(E(B-V) > 0.02\). The stellar distances are based on the reanalysed Hipparcos parallaxes (van Leeuwen 2007). Five stars HD 23261, HD 69582, HD 180890, HD 192020, and PLX 1219 do not have Hipparcos parallaxes. Their extinction was estimated using the method of Carney (1983) which is based on V JK photometry. These five stars do not have a Hipparcos number in Table B.1.

For two of the 15 studies, we note that no star redder than \((b - y)_0 > 0.6\) remained after the dereddening (see Table I). These studies were nevertheless kept in the compilation as they provide valuable additional stars close to this border. Figure 4 b. shows the distribution of the stars in the HR-diagram and Fig 5 shows the distributions of both the Strömgren indices and [Fe/H] for the spectroscopic catalogue.

4. Metallicities from uvby photometry - a critical evaluation

The literature contains many calibrations that make it possible to derive metallicities from Strömgren photometry. Most of them are empirical but theoretical investigations also exist (see, e.g., Onehag et al. 2009, for a recent example). The early metallicity calibrations (Strömgren 1964, Crawford 1975, Olsen 1984) were mostly based on how much the colour indices \(m_1\) and \(c_1\) differed from a given standard relation, \(\delta m_1 = m_{1,\text{std}} - m_{1,\text{obs}}\) and \(\delta c_1 = c_{1,\text{obs}} - c_{1,\text{std}}\). The \(m_{1,0} - (b - y)_0\) and \(c_{1,0} - (b - y)_0\) relations used in these calibrations are usually derived from observations of stars belonging to the Hyades stellar cluster (for \(m_{1,0} - (b - y)_0\)) and from field stars that are believed to be on the ZAMS (for \(c_{1,0} - (b - y)_0\)). Olsen (1984) provides an example of how the preliminary standard sequences were derived.

More recent calibrations for dwarf stars have abandoned the use of standard relations (with the exception of Haywood 2002) and derive [Fe/H] directly from the colour indices \((b - y)_0\), \(m_{1,0}\), and \(c_{1,0}\) (Schuster & Nissen 1989; Malyut 1994).
Table 2. Metallicity calibrations evaluated in Sect 4.

| Reference                      | $(b-y)_0$ | [Fe/H] | $[Fe/H] - [M/H]$ | $\Delta [Fe/H] - [M/H]$ | $\sigma$ | Comment               |
|-------------------------------|-----------|--------|------------------|--------------------------|---------|----------------------|
| Olsen (1984)                  | 0.29 - 1.00 | -2.60 - 0.39 | 0.11 ± 0.34 | Their Eq. (15)           |         |
| Schuster & Nissen (1989b)     | 0.22 - 0.38 | -3.5 - 0.2 | 0.06 ± 0.16 | F-type dwarfs            |         |
| Haywood (2002)                | 0.22 - 0.59 | -2.0 - 0.5 | 0.00 ± 0.18 | G-type dwarfs            |         |
| Martell & Smith (2004)        | 0.288 - 0.591 | -2.0 - 0.5 | 0.05 ± 0.13 | G-type dwarfs            |         |
| Nordström et al. (2004)       | 0.18 - 0.38 | -2.0 - 0.8 | -0.17 ± 0.52 |                          |         |
| Ramírez & Meléndez (2005a)   | 0.19 - 0.35 | -3.5 - 0.4 | 0.04 ± 0.14 | F-type dwarfs            |         |
| Holmberg et al. (2007)        | 0.24 - 0.63 | -1.00 - 0.37 | 0.08 ± 0.16 | G-type dwarfs            |         |

Column 1 lists the reference for the calibration. In Cols. 2 to 5 we quote the ranges, for $(b-y)_0$ and $[Fe/H]$, within which the calibrations is valid. Column 6 gives the mean difference between $[Fe/H]$ and $[M/H]$ and the associated $\sigma$. Column 7 provides additional comments.

Fig. 6. The difference between $[Fe/H]$ and $[M/H]$, derived from the calibrations listed in Table 2 as a function of $[Fe/H]$ (left hand panels) and $(b-y)_0$ (right hand panels). The metallicity calibrations used are labelled as follows: SN89 for Schuster & Nissen (1989b), MS04 for Martell & Smith (2004), H07 for Holmberg et al. (2007), H02 for Haywood (2002), and RM05 for Ramírez & Meléndez (2005a). The mean differences (dashed lines) and the $\sigma$ (dotted lines) are listed in Table 2.
Fig. 7. The difference between [Fe/H] and [M/H], derived from the calibrations listed in Table 2, as a function of $m_{1.0}$ (left-hand panels) and $c_{1.0}$ (right-hand panels). The metallicity calibrations used are labelled as follows: SN89 for Schuster & Nissen (1989b), MS04 for Martell & Smith (2004), H07 for Holmberg et al. (2007), H02 for Haywood (2002), and RM05 for Ramírez & Meléndez (2005a). The mean differences (dashed lines) and the $\sigma$ (dotted lines) are listed in Table 2.

Fig. 8. The difference between [Fe/H] and [M/H] calculated using the calibration by Olsen (1984) ([M/H]$_{O84}$). The comparison is made in the colour interval $0.514 < (b - y)_0 < 1.000$. The mean difference is 0.03 dex (dashed line) with a $\sigma$ of 0.39 dex (dotted lines).

Fig. 9. A comparison of the [M/H] calculated using the calibration by Olsen (1984) ([M/H]$_{O84}$) and the calibration by Ramírez & Meléndez (2005a) ([M/H]$_{RM05}$). The comparison is made in the colour interval $0.514 < (b - y)_0 < 0.800$. The mean difference is $-0.02$ dex (dashed line) with a $\sigma$ of 0.39 dex (dotted lines).
In summary, we find that both Schuster & Nissen (1989b) and Ramírez & Meléndez (2005a) perform very well in all four comparisons. However, as Ramírez & Meléndez (2005a) covers a much larger parameter space we would recommend it over Schuster & Nissen (1989b), but again recall that in the regions where the two calibrations overlap they perform equally well.

However, Ramírez & Meléndez (2005a) extends only to \((b - y) = 0.8\). We therefore investigated the redder calibration of Olsen (1984). In Fig. 8 we compare the \([\text{Fe}/\text{H}]\) with the resulting \([\text{M/H}]\) from that calibration, finding good agreement. In Fig. 9 we compare the results from Olsen (1984) with the results from Ramírez & Meléndez (2005a) as a function of \((b - y)\), and again find close agreement. From these tests, we conclude that Olsen (1984) provides an adequate extension of Ramírez & Meléndez (2005a) for stars redder than \((b - y) = 0.8\).

As discussed in Sect. 5.1, if the reddening towards a star is less than 0.02 we do not apply a reddening correction (Table B.1). The effect of this omission is small. For example, if we use the calibration of Ramírez & Meléndez (2005a) to calculate \([\text{M/H}]\) and assume that stars with \((E(B - V)) < 0.02\), have an \((E(B - V)) = 0.02\) the mean difference between \([\text{Fe}/\text{H}]\) and \([\text{M/H}]\) changes from 0.04±0.140 to −0.03±0.148. The trends with \([\text{Fe}/\text{H}]\) and the photometric indices change very little. To the eye, it appears that, e.g., for redder \((b - y)\) the scatter increases. Similar trends are seen for the other indices.

4.2. Metallicity calibrations for red giant branch stars

Faria et al. (2007) undertook a detailed investigation of the calibrations then available and found that the calibration of Hilker (2000) was by far the most successful when comparing with high-resolution spectroscopy. However, Faria et al. (2007) only gives a limited comparison of metal-poor, faint red giant stars in the Draco dwarf spheroidal galaxy. Ramírez & Meléndez (2004) undertook a comparison with field giants in the Milky Way ranging from solar all the way down to −2.5 dex. They found that the Hilker (2000) calibration underestimated the intermediate metallicities but overestimated the lowest metallicities when compared to the spectroscopically derived iron abundances. Solar metallicities were well reproduced. Ramírez & Meléndez (2004) provide a correction formula to place the calibrations of Hilker (2000) onto the spectroscopic scale. Since then, Calamida et al. (2007) presented a new, and very comprehensive, study of metallicities of red giant stars and their iron abundance. This study used giant stars in globular clusters as a reference for their calibration. Calamida et al. (2007) used the more metallicity sensitive index \((v - y)\), rather than \((b - y)\) used in Hilker (2000). As discussed already by Strömgren (1964), the position of the \(v\) filter provides a measure of the total decrement due to the presence of metallicity sensitive pollutants. We refer the reader to Calamida et al. (2007) and Calamida et al. (2009) (which provides an update to Calamida et al. 2007) for an extended discussion of the derivation of their metallicity calibration for red giant stars.

Fig. 10 compares the different calibrations applied to metal-poor red giant branch stars in three nearby dwarf spheroidal galaxies (Draco, Sextans, and Hercules). For this comparison, we use the calibration by Calamida et al. (2007) as reference. Data for Draco and Sextans are taken from Adén et al. (in prep.) and data for Hercules from Adén et al. (2009a). The data in Adén et al. (in prep.) will supersede those of Faria et al. (2007).

The comparison between Calamida et al. (2007) and Hilker (2000) shows the same banana shape noted by Ramírez & Meléndez (2004). This is most prominently seen for...
stars in the Draco dwarf spheroidal galaxy. The difference between Calamida et al. (2007) and Calamida et al. (2009) is, as expected, very small, the major difference being at the most metal-poor end. Comparing Calamida et al. (2007) and the corrected Hilker (2000) calibration by Ramírez & Meléndez (2004) indicates that the calibration by Ramírez & Meléndez (2004) would produce a more metal-poor as well as more concentrated metallicity distribution function for the three galaxies than if we used the calibration by Calamida et al. (2007). Calamida et al. (2009) use \((v−y)\) and \((u−v)\) for their calibrations; although these colours are more sensitive to metallicity than \((b−y)\) they are also sensitive to CH and CN. It appears, however, from the comparison carried out here, that the choice of colours to use in the calibration might not be very sensitive to the presence of molecules (at least for the giant stars in the dwarf spheroidal galaxies). This should, however, be further studied.

We note that all of these calibrations are poorly constrained at the metal-poor end and more calibration data are required to improve the calibrations. Many studies currently target stars in the metal-poor dwarf spheroidal galaxies and these data will thus become available soon. We also note that to date only the calibration by Ramírez & Meléndez (2004) extends to solar metal-
licity, which is an important property for investigations where more metal-rich stars can be expected.

Calibrations of $uvby$ photometry for red giant stars with metallicities below $-2$ dex have not been rigorously tested because $uvby$ photometry and iron abundances based on high-resolution spectroscopy for metal-poor field red giant have been largely unavailable. However, a first look at data for Hercules (Adén et al. submitted) indicates that [Fe/H] based on high-resolution spectroscopy for about ten red giant branch stars infers lower iron abundances than predicted from photometry using any of the metallicity calibrations discussed here. In addition, preliminary comparisons with data from Kirby et al. (2008) find the same result (Adén et al. 2009a, and Adén et al., submitted). This conclusion is supported by a comparison with the new Draco data by Cohen & Huang (2009), who obtained high-resolution spectroscopy of eight of the brighter red giants in the Draco dwarf spheroidal. We have Strömgren photometry for six of these stars. A comparison with [M/H] derived using the calibration of Calamida et al. (2009) gives a mean difference of $-0.21$ dex and a $\sigma$ of 0.19 dex. A similar comparison but using the calibration by Ramírez & Meléndez (2004) gives a mean difference of $-0.25$ dex and a $\sigma$ of 0.22 dex. Cohen & Huang (2009) noted a similar difference when they compared their spectroscopic [Fe/H] with those metallicities derived using the calibration of Hilker (2000). We note that the most metal-poor stars in the sample cause the largest deviations. Above about $-2$ dex, the comparison is very favourable. As part of our ongoing work on $uvby$ photometry for red giant stars in dwarf spheroidal galaxies, we are evaluating the possibilities to extend current metallicity calibrations for $uvby$ photometry to metallicities below $-2$ dex.

We also compared the iron abundances of giant stars in the Draco dwarf spheroidal galaxy determined in Cohen & Huang (2009) with metallicities derived from $ugriz$ photometry using the calibration of Ivezić et al. (2008). The scatter is very large and some of the metallicities are clearly incorrect. The differences are such that even with a very large sample and considering, e.g., only the mean metallicity of the sample the conclusions would be at best indicative (see also Sect. 4.3 below).

4.3. A comparison with photometric metallicities from SDSS – both dwarf and giant stars

The SDSS (York et al. 2000) is one of the most influential studies covering a very large portion of the sky. The stellar part contains not only $ugriz$ photometry but also spectra for a large fraction of the objects. This and additional spectroscopic campaigns provide [M/H] (e.g., Lee et al. 2008). It is of great interest to attempt to derive calibrations to use the $ugriz$ photometry to provide stellar parameters and in particular [M/H] (Ivezić et al. 2008). If good calibrations can be obtained, much new information about the thick disk and the halo can be obtained (see, e.g., Carollo et al. 2008). Because of the potential impact of SDSS, it remains important to test the calibrations against independent metallicity measures. Our Strömgren photometry provides an opportunity to do so for a large sample of fairly faint dwarf and giant stars.

To perform these comparisons we use $uvby$ photometry of dwarf stars from Árnadóttir et al. (in preparation) and data for red giant stars from Faria (2006), Faria et al. (2007), Lagerholm (2008), Adén et al. (2009a), and Adén et al. (in prep.). The identification of dwarfs and giants is unambiguous for the stars we use (see e.g., Faria et al. 2007; Adén et al. 2009a). The $ugriz$ photometry is from SDSS DR7 (Abazajian et al. 2009).

For the $uvby$ photometry, we use the calibrations of Ramírez & Meléndez (2005a) and Olsen (1984) (for dwarf stars) and Calamida et al. (2007) (for giant stars) to calculate [M/H]$_{uvby}$. For the $ugriz$ photometry, we use the calibration of Ivezić et al. (2008) to calculate [M/H]$_{ugriz}$. The comparisons between [M/H]$_{uvby}$ and [M/H]$_{ugriz}$ are shown in Figs. 11 and 12.

We first note that for the dwarf stars in Fig. 11 there is good agreement at metallicities around $-1$ dex, but that agreement quickly deteriorates as we move to higher or lower metallicities. There is some scatter but there is a distinctive linear relation such that [M/H]$_{ugriz}$ is higher than [M/H]$_{uvby}$ at low metallicities and the opposite is true for solar metallicities. At solar metallicity, the offset is about 0.5 dex and at [M/H]$_{uvby} = -2$ the offset is about 1.5 dex. Given the fairly extensive tests that have been performed to compare [M/H]$_{uvby}$ to [Fe/H] derived from stellar spectroscopy provided both in this study (see Sect. 4.2) and Figs. 5 and 7 and elsewhere, these differences are a concern.

A comparison for metallicities for giants presented in Fig. 12 is perhaps even less encouraging. For $-3 < [M/H]_{uvby} < -2$, there is a trend similar to that for the dwarf stars, but at higher metallicities the relation appears to break down completely. We note that our datasets for the giant stars are small but we believe that the more populated red giant branch of the Draco dwarf spheroidal galaxy provides a fairly unambiguous result. It is beyond the scope of this paper to explain these differences. However, given the very large discrepancies in some cases caution is required when using [M/H]$_{ugriz}$ to infer the properties of the halo, where clearly many of the targets will be giants. Given the overall scatter for giant stars of metallicity $-2$ dex, a typical halo metallicity, in Fig. 12 these inferences must be regarded as only indicative.

The comparison between [M/H]$_{uvby}$ and [Fe/H] from high resolution spectroscopy indicates that [M/H]$_{uvby}$ is overestimated (Sect. 4.2. If [M/H]$_{uvby}$ were corrected to more closely match [Fe/H], then the difference between [M/H]$_{ugriz}$ and [M/H]$_{uvby}$ would be even greater.

5. The $uvby$ system’s ability to distinguish between dwarf, sub-giant, and giant stars – New stellar sequences

The Strömgren $uvby$ system has a proven ability to distinguish between dwarf and giant stars for certain colour ranges. We have used this in two studies of dwarf spheroidal galaxies to remove the foreground contamination by Milky Way dwarf stars (Faria et al. 2007; Adén et al. 2009a). In the most recent paper, we showed that about 30% of the stars that would otherwise be assumed to be radial velocity members of the Hercules dwarf spheroidal galaxy are instead foreground dwarf stars. This result has lead to a re-evaluation of the minimum common mass for such galaxies (compare, e.g., Strigari et al. 2008; Adén et al. 2009b).

A significant drawback is that the stellar sequences merge around $(b-y)_0 = 0.55$ in the $c_{1,0}$ vs. $(b-y)_0$ diagram. For bluer colours, the lower red giant branch almost meets the main sequence and the subgiant branch and turn-off forms a loop (see Fig. 2). Twarog et al. (2007) investigated whether a new index could be developed to distinguish between dwarf, sub-giant, and giant stars at bluer colours. We also performed fairly extensive tests with our datasets described in Sect. 4.2 based on our studies of dwarf spheroidal galaxies (Faria et al. 2007; Adén et al. 2009a); we found that for larger datasets the proposed new in-
Fig. 11. A comparison of metallicities for dwarf stars derived from $uvby$ photometry ([M/H]$_{uvby}$) using the calibrations by Ramírez & Meléndez (2005a) and Olsen (1984) and metallicities derived from SDSS $ugriz$ photometry ([M/H]$_{ugriz}$) using the calibration of Ivezić et al. (2008). The stars are along the lines-of-sight in the directions of the Hercules, Draco, and Sextans dwarf spheroidal galaxies. A full description of how these stars were selected will be provided in Árnadóttir et al. (in preparation). All stars have $15 < V_0 < 18.5$. The dashed line indicates a metallicity difference of zero. On the abscissa the left-hand panel has [M/H]$_{uvby}$ and the right-hand panel has [M/H]$_{ugriz}$.

Fig. 12. A comparison of metallicities derived from $uvby$ photometry and $ugriz$ photometry (using the calibration of Ivezić et al. 2008), respectively, for giant stars in dwarf spheroidal galaxies. The top panels uses the calibration by Ramírez & Meléndez (2004) and the bottom panels the calibration by Calamida et al. (2009) to obtain metallicities from $uvby$ photometry. a. Comparison for red giant branch stars in the Draco dwarf spheroidal galaxy ($uvby$ photometry: Adén et al. in prep.). b. Comparison for red giant branch stars in the Sextans dwarf spheroidal galaxy ($uvby$ photometry: Adén et al. in prep. and Lagerholm 2008). c. Comparison for red giant branch stars in the Hercules dwarf spheroidal galaxy ($uvby$ photometry: Adén et al. 2009a).

Metallicity does not appear to have the desired ability to distinguish between the bluer dwarf, sub-giant, and giant stars.

5.1. Metallicity-dependent dwarf star sequences

Dwarf star sequences in the Strömgren $c_{1.0} - (b - y_0)$ plane were introduced for F-type dwarf stars by Crawford (1975) and later extended to $(b - y) = 1.0$ by Olsen (1984). These sequences
were drawn by hand tracing the lower envelope of field stars in the relevant diagram. No attempts were made to investigate if the stellar sequences were metallicity dependent, although this possibility was discussed already by Strömgren (1964). It is clear, in the $c_{\odot}$ vs. $(b - y)_0$ diagram, when we compare the dwarf star sequence of Olsen (1984) to the dwarf region for metal-poor stars, given by Schuster et al. (2004), that the metal-poor dwarf stars have lower $c_{\odot}$ indices than the, mainly, solar metallicity stars used to define the sequence in Olsen (1984). This can be seen, e.g., in Fig. 2.

We are now in a position to extend the study of Olsen (1984) and investigate the metallicity dependence of dwarf star sequences in both the $c_{\odot}$ vs. $(b - y)_0$ diagram and the $c_{\odot}$ vs $(v - y)_0$ diagram. For stars in our photometric catalogue $[\text{M/H}]$ were calculated (see Sect. 3.2) using the metallicity calibrations by Ramírez & Meléndez (2005a) for dwarf and subgiant stars.

Table 3. New metallicity-dependent sequences for dwarf stars (see Sect. 5.1 and Figs. 13, and A.1 to A.14). For each range of metallicity (as indicated in the top two rows), we list the $c_{\odot}$ value for each $(b - y)_0$, as listed in the first column.

| $[\text{M/H}]$ | $(b - y)_0$ | $c_{\odot}$ |
|---------------|-------------|-------------|
| 0.50          | 0.50        | 0.50        |
| 0.40          | 0.40        | 0.40        |
| 0.30          | 0.30        | 0.30        |
| 0.20          | 0.20        | 0.20        |
| 0.10          | 0.10        | 0.10        |
| 0.05          | 0.05        | 0.05        |
| 0.50          | 0.50        | 0.50        |
| 0.30          | 0.30        | 0.30        |
| 0.20          | 0.20        | 0.20        |
| 0.10          | 0.10        | 0.10        |
| 0.05          | 0.05        | 0.05        |

Fig. 13. Two examples of how the dwarf sequences in the $c_{\odot}$ vs. $(b - y)$ diagram, discussed in Sect. 5.1 were established. The left hand panel shows dwarf stars with $0.15 < [\text{M/H}] < 0.25$ and the right hand panel dwarf stars with $-0.55 < [\text{M/H}] < -0.45$. A complete set of similar plots for all metallicities can be found in Appendix A (available online). The standard relations are listed in Tables 3 and 4.
Table 4. New metallicity-dependent sequences for dwarf stars (see Sect. 5.1). For each range of metallicity (as indicated in the top two rows), we list the $c_{1,0}$ value for each $(y - y)_0$, as listed in the first column.

| [M/H] | $c_{1,0}$ | $(y - y)_0$ | $(v - y)_0$ |
|-------|---------|-------------|-------------|
| ±     | 0.05    | 0.05        | 0.05        |
| 0.50  | 0.350   | 0.350       | 0.350       |
| 0.40  | 0.350   | 0.350       | 0.350       |
| 0.30  | 0.292   | 0.292       | 0.292       |
| 0.20  | 0.200   | 0.200       | 0.200       |
| 0.10  | 0.117   | 0.117       | 0.117       |
| 0.00  | 0.050   | 0.050       | 0.050       |

Table 5. The upper envelope for dwarf stars in the solar neighbourhood.

| $c_{1,0}$ | $(b - y)_0$ | $(v - y)_0$ |
|-----------|-------------|-------------|
| 0.396     | 0.350       | 0.350       |
| 0.423     | 0.375       | 0.947       |
| 0.448     | 0.400       | 1.010       |
| 0.458     | 0.410       | 1.044       |
| 0.461     | 0.430       | 1.085       |
| 0.450     | 0.450       | 1.131       |
| 0.424     | 0.470       | 1.205       |
| 0.385     | 0.490       | 1.305       |

with $(b - y)_0 < 0.8$ and the calibration by Olsen (1984) for dwarf stars with $0.80 < (b - y)_0 < 1.00$.

To trace the stellar (standard) sequences, we plotted $c_{1,0}$ vs. $(b - y)_0$ and $c_{1,0}$ vs. $(v - y)_0$ for the dwarf stars, but each time only for a narrow range in metallicity. Following the procedure in Olsen (1984), we trace the lower envelope of the stellar distribution in both the $c_{1,0}$ vs. $(b - y)_0$ and $c_{1,0}$ vs. $(v - y)_0$ diagrams. This lower envelope is sensitive to metallicity. For $(b - y)_0 > 0.7$, all dwarf stars fall on a tight relation without any dependence on metallicity. We use all data redder than $(b - y)_0 > 0.7$ to define the sequence up to $(b - y)_0 = 1.0$. Our data set has no stars redder than 1.0. Figure 13 shows two examples of how these tracings were done. Figures A.10 to A.14 in Appendix A show all tracings. The sequences are tabulated in Tables 3 and 4.

Although we have extended the tracings to as blue as possible in Figs. A.10 to A.14, it is clear that for colours bluer than $(b - y)_0 = 0.4$ the data are not substantial enough in quantity at any metallicity to provide a secure tracing. Moreover, we use only stars classified as GKV in Olsen (1993), Olsen (1994a), and Olsen (1994b), and therefore exclude bluer main sequence stars. This exclusion is also colour dependent because it depends on the metallicity of the stars. Because of these limitations we refrain from showing the tracings bluer than $(b - y)_0 = 0.4$ and $(v - y)_0 = 1.1$.

We also traced a global upper envelope for all dwarf stars. This upper envelope is listed in Table 5.

5.2. The ability of the ugriz photometric system to identify giant stars

Helm et al., 2003 used ugriz photometry to identify metal-poor giant stars. We test this method using stars in the direction of the Draco dwarf spheroidal galaxy. The field contains both foreground dwarf stars in the Milky Way as well as metal-poor giant stars in the dwarf spheroidal galaxy Faria (2006; Faria et al. 2007; Árnadóttir et al. in prep.; Adén et al. in prep.).

Helm et al., 2003 defined a new colour index, $s = -0.249u + 0.794g - 0.555r + 0.243$ which is used to identify the metal-poor giant stars. They find that metal-poor giant stars in general have larger $s$-indices than the dwarf stars and define a giant star as a star with an $s$-index more than 0.05 magnitudes above the median $s$-index for the field.

We use metal-poor giant stars in the Draco dwarf spheroidal galaxy and foreground stars along the same line-of-sight to test the ability of the $s$-index to distinguish dwarf from giant stars. The ugriz colour-magnitude diagram for the field used is shown...
Fig. 14. a) Colour–magnitude diagram showing the selection of stars along the line of sight towards the Draco dSph galaxy used for testing the giant star identification of Helmi et al. (2003). These have $16.0 < V_0 < 19.2$, $1.1 < (u-g) < 2.0$ and $0.3 < (g-r) < 0.8$ (marked with a box). Stars identified as giant stars in the $c_{1,0}$ vs. $(b-y)_0$ plane are shown as filled dots. b) The same stars but in a colour–magnitude diagram based on Strömgren photometry. Same symbols as in panel a. The box indicated by a dotted line in a. is not included as it is a non-square area once mapped into this colour–magnitude plane. c) Identification of giant stars (filled dots) in the $c_{1,0}$ vs. $(b-y)_0$ plane. Grey hashed area shows the dwarf region used in Árnadóttir et al. (in prep). Our new dwarf star sequences (solid lines) are shown along with the preliminary relations by Olsen (1984) and Crawford (1975) (dashed line), and an isochrone with an age of 12 Gyr and $[\text{Fe}/\text{H}] = -2.3$ (thick solid line, Vandenberg & Bell 1985; Clem et al. 2004). d) The distribution of identified giant stars (filled dots) in the $s$-index of Helmi et al. (2003). Dashed line indicates the median $s$ of the selected stars (0.016) and the dotted line indicates the limit above which metal-poor giant stars are identified according to Helmi et al. (2003).

6. A comparison of stellar sequences and model predictions

The stellar sequences for dwarf stars constructed in Sect. 5.1 can be compared with model predictions based on stellar evolutionary tracks and stellar model atmospheres. Such comparisons are important for two reasons, they help us to understand the physical processes occurring inside stars (stellar evolution) and the processes in the stellar photospheres (e.g., how well we can model the lines in the resulting stellar spectra). Additionally, after ensuring that we understand these processes (to a certain level), we may utilise the resulting stellar isochrones and theoretically calculate indices to infer, e.g., the age of a globular cluster.

In Fig. 15 we compare our new stellar sequences for dwarf stars with the preliminary relations of Olsen (1984) and Crawford (1975). As can be seen, the metallicity dependence is significant and the lower envelope changes by about 0.1 in $c_1$ as we change the metallicity with 0.5 dex. For the reddest part, we...
agreed with the preliminary sequences in that there is only a single relation (see discussion in Sect. 5.1), although the slopes of the sequences differ.

6.1. A comparison with stellar isochrones

Few isochrones have been calculated for the Strömgren photometric system, the most important set is probably that provided by Vandenberg & Bell (1985) and derivations from that work. To convert theoretical stellar evolutionary sequences into stellar isochrones, a colour-temperature relation is required (e.g., Lester et al. 1986; Clem et al. 2004). The empirical calibration of Clem et al. (2004) is the most recent and is used to convert, e.g., the isochrones of Vandenberg & Bell (1985) and their derivations onto the observed plane. Clem et al. (2004) performed a detailed comparison between stellar isochrones produced using their colour-temperature relation and sequences of, e.g., red giant branches for globular clusters with different metallicities, finding a good agreement.

Faria et al. (2007) performed an additional comparison of the stellar isochrones produced using the colour-temperature relation by Clem et al. (2004) with uvby photometry for field stars for which [Fe/H] had been determined by high-resolution spectroscopy. Their dataset is essentially identical to that used by Clem et al. (2004) to obtain the interpolated colour-temperature relation for metallicities between –2 dex and supersolar metallicities. The comparison found some (still) unexplained discrepancies between the data and the isochrones. However, it was confirmed that the isochrones for about –2 dex and solar metallicity fit the field stars, with those metallicities, very well. Hence, there might be some problems with the empirical calibration needed for the colour transformation at intermediate metallicities. Here, we therefore repeat the comparison, this time as a comparison between our stellar sequences for dwarf stars and the isochrones derived using the colour-temperature relation by Clem et al. (2004).

The comparison is shown in Fig. 16. The stellar sequences and the isochrones in general agree well with our sequences for dwarf stars at 0.45 < (b − y)0 < 0.7. We note, however, that the stellar sequences trace the lower envelope of all stars that have a narrow range of metallicities (see Table 3) and the isochrones should reproduce the mean metallicity. Hence, there might be some offset with respect to the c1.0 index, but otherwise the agreement is good for this fairly narrow magnitude range of dwarf stars. This comparison spans the main sequence from the turn-off, late F-type dwarf stars to three magnitudes down the main sequence to $M_V \sim 8$ (compare with Fig. 4b).

We performed a comparison between our sequences for dwarf stars, the stellar isochrones, and the calculated indices in the $c_{1.0}$ vs. $(b − y)_0$ diagram. This makes for an easy comparison with earlier works that often used $(b − y)_0$ as the colour along the x-axis. However, the $(v − y)_0$ colour is more sensitive to metallicity, as shown, e.g., by Calamida et al. (2007). This is true for both giant and dwarf stars. Although the $(v − y)_0$ is more sensitive to metallicity than $(b − y)_0$, it has the disadvantage that this is also sensitive to the presence of CH and CN molecules in the stellar atmosphere.

6.2. A note about calculated indices

Theoretical indices in the Strömgren system have been studied in several articles, including Lester et al. (1986),
Gustafsson & Bell (1979), and Onehag et al. (2009). In Fig. 17, we perform a non-exhaustive comparison between our stellar sequences for dwarf stars and indices calculated by Onehag et al. (2009) for stars with log $g = 4.5$. We show stellar sequences for 0 and $-0.5$ dex because we believe that the sequence for $-1$ dex is less robust (compare Fig. A.14). It is clear from this comparison that the calculated indices do not reproduce the colours found for field dwarf stars in the solar neighbourhood for $(b-y)_0 > 0.45$.

Based on the calculated indices, Onehag et al. (2009) derive a metallicity calibration that is nominally valid for stars with $0.22 < (b-y)_0 < 0.59$. In Table 2, we compare this calibration with the spectroscopic catalogue, in the same way as for the empirically derived metallicity calibrations. We find an offset of 0.33 dex with a scatter of 0.3 dex. This calibration clearly reproduces the spectroscopically derived iron abundances more poorly than the empirical calibrations available in the literature. This shortcoming of the theoretical calibrations was already noted and discussed by Onehag et al. (2009).

6.3. log $g$ from uvby photometry - a critical evaluation

Although the Strömgren system is clearly capable of distinguishing between dwarf and giant stars for colours redder than $(b-y)_0 > 0.55$, the situation is far less clear when we consider the turn-off and sub-giant region. To separate, e.g., dwarf field stars from field sub-giants, we need a measure of their surface gravity for which any metallicity dependence has been taken into account, before being able to distinguish between the dwarf, sub-giant, and giant stars in this narrow colour space (compare Fig. 3).

Hence, it would be desirable to derive log $g$ directly from the photometry itself. To our knowledge, the only log $g$ calibration based only on uvby photometry is that of Olsen (1984). If $b$ were to be included, additional calibrations would be available (including van Leeuwen 2009, Edvardsson et al. 1993, where the calibration is only shown graphically).

Using the stars in Table B.1 with log $g$ determinations from Valenti & Fischer (2005), we test the calibration of Olsen (1984). Figure 18 shows the log $g$ derived in the spectroscopic study of Valenti & Fischer (2005) ($\log g_{\text{spec}}$) minus the log $g$ derived from the photometry ($\log g_{\text{phot}}$). As can be seen, the calibration has a strong dependence on [Fe/H].

We now attempt the construction of a new calibration to derive log $g$ directly from dereddened uvby photometry, using the spectroscopic catalogue in Table B.1. We start with a third order polynomial in $(b-y)_0$, $m_1$, and $c_1$. We note that some calibrations include terms in [Fe/H], which we do not because we derive [M/H] from the same photometry and hence adding [M/H] terms...
would only mean adding yet more terms to the equation without gaining any further knowledge.

After removing terms that do not contribute significantly, we obtain the fifteenth order polynomial

\[
\log g = -178.0420(b - y)_0 + 109.7056m_{1,0} + 47.4263c_{1,0} + 615.0911(b - y)_0^2 + 47.0152m_{1,0}^2 - 114.8399c_{1,0}^2 - 525.0138(b - y)_0m_{1,0} - 112.5602m_{1,0}c_{1,0} - 598.8569(b - y)_0^3 + 674.8341(b - y)_0m_{1,0} + 267.7717(b - y)_0^2c_{1,0} - 147.5764m_{1,0}c_{1,0}(b - y)_0 + 265.3608c_{1,0}^2(b - y)_0 + 266.5860(b - y)_0m_{1,0}c_{1,0} + 14.3503.
\]

(3)

If we were to include \([\text{Fe/H}]\) the term would be a ninth order polynomial. However, as we want to derive both metallicity and surface gravity from the photometry itself, the 15th order polynomial presented above is a better choice.

Figure 19 shows a comparison with \(\log g\) from Table B1. The comparison is good for stars with \(\log g \geq 4.0\) but is progressively poorer towards more evolved stars, including the regime where we would most need a good calibration to separate dwarf and sub-giant stars with similar colours! Hence, the use of our new calibration is limited to \(\log g \geq 4.0\). Equation 3 is calibrated using dwarf stars in the parameter ranges \(0.236 < (b - y)_0 < 0.616, 0.122 < c_{1,0} < 0.441, 0.075 < m_{1,0} < 0.679\), and \(-1.64 < \langle \text{Fe/H} \rangle < 0.49\).

We also considered restricting ourselves to the region of \(c_{1,0} - (b - y)_0\) plane where we must need a calibration \((b - y)_0 < 0.55, 0.24 < c_{1,0} < 0.44,\) and \(c_{1,0} < -1.504 + (b - y)_0 + 1.147\). This also failed in the same way as described for the wider parameter ranges, i.e., we were not able to reliably determine the \(\log g\) for subgiant stars. We also attempted to make a calibration that would retrieve the original \(\log g\)s in a synthetic stellar population, this also failed. Hence, there does not appear to be an easy, straightforward way to derive \(\log g\) directly from the Strömgren uvby photometry for turn-off and subgiant stars.

Based on their theoretical investigation, Onegah et al. (2009) find that for dwarfs stars cooler than the Sun \(c_{1,0}\) is not a good measure of stellar gravity. However, from our empirical comparison of \(\log g\) derived using the calibration by Olsen (1984) and from spectroscopy we find that for stars redder than \((b - y)_0 \sim 0.5\) the spectroscopic \(\log g\) compares very well with the photometric \(\log g\). For stars with \(\log g \sim 4.5\), the comparison is also good. It thus seems that for main sequence, cool dwarf stars the Strömgren system is able to predict the surface gravity of the star.

7. Summary

As part of our studies of the properties of the Milky Way disk system we have undertaken a critical evaluation of the Strömgren system’s ability to provide accurate stellar parameters and to distinguish between dwarf, sub-giant, and giant stars.

We have found that the metallicity calibration for dwarf stars by Ramírez & Meléndez (2005) is the most widely applicable calibration for determining metallicities for dwarf and subgiant stars. The calibration of Olsen (1984) provides an extension from \((b - y)_0 = 0.8\) to \((b - y)_0 = 1.0\). We also note that the older calibration of Schuster & Nissen (1989b) performs almost equally well, but it does not extend to as red colours as the calibration of Ramírez & Meléndez (2005).

Although we have found that uvby photometry can readily distinguish between giant and dwarf stars for redder colours, it is disconcerting that no calibration of \(\log g\) for dwarf and subgiant stars, is able to reproduce \(\log g\) derived from either spectra or Hipparcos parallaxes. In his provisional calibration van Leeuwen (2003) also notes the same.

Using the catalogues of Olsen (1993), Olsen (1994a), and Olsen (1994b) and the metallicity calibration of Ramírez & Meléndez (2005a), we have traced new, improved standard sequences for dwarf stars. These new sequences are metallicity dependent and provide crucial calibrations for, e.g., stellar isochrones.

Even though we have found that stellar isochrones in the uvby system reasonably well reproduce empirical stellar sequences it is clear that the disagreement between theoretically calculated Strömgren indices and observed ones can be large. This appears somewhat surprising as stellar isochrones employ the same type of model atmospheres to get the predicted colours as is often used for the elemental abundance studies. This state of affairs is unsatisfactory and we encourage future theoretical studies to resolve these problems.

As part of this work, we have compiled a catalogue of dwarf stars with uvby photometry as well as \([\text{Fe/H}]\) derived from high-resolution, high S/N spectroscopy. The iron abundances have been homogenised to the scale provided by Valenti & Fischer (2005). This catalogue is provided in full (in electronic form) with this paper.

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Appendix A: Stellar sequences

Fig. A.1. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with \([\text{Fe/H}] = 0.50 \pm 0.05\) plotted in the \(c_{1,0}\) vs \((b-y)_0\) diagram.
Fig. A.2. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with [Fe/H] = 0.40 ± 0.05 plotted in the $c_{1,0}$ vs $(b-y)_0$ diagram.

Fig. A.3. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with [Fe/H] = 0.30 ± 0.05 plotted in the $c_{1,0}$ vs $(b-y)_0$ diagram.
Fig. A.4. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with $[\text{Fe/H}] = 0.20 \pm 0.05$ plotted in the $c_{1,0}$ vs $(b-y)_0$ diagram.

Fig. A.5. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with $[\text{Fe/H}] = 0.10 \pm 0.05$ plotted in the $c_{1,0}$ vs $(b-y)_0$ diagram.
Fig. A.6. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with \([\text{Fe/H}] = 0.00 \pm 0.05\) plotted in the \(c_{1,0}\) vs \((b-y)_{0}\) diagram.

Fig. A.7. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with \([\text{Fe/H}] = -0.10 \pm 0.05\) plotted in the \(c_{1,0}\) vs \((b-y)_{0}\) diagram.
Fig. A.8. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with \([\text{Fe}/\text{H}] = -0.20 \pm 0.05\) plotted in the \(c_{1,0}\) vs \((b-y)_0\) diagram.

Fig. A.9. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with \([\text{Fe}/\text{H}] = -0.30 \pm 0.05\) plotted in the \(c_{1,0}\) vs \((b-y)_0\) diagram.
Fig. A.10. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with $[\text{Fe}/\text{H}] = -0.40 \pm 0.05$ plotted in the $c_{1,0}$ vs $(b-y)_0$ diagram.

Fig. A.11. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with $[\text{Fe}/\text{H}] = -0.50 \pm 0.05$ plotted in the $c_{1,0}$ vs $(b-y)_0$ diagram.
Fig. A.12. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with $[\text{Fe}/\text{H}] = -0.60 \pm 0.10$ plotted in the $c_{1,0}$ vs $(b-y)_{0}$ diagram.

Fig. A.13. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with $[\text{Fe}/\text{H}] = -0.80 \pm 0.15$ plotted in the $c_{1,0}$ vs $(b-y)_{0}$ diagram.
Fig. A.14. The figure shows how the dwarf star sequence was traced from nearby dwarf stars with $[\text{Fe/H}] = -1.00 \pm 0.20$ plotted in the $c_{1,0}$ vs $(b-y)_0$ diagram.
Appendix B: Table containing the data collected to test calibrations of [Fe/H] in Sect.

How the catalogue is constructed is explained in detail in Sect. 3.

Column 1 lists the Hipparcos number of the star and Col. 2 gives an alternative stellar name. Column 3 gives the photometry reference (SN88 for Schuster & Nissen (1988), O84 for Olsen (1984), O93 for Olsen (1993), and O94 for Olsen (1994a)) and Columns 4 to 7 give the \textit{uvby} photometry. Column 8 gives the colour excess of the star, Columns 9 to 12 give the dereddened \textit{uvby} photometry. Column 13 and 14 give the average [Fe/H] (on the Valenti & Fischer (2005) scale) and the full range of [Fe/H] (on the same scale as in column 13) if the star was found in more than one study. Columns 15 and 16 give the number of references for the [Fe/H] and lists them (1: Valenti & Fischer (2005), 2: Favata et al. (1997), 3: Feltzing & Gustafsson (1998), 4: Chen et al. (2000), 5: Thorén & Feltzing (2000), 6: Santos et al. (2001), 7: Heiter & Luck (2003), Yong & Lambert (2003), 9: Mishenina et al. (2004), 10: Santos et al. (2004), 11: Bonfils et al. (2005), 12: Luck & Heiter (2005), 13: Santos et al. (2005), 14: Woolf & Wallerstein (2005), and 15: Sousa et al. (2006)). The data will be made publicly available through CDS.
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| Star Name | Metallicities | Stellar Classification | Strömgren | Strömgren | Strömgren | Strömgren | Strömgren | Strömgren | Strömgren |
|-----------|---------------|------------------------|------------|------------|------------|------------|------------|------------|------------|
| HD 25918  | 19301         | O93                    | 7.730      | 0.400      | 0.242      | 0.319      | 0.2845     | 0.2645     | 0.3062     |
| HD 25665  | 19422         | O93                    | 7.703      | 0.541      | 0.497      | 0.238      | 0.2265     | 0.2145     | 0.3025     |
| HD 28447  | 21010         | O93                    | 6.526      | 0.495      | 0.990      | 0.355      | 0.3476     | 0.3356     | 0.3576     |
| HD 30295  | 21889         | O93                    | 8.856      | 0.389      | 0.336      | 0.362      | 0.3625     | 0.3625     | 0.3625     |
| HD 30825  | 22633         | O93                    | 6.721      | 0.425      | 0.255      | 0.320      | 0.3205     | 0.3205     | 0.3205     |
| HD 34575  | 25094         | O93                    | 7.095      | 0.458      | 0.264      | 0.404      | 0.397      | 0.397      | 0.397      |
| HD 35171  | 25220         | O93                    | 7.920      | 0.624      | 0.650      | 0.160      | 0.1605     | 0.1605     | 0.1605     |
| HD 36308  | 25873         | O93                    | 6.721      | 0.517      | 0.311      | 0.320      | 0.3205     | 0.3205     | 0.3205     |
| HD 41004  | 28393         | A                      | 8.639      | 0.518      | 0.392      | 0.312      | 0.3125     | 0.3125     | 0.3125     |
| HD 44594  | 30104         | O93                    | 6.615      | 0.410      | 0.212      | 0.373      | 0.3735     | 0.3735     | 0.3735     |
| HD 44821  | 30344         | O93                    | 7.356      | 0.420      | 0.238      | 0.303      | 0.3035     | 0.3035     | 0.3035     |
| HD 47157  | 31655         | O93                    | 7.613      | 0.440      | 0.268      | 0.407      | 0.4075     | 0.4075     | 0.4075     |
| HD 56274  | 35139         | O93                    | 7.750      | 0.384      | 0.157      | 0.273      | 0.2735     | 0.2735     | 0.2735     |
| HD 58895  | 35910         | O93                    | 6.594      | 0.442      | 0.235      | 0.429      | 0.4295     | 0.4295     | 0.4295     |
| HD 59747  | 36704         | O93                    | 7.697      | 0.517      | 0.403      | 0.284      | 0.2845     | 0.2845     | 0.2845     |
| HD 62301  | 37789         | SN88                   | 6.740      | 0.361      | 0.126      | 0.312      | 0.3125     | 0.3125     | 0.3125     |
| HD 65430  | 39064         | O93                    | 7.667      | 0.490      | 0.347      | 0.299      | 0.2995     | 0.2995     | 0.2995     |
| HD 69830  | 40693         | O93                    | 5.958      | 0.457      | 0.297      | 0.314      | 0.3145     | 0.3145     | 0.3145     |
| HD 71334  | 41317         | O93                    | 7.814      | 0.415      | 0.210      | 0.324      | 0.3245     | 0.3245     | 0.3245     |
| PLX 2019  | 41661         | SN88                   | 11.919     | 0.549      | 0.387      | 0.160      | 0.1605     | 0.1605     | 0.1605     |

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| HD      | O93   | 7.494 | 0.451 | 0.262 | 0.373 | < 0.02 | 7.494 | 0.451 | 0.262 | 0.373 | 0.28 | 0.02 | 2 | 1.15 |
|---------|-------|-------|-------|-------|-------|--------|-------|-------|-------|-------|-----|-----|---|------|
| HD      | O93   | 7.621 | 0.619 | 0.666 | 0.183 | < 0.02 | 7.621 | 0.619 | 0.666 | 0.183 | 0.20 | ... | 1 | 5    |
| HD      | O93   | 7.702 | 0.416 | 0.175 | 0.338 | < 0.02 | 7.702 | 0.416 | 0.175 | 0.338 | 0.00 | ... | 1 | 1    |
| HD      | O94   | 7.415 | 0.476 | 0.328 | 0.331 | < 0.02 | 7.415 | 0.476 | 0.328 | 0.331 | 0.22 | 0.10 | 3 | 1.2, 15 |
| HD      | SN88  | 7.410 | 0.357 | 0.116 | 0.310 | < 0.02 | 7.410 | 0.357 | 0.116 | 0.310 | −0.66 | ... | 1 | 4    |
| HD      | O93   | 6.056 | 0.422 | 0.215 | 0.394 | < 0.02 | 6.056 | 0.422 | 0.215 | 0.394 | 0.22 | ... | 1 | 1    |
| HD      | O93   | 6.450 | 0.622 | 0.630 | 0.177 | < 0.02 | 6.450 | 0.622 | 0.630 | 0.177 | 0.09 | 0.01 | 2 | 6.10 |
| HD      | SN88  | 6.175 | 0.455 | 0.295 | 0.374 | < 0.02 | 6.175 | 0.455 | 0.295 | 0.374 | 0.38 | 0.03 | 4 | 1.7, 6, 10 |
| HD      | O93   | 8.041 | 0.416 | 0.215 | 0.408 | < 0.02 | 8.041 | 0.416 | 0.215 | 0.408 | 0.31 | ... | 1 | 1    |
| HD      | O93   | 5.545 | 0.571 | 0.552 | 0.268 | < 0.02 | 5.545 | 0.571 | 0.552 | 0.268 | 0.11 | 0.23 | 4 | 1.7, 12, 9 |
| HD      | O94   | 6.131 | 0.478 | 0.255 | 0.350 | < 0.02 | 6.131 | 0.478 | 0.255 | 0.350 | −0.12 | ... | 1 | 1    |
| HD      | O94   | 7.502 | 0.399 | 0.197 | 0.326 | < 0.02 | 7.502 | 0.399 | 0.197 | 0.326 | −0.01 | ... | 1 | 2    |
| HD      | SN88  | 7.793 | 0.510 | 0.416 | 0.253 | < 0.02 | 7.793 | 0.510 | 0.416 | 0.253 | −0.31 | ... | 1 | 1    |
| HD      | SN88  | 6.750 | 0.500 | 0.362 | 0.342 | < 0.02 | 6.750 | 0.500 | 0.362 | 0.342 | 0.01 | ... | 1 | 1    |
| HD      | O94   | 5.818 | 0.427 | 0.235 | 0.441 | < 0.02 | 5.818 | 0.427 | 0.235 | 0.441 | 0.34 | 0.01 | 2 | 1.15 |
| HD      | SN88  | 6.862 | 0.397 | 0.159 | 0.327 | < 0.02 | 6.862 | 0.397 | 0.159 | 0.327 | −0.40 | ... | 1 | 1    |
| HD      | O94   | 7.068 | 0.561 | 0.523 | 0.239 | < 0.02 | 7.068 | 0.561 | 0.523 | 0.239 | −0.24 | 0.08 | 3 | 1.6, 10 |
| HD      | SN88  | 7.185 | 0.477 | 0.327 | 0.282 | < 0.02 | 7.185 | 0.477 | 0.327 | 0.282 | −0.14 | 0.05 | 3 | 1.6, 10 |
| HD      | O93   | 7.117 | 0.423 | 0.197 | 0.407 | < 0.02 | 7.117 | 0.423 | 0.197 | 0.407 | 0.18 | 0.01 | 2 | 1.15 |
| HD      | O93   | 8.041 | 0.423 | 0.215 | 0.394 | < 0.02 | 8.041 | 0.423 | 0.215 | 0.394 | ... | ... | 1 | 1    |
| HD      | O93   | 8.382 | 0.304 | 0.381 | 0.290 | < 0.02 | 8.382 | 0.304 | 0.381 | 0.290 | −0.04 | ... | 1 | 8    |
| HD      | SN88  | 8.688 | 0.414 | 0.203 | 0.382 | < 0.02 | 8.688 | 0.414 | 0.203 | 0.382 | 0.12 | ... | 2 | 1.15 |
| HD      | SN88  | 8.763 | 0.452 | 0.263 | 0.397 | < 0.02 | 8.763 | 0.452 | 0.263 | 0.397 | 0.30 | ... | 1 | 1    |
| HD      | O93   | 8.336 | 0.456 | 0.272 | 0.366 | < 0.02 | 8.336 | 0.456 | 0.272 | 0.366 | 0.23 | ... | 1 | 1    |
| HD      | O93   | 7.867 | 0.445 | 0.228 | 0.325 | < 0.02 | 7.867 | 0.445 | 0.228 | 0.325 | −0.17 | ... | 1 | 1    |
| HD      | O93   | 7.750 | 0.458 | 0.267 | 0.326 | < 0.02 | 7.750 | 0.458 | 0.267 | 0.326 | −0.03 | ... | 1 | 1    |
| HD      | SN88  | 7.896 | 0.403 | 0.200 | 0.341 | < 0.02 | 7.896 | 0.403 | 0.200 | 0.341 | −0.04 | ... | 1 | 1    |
| PLX     | SN88  | 11.515 | 0.522 | 0.293 | 0.144 | < 0.02 | 11.515 | 0.522 | 0.293 | 0.144 | −1.67 | ... | 1 | 8    |
Metal poor regions:
1. SL–BHB
2. BHB
3. HB
4. RHB–AGB
5. BS
6. BS–TO
7. Turn–off
8. Main sequence
9. Sub–giants
10. Red giants
11. SL

\[ [\text{Fe/H}] = -2.0 \]