On the metallicity of the Milky Way thin disc
and photometric abundance scales

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ABSTRACT
The mean metallicity of the Milky Way thin disc in the solar neighbourhood is still a matter of debate, and we recently proposed an upward revision. Our star sample was drawn from a set of solar neighbourhood dwarfs with photometric metallicities. In a very recent study, it has been suggested that our metallicity calibration, based on Geneva photometry, is biased. We show here that the effect detected is not a consequence of our adopted metallicity scale, and we confirm that our findings are robust. On the contrary, the application to Strömgren photometry of the Schuster & Nissen metallicity scale is problematic. Systematic discrepancies of $\sim$0.1–0.3 dex affect the photometric metallicity determination of metal-rich stars, on the colour interval $0.22 < b - y < 0.59$, i.e. including F and G stars. For F stars, it is shown that this is a consequence of a mismatch between the standard sequence $m_1(b - y)$ of the Hyades used by Schuster & Nissen to calibrate their metallicity scale, and the system of Olsen. It means that although the calibration of Schuster & Nissen and Olsen’s photometry are intrinsically correct, they are mutually incompatible for metal-rich F-type stars. For G stars, the discrepancy is most probably the continuation of the same problem, albeit worsened by the lack of spectroscopic calibrating stars. A corrected calibration is proposed that renders the calibration of Schuster & Nissen applicable to the catalogues of Olsen. We also give a simpler calibration referenced to the Hyades sequence, valid over the same colour and metallicity ranges.

Key words: stars: late-type – Galaxy: abundances – Galaxy: evolution – solar neighbourhood.

1 INTRODUCTION
Solar neighbourhood stars serve as reference to which we compare the characteristics of the Galaxy outside the immediate solar vicinity, and their properties scale our measurements of the galactic structure and evolution. In view of their importance, it is somewhat surprising that their general properties, such as the mean metallicity of the galactic disc stars, is still a matter of debate. In a recent paper (Haywood 2001), we constructed a metallicity distribution from stars within 20 pc from the Sun. This new metallicity distribution was shown to be centred on the solar metallicity, or 0.1–0.2 dex higher than the value found in most previous studies. We discussed that this discrepancy is the result of various biases that enter the definition of these samples, the principal effect being caused by the selection of samples on the basis of spectral type. Another sensitive effect comes from the adopted metallicity scale. The choice of a given metallicity scale is determined from two criteria: the necessity to utilize stars with as low masses as possible (in order to avoid biases favouring young stars) and the available photometry. The most widely used photometry for studying the metallicity distribution is the Strömgren photometry, with the metallicity scale from Schuster & Nissen (1989) (hereafter SN). In our own study, and while the calibration of SN is given as being valid down to $b - y = 0.59$ ($B - V \approx 1.0$), we used Geneva photometry and the metallicity scale from Grenon (1978) for stars redder than $b - y \approx 0.42$ ($B - V \approx 0.67$). The reason for this choice was that Geneva photometry is available for a larger set of solar neighbourhood K dwarfs. Hence, in the initial sample used by Haywood (2001), approximately half the stars had their metallicity determined from Strömgren photometry and the other half from Geneva photometry.

In a recent paper, Reid (2002) found that the $(B - V, [\text{Fe/H}])$ distribution of our sample shows a trend of $\sim$0.2 dex from $B - V = 0.5$ to 1.0, suggesting that the calibration from Grenon (1978) is plagued by a systematic error. In contrast, his $(B - V, [\text{Fe/H}])$ distribution, based entirely on the metallicity scale of SN, shows no such trend, if characterized by a simple linear regression. Most recently, and while finishing our paper, a study on the same subject was presented by Twarog, Anthony-Twarog & Tanner (2002), pointing out exactly the problem we had discovered in Reid (2002) and that motivated the present work – a severe apparent deficiency in the metallicity scale.

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Figure 1. Metallicity distribution as a function of $B - V$ for our sample (a) and the sample of Reid (2002) (b). Our sample is a mixture of stars with Strömgren metallicity (squares) and Geneva metallicity (circles). The horizontal line represents the metallicity of the Hyades cluster from Perryman et al. (1998), at [Fe/H] = +0.14. The star symbols are Hyades members from de Bruijne et al. (2001), with metallicity determined from the calibration of Grenon (1978). The region delimited on the right lower part of the plot is the region where Favata et al. (1997) found no objects in their sample. In the sample of Reid (2002) (plot b), all stars have their metallicity determined from Strömgren photometry, through Schuster & Nissen (1989) calibration. Star symbols also represent Hyades members for which the metallicity has been calculated through the calibration of Schuster & Nissen (1989). Our Strömgren metallicities in plot (a) were determined with the calibrations of SN but corrected as described in Haywood (2001), and are not strictly equal to those of Reid (2002), although patterns common to the two ($B - V$, [Fe/H]) distributions can be seen.

2 THE COLOUR–METALLICITY DISTRIBUTION

Reid (2002) suggested that the Geneva calibration used in Haywood (2001) may be affected by a colour term. This is illustrated in his fig. 6(b), also shown here (Fig. 1a) for convenience. The linear regression on plot (a) shows that there is a trend of metallicity with colour. We note that although Reid (2002) presents the trend as being caused by the Geneva metallicity calibration, his fit is, however, made on the entirety of our sample, which is a mixture of Geneva and Strömgren metallicities (the Geneva metallicities being used for stars redder than $B - V \approx 0.67$). His remark stems from the fact that Strömgren metallicities (using the calibration of SN) in his sample show no such trend (the regression line in Fig. 1b). This implies a priori that our calibration for red stars is questionable. Reid does not seem to envisage an intrinsic trend in our sample nor an effect caused by the metallicity scale of SN. He suggests that the trend is caused by the metallicity of the reddest stars in our sample. However, looking at fig. 6(a) in Reid (2002) (our Fig. 1b), we find the strangely distorted feature that makes the upper part of the colour–metallicity distribution rather suspect (it seems to imply that there are no stars with super-solar metallicities at $B - V = 0.85$–0.95). In order to elucidate the origin of these different trends, we decided to investigate in more detail the behaviour of these two calibrations.

There may be three reasons for the trend reflected in the linear regression of Fig. 1(a).
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(i) The Geneva calibration is biased, as suggested by Reid (2002), giving overestimated metallicities for red \((B-V > 0.8)\) objects.

(ii) The Strömgren calibration is biased, giving underestimated metallicities in the blue \((B-V < 0.67)\). However, then, we must understand why Reid’s (2002) sample shows no apparent trend in colour.

(iii) The trend is real and is determined by the sample selection. However, then why Reid’s sample shows no such effect must also be explained.

There are two different ways we can check the metallicity calibrations. We can use cluster data, and test each calibration on clusters with well-determined metallicities. The Hyades sequence is appropriate for such work, and will be used below. A second way is to use spectroscopic data. A number of spectroscopic metallicities have been published in recent years. And while they are still relatively sparse for K-type stars, we shall pay particular attention to possible colour effects. To complement these methods, we can search for systematic effects with the position of stars in the Hertzsprung–Russell (HR) diagram. For example, the scarcity of stars redder than \(B-V = 0.8\) and more metal-poor than \([\text{Fe/H}] = -0.4\) contributes to the trend that is seen in Fig. 1(a) (we note, however, that this feature is also present in the Strömgren sample, Fig. 1b). We may check whether a corresponding feature is also seen in the HR diagram in our sample.

2.1 The Hyades cluster test

Figs 1(a) and (b) shows the \((B-V, [\text{Fe/H}]_{\text{photo}})\) diagrams for the samples of Haywood (2001) and Reid (2002). The horizontal line shows the median metallicity of the Hyades cluster as determined from a sample of spectroscopic metallicities in Perryman et al. (1998) at \([\text{Fe/H}] = +0.14\). The star symbols show Hyades members with metallicity as determined from the calibration of Grenon (Fig. 1a) and the calibration of SN (Fig. 1b). Since the calibration by Grenon (1978) was designed by reference to the Hyades sequence, it is not surprising (but reassuring) that the plot shows consistency with the spectroscopic determination.

The result of the calibration of SN applied to the Hyades cluster members is different, as can be seen in Fig. 1b. The figure shows systematic deviations from the Hyades metallicity, which follow those of field stars. The Hyades metallicity is underestimated by \(\sim 0.15\) dex at \(B-V = 0.5\)–0.60, and the effect is even stronger at \(B-V > 0.8\) with a \(0.3\)–\(0.4\) dex offset. The latter feature is the one discussed by Twarog et al. (2002). In the blue part of the interval, it is not clear how much solar metallicities (i.e. \([\text{Fe/H}] \approx 0\)) would be affected by the bias, at least solely from the Hyades cluster test. The bias may affect only metal-rich stars. At redder colours, it is, however, probable that even solar metallicity stars have their metallicities underestimated by at least 0.15 dex. This can be checked on spectroscopic data (Section 2.2). While we postpone our explanation to Section 3, it is worth noting here that the calibration itself is not responsible for the effect that is seen in Fig. 1b at \(B-V < 0.375\). It is its application to available Strömgren photometry that is in question. What is relevant at the moment is that the \((B-V, [\text{Fe/H}]_{\text{SN}})\) distribution of Fig. 1(b) is strongly biased and the apparent lack of correlation given by the linear regression is meaningless.

Reid (2002) notes a general offset of \(\sim 0.1\) dex in the Strömgren metallicity scale, following the similar result of Alonso, Arribas & Martínez-Roger (1996) and Haywood (2001). Since all the comparisons in Reid (2002) are relative and made in the system of the SN calibrations, the zero-point is a priori not crucial. However, the differential effect in colour is sufficiently strong that Reid (2002) acknowledges that his metallicity distribution (after rescaling by 0.1 dex) still has a less extended tail towards metal-rich stars compared with Favata, Micela & Scintino (1997) and Haywood (2001). Although Reid (2002) does not question further on the possible origin of this discrepancy, the direct reason for this effect is particularly conspicuous on the \((B-V, [\text{Fe/H}]_{\text{SN}})\) distribution: SN metallicities are artificially lowered below \([\text{Fe/H}] = -0.1\) at 0.8 < \(B-V < 0.95\) and below \([\text{Fe/H}] = 0\) at \(B-V < 0.65\).

2.2 Spectroscopic check

2.2.1 Schuster & Nissen (1989)

A second check can be made using spectroscopic metallicities from the literature. We have used mainly data from Edvardsson et al. (1993), Favata et al. (1997), Fulbright (2000), Feltzing & Gustafsson (1998), plus some additional objects from the catalogue of metallicities by Cayrel de Strobel, Soubiran & Ralite (2001) for red \((B-V > 0.65)\) objects. Fig. 2 shows the difference between photometric (SN) and spectroscopic metallicities, for four metallicity intervals. Around solar metallicities, the colour variation is similar to that detected on the Hyades. It confirms that the calibration
of SN underestimates metallicities above $[\text{Fe/H}] > -0.25$ by 0.1–0.2 dex for stars bluer than $B - V < 0.65$ and by 0.1–0.3 dex in the colour interval $0.75 < B - V < 0.9$. At $-0.25 > [\text{Fe/H}] > -1.0$, the combination of the two distinct calibrations is apparent, with the calibration for $b - y > 0.375$ overestimating the metallicity and the calibration at $b - y < 0.375$ underestimating metallicities. Finally, the calibration seems to overestimate the metallicity slightly at $[\text{Fe/H}] < -1.0$.

Because the calibration of SN has been applied mostly to F stars, the discrepancy of $\sim 0.1$ dex that is visible at $B - V < 0.65$ and for $[\text{Fe/H}] > -1.0$ has already been noted by different authors (see, in particular, Alonso et al. 1996). In our own sample, it has been corrected as $[\text{Fe/H}] = [\text{Fe/H}]_{\text{obs}} / 0.865 + 0.06$ (Haywood 2001).

### 2.2.2 Grenon (1978)

In Haywood (2001), we checked the calibration of Grenon (1978) with spectroscopic determinations. Fig. 3 shows the result of this calibration compared with the same data as for the calibration of SN, within colour limits that define the calibration, which is $0.40 < B_2 - V_1 < 0.65$. The data are very sparse for red metal-poor dwarfs, and not much can be said concerning the calibration below $[\text{Fe/H}] \approx -0.25$ dex. At $[\text{Fe/H}] > -0.2$, the spectroscopic data shows no offset. It is clear, however, that a secure calibration would require a larger data set.

The consistency of the Geneva metallicity scale can also be checked on the HR diagram. The Hyades cluster was already used in Haywood (2001). We further detail our comparison with the cleaner Hyades sequence of de Bruijne, Hoogerwerf & de Zeeuw (2001). Fig. 4 shows our sample with the Hyades sequence.

We note two features:

(i) There are no stars above the Hyades sequence around $B - V = 0.9$ in metallicity. A corresponding feature is visible in the HR diagram, Fig. 4(b). Only three stars stand clearly above the Hyades sequence between $0.82 < B - V < 0.93$, consistently in both diagrams.

(ii) There are no field stars in the HR diagram at $B - V > 0.87$ and $M_v > 7.2$. Such dwarfs would be expected to have $[\text{Fe/H}] < -0.5$, and we note a corresponding lack of stars in Fig. 1(a) (one star only). It is appropriate to remind the reader that this feature is visible on many studies of the solar neighbourhood metallicity distribution (even with pre- Hipparcos parallaxes). The first study to mention this effect was Favata et al. (1997) (see also Flynn & Morell 1997, their fig. 5). The samples considered in solar neighbourhood studies are too small to investigate whether this is only a statistical effect or a real absence of midly deficient stars at that colour.

In the HR diagram at $B - V < 0.7$, field stars above the Hyades sequence probably have evolved off the zero-age main sequence (ZAMS) (the turn-off $B - V$ colour for solar metallicity stars at 12 Gyr is $\sim 0.70$). At the bottom of the HR diagram ($B - V > 0.95$), four stars with $[\text{Fe/H}] > 0.14$ lie clearly below the Hyades sequence, which may be the signature of a bias overestimating metallicities in the Grenon calibration at $B - V > 0.95$. Among these four stars, only HIP 116745 has a measured spectroscopic metallicity at $[\text{Fe/H}] = -0.22$ in the catalogue of metallicities of Cayrel de Strobel et al. (2001).

We conclude that there is no significant deviation between the HR diagram and the colour–metallicity distribution of Fig. 1(a).

### 3 THE STRÖMGREN METALLICITY SCALE

The calibration designed by Schuster & Nissen (1989) has proved to be most useful for a variety of studies using Strömgren photometry, and this has become still more evident with the advent of Hipparcos data. The results of Section 2 show, however, that its application to the available data is problematic for metal-rich stars. We now try to explain the probable cause of that problem.

#### 3.1 A diagnostic

The Strömgren metallicities at $0.22 < b - y < 0.40 - 0.41$ (or $0.35 < B - V < 0.65$) are affected by a bias, with the Hyades having their abundance underestimated by $0.1 - 0.2$ dex. Such a strong effect is somewhat puzzling since the F-star calibration of SN is said to be constrained using the standard (Hyades) sequence of Crawford (1975) at a metallicity of 0.13 dex (and it is given double weight in the calibration of SN). This failure is interesting because it gives us some clue on the possible general origin of the problem. Since the photometric Hyades metallicity adopted by SN should be consistent with the spectroscopic value at $[\text{Fe/H}] \approx 0.13$, the only possible cause for the defect that is seen in Fig. 1 must come from the Strömgren indices that are used to represent the Hyades sequence.

(i) F stars $0.22 < b - y < 0.375$. Fig. 5 shows the $m_1(b - y)$ sequence for the Hyades, on the relevant colour range, from two different sources. The continuous line is the standard sequence from Crawford (1975) used by SN to calibrate their metallicities. Diamond symbols are Hyades members with Strömgren photometry from the GCPD (The General Catalogue of Photometric Data, Mermilliod, Mermilliod & Hauck 1997). The $b - y$ and $m_1$ indices of Fig. 5 are the mean of measurements from different sources as given by the GCPD. Most of these points indicate one or several measurements by Olsen (1993) and/or Olsen (1994a,b). These various origins have been differentiated in Fig. 5 as follows: black diamonds are those stars for which indices contain only measurement from Olsen (1993) and/or Olsen (1994a,b). Grey diamonds are a mixture of Olsen (1993, 1994a,b) and measurements from other sources. Finally, empty diamonds represent those stars that were not observed by Olsen (1993, 1994a,b). Since the Hyades sequence is mostly dominated by the measurements of Olsen, we call it the ‘Olsen sequence’ hereafter. In the $b - y$ range of interest ($b - y < 0.375$), the two $m_1(b - y)$ scales (Crawford 1975 and the...
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Figure 4. The (B − V, metallicity) distribution of the stars in our sample with Geneva metallicities, and the corresponding HR diagram. Star symbols are the Hyades selected by de Bruijne et al. (2001). There is a good overall consistency between the metallicity of the stars and their position in the HR diagram. See the text for details.

Olsen sequence) clearly show an offset of approximately \( \Delta m_1 \approx 0.01 \) mag. For F-type stars, \( m_1 \) is the index sensitive to the metallicity, with \( \Delta m_1 = 0.01 \) mag corresponding to \( \Delta [\text{Fe/H}] \approx 0.1 \) dex on the metallicity scale.

Since the huge data base established by Olsen is the main source for Strömgren photometry, and since the calibration of SN is based on the sequence of Crawford (1975), it is expected that metallicity estimates that combine both will be incorrect by \( \sim 0.1 \) dex, even though the calibration of SN is correct and Olsen indices are precise.

(ii) G stars \( 0.375 < b − y < 0.59 \). The continuity in the deviations of metallicity estimates in Fig. 1(b) across the limit that separate the two calibrations suggest a similar origin for the defects at \( b − y < 0.375 \), and \( b − y > 0.375 \). It is seen in Fig. 1(b) that the photometric metallicity offset of 0.1 dex is continuous across the two intervals, i.e. it is left unaffected by the change of calibration, at least up to \( b − y = 0.40 \). This is in support to the fact that the discrepancy originates in the indices rather than in the calibration itself.

At \( 0.375 < b − y < 0.59 \), and for the metal-rich part of their calibration, SN have used the two reddest points in the sequence of Crawford (1975) (at \( b − y = 0.394 \) and 0.412), and 'to give more weight to the Hyades, four individual stars with an average [Fe/H] = +0.09 from Cayrel de Strobel et al. (1985) and from Cayrel, Cayrel de Strobel & Campbell (1985) were included with single weight’. We could find only one star from the Hyades satisfying this description and that had Strömgren indices measurement available in 1989. This star (vb79), which is sufficiently red to have been useful for calibrating the reddest part of the metallicity scale, has \( b − y = 0.497 \) and \( m_1 = 0.341 \) (Carney 1983). Another star from the catalogue of Cayrel de Strobel et al. (1985), not belonging to the Hyades cluster, but with [Fe/H]_{spectro} = 0.25 is also shown in Fig. 5.

In Fig. 5, we have extrapolated the standard sequence of Crawford (1975) at \( b − y > 0.41 \) with a polynomial. The calibration given by SN is not explicitly referenced to the Hyades sequence, but the standard sequence is implicitly integrated in their functional form. Although we cannot quantify the difference between the Olsen sequence and the one adopted de facto by SN, we suggest that the lack of data and the functional form of the calibration of SN has probably led to a sequence resembling that proposed as an extrapolation in Fig. 5. Several features support this suggestion.

First, it is significant that the Crawford and extrapolated sequence in Fig. 5 crosses the Olsen sequence between \( 0.40 < b − y < 0.45 \) (0.65 < B − V < 0.74). It implies that on this interval, both \( m_1 \) indices from Olsen or the extrapolated sequence overlap, and will give similar metallicities. As a matter of fact, this is precisely the interval where the calibration of SN (using Olsen Strömgren indices), gives a metallicity for the Hyades nearest to the spectroscopic value.

Secondly, between \( 0.45 < b − y < 0.57 \), the offset \( \Delta m_1 \) between the polynomial sequence and the Olsen sequence reaches 0.03–0.05,
which is precisely the offset that is necessary in order to level up the photometric Hyades metallicities to 0.14 dex, if Olsen \( m_1 \) indices are used in the calibration of SN.

Thirdly, the polynomial sequence rises more steeply than the observed sequence, which flattens to reach a maximum in \( m_1 \) at \( b - y \approx 0.75 \). It is expected that the extrapolated polynomial sequence rejoins the observed (Olsen) sequence at some colour in the interval \( 0.5 < b - y < 0.7 \). That means that at this colour, the two sequences should again give the same metallicity. This is precisely what is observed in Fig. 1 at \( b - y = 0.57 \) (i.e. the calibration of SN and Olsen indices give \([\text{Fe/H}] \approx +0.14\), which is the metallicity expected from the standard relation).

Altogether, these clues convey the impression that it is the offset between the two \( m_1(b - y) \) sequences that is responsible for the strong colour dependence and the systematic discrepancy seen in Fig. 1. It is meaningful that the Crawford and extrapolated polynomial sequence of Fig. 5 lie, respectively, above and below the Olsen sequence in just the correct intervals to explain the behaviour of the photometric metallicity seen in Fig. 1(b).

### 3.2 Consistency argument

Following this last remark, it is possible to use the calibration given by SN to recover the Hyades sequence and check the consistency of our argument. Assuming relations between \((b - y, c_1)\) and \((b - y, [\text{Fe/H}]_{\text{SN}})\), \( m_1 \) can be calculated as the root of the equation:

\[
(-53.8 + 145.5b - y - 137.2c_1)m_1^2 + (22.45 + 85.1c_1 - 62.04b - y)m_1 - 2.0965 - 13c_1^2 - [\text{Fe/H}]_{\text{SN}} = 0. \tag{1}
\]

The \((b - y, [\text{Fe/H}]_{\text{SN}}), (b - y, c_1)\) relations for the Hyades have been assumed to be polynomial fits to the Hyades data, as shown in Figs 6(a) and (b). Because we do not know the exact \((b - y, c_1)\) sequence endorsed by SN at \( b - y > 0.4 \), we have assumed a set of \((b - y, c_1)\) relations, as given in Fig. 6(b).

They are used to calculate the coefficients of the polynomial (1), which is solved for \( m_1 \), at different \( b - y \). The result is shown in Fig. 6(c) and is consistent with our discussion above.

### 3.3 Twarog et al. (2002)

In their paper, Twarog et al. (2002) proposed another cause for the discrepancy. They state that the calibration of SN underestimates the \( c_1 \) dependence of metallicity for stars redder than \( b - y = 0.47 \). Their argument relies on their \( (b - y, c_1) \) relation, which shows the correlation between metallicity (both spectroscopic and photometric) and \( c_1 \) for stars with \( b - y > 0.47 \). If the argument is correct, we would expect, however, that \( c_1 \) correlates differently for spectroscopic and photometric (SN) metallicities. Their fig. 5 seems to illustrate, at variance with their claim, that the correlation is approximately similar for both spectroscopic and photometric abundances, which means that the photometric metallicities of SN are correctly tied to the \( c_1 \) index.

The interpretation that Twarog et al. give of their fig. 5 is qualitative and relies on a dozen stars. Among these, two objects that are outliers can give the favourable impression that the slopes of the photometric and spectroscopic \([\text{Fe/H}] + c_1\) data sets are different. Even if this were the case, it would remain to be demonstrated that this is due solely to the \( c_1 \) index.

In order to extend the comparison of Twarog et al. (2002) to a greater number of stars, we use our Geneva photometric...
...metallicities instead of the spectroscopic metallicity scale. We select in our sample all stars having $0.85 < B - V < 0.95$ (equivalent to $0.50 < b - y < 0.55$), giving 37 objects (32 are within the limits of Fig. 7). We plot in Fig. 7 the photometric metallicities $[\text{Fe/H}]_{\text{SN}}$ and $[\text{Fe/H}]_{\text{GEN}}$ as a function of $c_1$, a figure similar to fig. 5 in Twarog et al. (2002), but now with the Geneva photometric scale being the reference. Of course, this comparison relies on the correctness of the Geneva metallicities. Following the arguments developed in Section 2, we assume that they are indeed valid. Interestingly, it seems that our Fig. 7 reveals the patterns that were only suggested in fig. 5 of Twarog et al. (2002). That is, Geneva metallicities show that there is a second group of stars (upper box) standing 0.15–0.20 dex above the sequence at $c_1 = 0.25–0.30$. Only a small part of that group is visible in Twarog et al. (2002), at $c_1 = 0.28–0.30$.

What is interesting is that this group is not differentiated in the metallicities of SN. This means that the calibration of SN lacks a dependence on one parameter, which clearly cannot be $c_1$. The mean and dispersion of $m_1$ for the eight stars in the upper box are 0.445 and 0.036. The lower box contains nine stars with a mean of $m_1 = 0.408$ and a dispersion of 0.030. We can estimate the corresponding difference in metallicity using Olsen (1984). The calibration of Olsen (1984) is valid for stars with $b - y > 0.514$, and the metallicity is proportional to $\delta m_1$ with a coefficient equal to 5.1. Using this coefficient, the difference in $m_1$ of our two groups corresponds to 0.19 dex in metallicity, similar to the difference given by the Geneva photometry.

If we restrict our comparison to stars in the lower box only and those at $c_1 > 0.39$, it is true that the difference between the reference (Geneva) metallicities and SN metallicities are larger at $c_1 > 0.39$. However, this could be just a statistical effect caused by the lack of data at $c_1 > 0.39$. In any case, the four stars at $c_1 > 0.39$ are a minority, and if we restrict our discussion to where the majority of the stars are (at $c_1 < 0.31$), the idea of a difference of slope between the two metallicity scales is meaningless. We conclude that Fig. 7 confirms our argument, with $m_1$ being the source of the problem in the calibration of SN.

3.4 A corrected SN calibration

Taking into account the above remarks, we give a modified version of the Schuster & Nissen calibrations, based on newer calibrating metallicities. We keep the same functional form as SN, but we re-determined the coefficients by a least-squares fitting procedure. In order to find the best-fitting coefficients, we use PIKAIA, a genetic algorithm developed for optimization problems by Charbonneau (1995), to which the reader should refer for an extensive description of this technique. A ‘fitness’ function must be defined for PIKAIA to optimize the fit between a set of spectroscopic metallicities and the photometric metallicities. Our fitness function is a least-squares minimization:

$$\chi^2 = \sum_{i=1}^{N} [y(x_i, a_i) - y_i]^2,$$

where $y_i$ are the spectroscopic metallicities, and $y(x_i, a_i)$ are the photometric metallicities, which are a function of the photometric indices $x_i$ and coefficients $a_i$.

(i) $0.22 < b - y < 0.37$. We first run the optimization procedure on a set of spectroscopic metallicities comprising the data of Edwardsson et al. (1993), dwarfs in the sample of Fulbright (2000), and a few Hyades stars, to which we attribute a metallicity of $[\text{Fe/H}] = +0.14$. That amounts to 211 stars. As in SN, the Hyades stars have been attributed a weight of 2. The fit is valid over $-2.0 < [\text{Fe/H}] < 0.5$,

$$[\text{Fe/H}] = -2.0 - 43.90m_1 + 353.4(b - y)m_1$$

$$+ 18.0(b - y)m_1^2 - 612.6(b - y)^2m_1$$

$$+ [6 - 48m_1 - 7.85(b - y)][\log(m_1 - c_1)]$$

and

$$c_3 = 0.627 - 7.04(b - y) + 11.25(b - y)^2.$$

(ii) $0.37 < b - y < 0.47$. The fit was made with 103 spectroscopic metallicities and 13 Hyades stars at $[\text{Fe/H}] = +0.14$:

$$[\text{Fe/H}] = -1.64 + 11.09m_1 - 29.29m_1^2 - 57.40(b - y)m_1$$

$$+ 116.96m_1^2(b - y)$$

$$+ (128m_1 - 22.231c_1 - 206.48m_1^2)c_1$$

(iii) $0.47 < b - y < 0.59$. The fit was made with 36 spectroscopic metallicities and 12 Hyades stars at $[\text{Fe/H}] = +0.14$:
[
\begin{align*}
[\text{Fe/H}] &= -1.64 + 16.75m_1 - 12.61m_1^2 - 52.17(b - y)m_1 \\
&+ 66.026m_1^2(b - y) \\
&+ (47.98m_1 - 3.99c_1 - 65.06m_1^2)c_1. \\
\end{align*}
\]

Fig. 8 shows the photometric metallicities calculated for a set of spectroscopic standards.

### 3.5 A calibration with reference to the Hyades sequence

Owing to its rather complicated form, the application of the calibration given above is somewhat tedious. Also, the non-explicit dependence on the Hyades sequence makes it difficult to understand the origin of problems such as the one presented here, afterwards. In contrast, a calibration directly based on the Hyades sequence, as that proposed by Olsen (1984) for G and K dwarfs, has a simple form, and can be straightforwardly improved as the Hyades sequence becomes better defined and as more spectroscopic metallicities become available. We used a Hyades sequence defined by the coefficients from Table 1. These coefficients were derived by fitting the \(m_1(b - y)\) ‘Olsen’ sequence to the Hyades data presented in Fig. 5.

Using \textsc{phkais} with the same fitness function and calibrating stars as in the previous section, we derive new calibrations as a function of \(\delta m_1\) and \(\delta c_1\).

We find the following relation valid for \(0.22 < b - y < 0.37\):

\([\text{Fe/H}]_{\text{avby}} = 0.108 - 14.91\delta m_1\) \hspace{1cm} (5)

### Table 1. Coefficients of the polynomials used to fit the observed Hyades sequence, and utilized to calculate the \(\delta m_1\) and \(\delta c_1\) indices (Section 3.5).

| \(m_1\) | \(0\) | \(+1.09\) | \(+10.03\) | \(+1.85\) | \(-123.43\) | \(-56.76\) | \(+786.09\) | \(+390.12\) | \(-2927.5\) | \(-1747.9\) | \(+6514.42\) | \(+5031.2\) | \(-8388.02\) | \(-8424.2\) | \(+5738.56\) | \(+7347.46\) | \(-1613.7\) | \(-2570.77\) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

and then

\([\text{Fe/H}]_{\text{avby}} = 0.0783 - 9.095\delta m_1 - 8.575(b - y)\delta c_1\) \hspace{1cm} (6)

for \(0.37 < b - y < 0.59\).

These calibrations are illustrated in Fig. 9.

### 4 SOME CONSEQUENCES AND CONCLUSIONS

Using the new calibration, it is now possible to recalculate metallicities for the set of local dwarfs. The new \((B - V, [\text{Fe/H}])\) distribution is shown in Fig. 10. The result is now satisfactory, but the occasion is taken to emphasize the need for a larger number of spectroscopic metallicities for cool dwarfs.

In the previous decade, the calibration of SN have been widely used in various studies, in particular to design the metallicity distribution for long-lived dwarfs in the solar neighbourhood. In one such study, we sampled the solar neighbourhood within 20 pc (Haywood 2001). The sample, before the selection of long-lived dwarfs, contained 177 stars for which the metallicity came from Geneva photometry, and 172 stars for which metallicity was calculated from Strömgren metallicity, mostly for stars bluer than \(B - V = 0.67\). Strömgren photometry was also used for 41 stars redder than this limit, for which no Geneva photometry was available. All stars with SN metallicities were corrected as \([\text{Fe/H}]_{\text{SN}}/0.865 + 0.06\). Only 20 stars with colour in the critical interval \(0.8 < B - V < 1.0\) were included in the sample. In view of the limited number of objects affected by the problem, it is unlikely that our metallicity distribution suffered much from this effect. We conclude that the trend seen in Fig. 1(a) between metallicity and colour is obviously real.

As a last check on our metallicities, we have searched for spectroscopic iron abundances for the stars in Fig. 1(a) in the catalogue of Cayrel et al. (2001). Fig. 11 shows both the photometric and spectroscopic values versus \(B - V\) colour and there is good general agreement between the two. The spectroscopic metallicities, although still very sparse, confirm the general shape of the \((B - V) - [\text{Fe/H}]\) distribution, and we conclude that our findings of Haywood (2001) are robust.

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Figure 9. Photometric metallicities (equations 5 and 6) versus spectroscopic metallicities.

Figure 10. Corrected metallicity distribution as a function of $B - V$ for the Strömgren photometry sample. The horizontal line represents the median metallicity of the Hyades cluster determined from a sample of spectroscopic metallicity from Perryman et al. (1998), $[\text{Fe/H}] = +0.14$. The filled star symbols are Hyades members from de Bruijne et al. (2001). All metallicities were calculated using the corrected calibration of SN as given by equations (2)–(4).

Figure 11. $(B - V)$–$[\text{Fe/H}]$ distribution for the sample in Haywood (2001). Circles represent stars for which spectroscopic measurements are available from the catalogue of Cayrel et al. (2001). The photometric measurements are shown as squares and are related to the spectroscopic value with a vertical line. This plot shows that there is no systematic deviation between spectroscopic metallicities and our photometric abundances.

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