The Harvard Family of Bibliography Styles

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1 Introduction

This document describes the harvard family of bibliographic styles which are provided in addition to those described in ? and ?. This style is primarily intended for use with the BibTeX bibliographic database management system. However, provision is also made for hand coding of bibliographies.

2 Citations

2.1 Complete Citations

There are two primary forms of citation in the harvard style dependent upon whether the reference is used as a noun or parenthetically. Additionally, where
there are more than two authors, all authors are listed in the first citation and in subsequent citations just the first author’s name followed by ‘et al.’ is used. The following example from ? illustrates these points.

The major improvement concerns the structure of the interview (Ulrich & Trumbo 1965, p. 112) . . . Later reports (Carlson, Thayer, Mayfield & Peterson 1971) record greatly increased interviewer reliability for structured interviews. Wright (1969, p. 408) comments that ‘undoubtedly interviewer skill is directly related to the validity, quantity and quality of the interview output’, and this would suggest some sort of interviewer training is called for. Rowe (1960), for example, found that trained interviewers are better able to evaluate applicants with some measure of reliability. In addition Wexley, Sanders & Yuki (1973) showed that by extensive interviewer training all significant contrast effects could be eliminated. The results of the 1971 study (Carlson et al. 1971) are still relevant, but efforts to . . .

To facilitate using a citation as a noun a new command \citeasnoun has been created which has the same syntax as the \cite command except that multiple citations are not permitted. The effect of this command is that

As \citeasnoun{btxdoc} and \citeasnoun{Annex~B}{latex} describe \ldots

produces

As ? and ? describe . . .

whereas

The \BibTeX\ \cite{btxdoc} and \LaTeX\ \cite{Annex~B}{latex} manuals \ldots

produces

The \BibTeX\ (?) and \LaTeX\ (? , Annex B) manuals . . .

A second new command \possessivecite is provided for those instances where it is desired to use the citation as a possessive noun phrase. This is a variation on the \citeasnoun command and multiple citations are not permitted. As an example of its use

\possessivecite{latex} description of this feature is \ldots

produces

? description of this feature is . . .

A third new command \citeaffixed allows text to be affixed inside the beginning of the parenthesis of a parenthetical citation. This command is like the the \cite command except that it takes a second argument – the text to be affixed after the opening parenthesis. For example

\BibTeX\ manuals \citeaffixed{latex,btxdoc}{e.g.} describe \ldots

produces

\BibTeX\ manuals (e.g. ?, ?) describe . . .
2.2 Citation Modes

By default, where appropriate, citations are abbreviated automatically after the first reference when bibliographies are produced by BibTeX. Provision is also made for this feature to be accessed during manual coding. This feature may be overridden by using the `\citationmode` command which takes `full`, `abbr` or `default` as its single argument. The command `\citationmode{full}` makes the system use full citations, `\citationmode{abbr}` makes the system use abbreviated citations and `\citationmode{default}` causes the default behaviour of using full citations for the first instance and abbreviated citations thereafter.

Alternatively, the citation mode may be selected as an `full`, `abbr` or `default` option to the `\usepackage` command that invokes the `harvard` package. Use of the `default` option is redundant in that, if no citation mode option is used, that mode will be selected automatically.

2.3 Partial Citations

In addition to the primary forms of citation, the citation commands `\citeyear` and `\citename` are provided as building blocks for more complex citations that authors may (from time to time) require. `\citeyear` behaves like the `\cite` command except that only the year portion of the citation label is used. For example,

```
\citeyear{btxdoc,latex}
```

produces (?, ?). The parenthesis around the year list may be omitted by modifying the command name with a single asterisk (e.g. `\citeyear*{btxdoc}`). `\citename` behaves like the `\citesnoun` command except that only the author name(s) portion of the citation label is used. For example,

```
\citename{btxdoc}
```

produces

?

The use of these commands does not trigger the use of abbreviated citations for subsequent `\citesnoun` and `\cite` references.

2.4 Exceptions for Individual Citations

Occasions arise where an author wishes to override the default behaviour for an individual citation (e.g. she may wish the citation to use the full list of authors where the default would use the abbreviated form). All commands that introduce authors’ names into a document (i.e. `\cite`, `\citesnoun`, `\citeaffixed`, `\possessivcite` and `\citename`) may be modified with the addition of a single asterisk in order to force them to use the full list of authors names and by a double asterisk to force them to use the abbreviated form.
3 Styles

3.1 Bibliography Styles

There are six bibliography styles currently available within the harvard family, agsm (used in this document) which is based on ?, dcu which is based upon the conventions in use in the Design Computing Unit, Department of Architectural and Design Science, University of Sydney, jnr for the Journal of Management Research, jphysicsB for the Journal of Physics B, kluwer which aspires to conform to the requirements of Kluwer Academic Publishers and nederlands which conforms to Dutch conventions. They are invoked by the \bibliographystyle as described in ? and effect the layout of the entries in the bibliography.

Provided there is no name clash with other harvard options the bibliography style may be selected by passing it as an option to the \usepackage command that invokes the harvard package.

3.2 Citation Styles

There are two citation styles currently available within the harvard family, agsm (used in this document) and dcu which for the previous example would produce:

The B\TeX \cite{btxdoc,latex} and L\TeX (? , Annex B) manuals . . .

and for multiple citations such as

The original documentation \cite{btxdoc,latex} say \ldots

the agsm citation style produces

The original documentation (? , ?) say . . .

and the dcu citation style produces

The original documentation (? , ?) say . . .

The default citation style is agsm and both styles have no effect on the appearance of the \citeasnoun citation format.

These styles are invoked by the \citationstyle command, for example:

\citationstyle{agsm}.

Because these styles affect the format of parenthetical citations, this command should appear before any \cite commands. Additionally the citation style may be selected by passing an option to the \usepackage command that invokes the harvard package. In order to avoid name clashes with the agsm and dcu bibliography styles the options agsmcite and dcucite are used with the \usepackage command in order to select agsm and dcu citation modes respectively.

3.3 Parenthesis Style

The type of parenthesis used in citations may be set using the \harvardparenthesis command which takes one argument. The argument to this command must be one of round, curly, angle, square or none. The default value is round.
If it is a requirement that different parenthesis types are required for paren- 
thetical cites that for the year portion for a \citeasnoun citation then the 
command \texttt{\textbackslash harvardyearparenthesis} may be used to set the year paren-
thesis seperately. This command must be issued after any \texttt{\textbackslash harvardparenthesis} 
command as that command sets both parenthetical and year parenthesis. If 
the bibliographic style chosen is \texttt{agsm} or \texttt{dcu} then the parenthesis style chosen 
using \texttt{\textbackslash harvardyearparenthesis} is used with the year portion of the entries in 
the bibliographic listing. The options \texttt{round}, \texttt{curly}, \texttt{angle}, \texttt{square} and \texttt{none} 
may also be used with the the \texttt{\textbackslash usepackage} command that invokes the \texttt{harvard} 
package.

Authors of style files for use with the \texttt{harvard} family who wish to make use of 
this feature should use the strings " \texttt{\textbackslash harvardleft} " and " \texttt{\textbackslash harvardright} " 
instead of the respective parenthesis characters where they wish them to be 
effected by the selection made with \texttt{\textbackslash harvardparenthesis}.

\subsection*{3.4 Conjunction Style}

In the previous examples for the \texttt{agsm} bibliographic style a “\&” character 
is used to signify conjunction between a pair of names or between the last 
two names of a list of names. Similarly the word “and” is used for the \texttt{dcu} 
style. With these two styles this convention may be overwritten by using 
\texttt{\textbackslash renewcommand} to redefine the command \texttt{\textbackslash harvardand}. This should be 
done after the \texttt{\textbackslash citationstyle} command (if used) as this command resets it to 
the default for the style selected.

\section{World Wide Web (WWW) References}

The \texttt{agsm}, \texttt{dcu}, \texttt{jmr}, \texttt{jphysicsB} and \texttt{kluwer} bibliographic styles support a 
new bibliographic entry field \texttt{URL} for specifying the \texttt{URL} of documents that 
are available via the World Wide Web. An example of this is the reference to 
\citep documentation for his \texttt{\LaTeX2HTML} package in the file \texttt{harvard.bib} that is 
enclosed with the source for this document. When processed by \texttt{\LaTeX2HTML} 
documents using the \texttt{harvard} bibliographic package will have hypertext links 
created from the citation within the text to the reference list. If an entry in the 
reference list has an \texttt{URL} field then a hypertext link to the document will be 
ceated using the data in that field.

\section{Doing It By Hand}

Hand coding is accomplished much the same as described in \citep except that the 
new command \texttt{\textbackslash harvarditem} is used in place of \texttt{\textbackslash bibitem}. The syntax of this 
command is

\texttt{\textbackslash harvarditem [abbr-citation]{full-citation}{citation-year}{cite-key}}

where

\texttt{abbr-citation} is the (optional) abbreviated citation (minus the year) to be 
used in the text subsequent to the first mention of a particular reference,
full-citation is the full citation (minus the year) to be used in the text on the first mention of a particular reference, citation-year the year portion of the citation including any suffices required to disambiguate citations, and cite-key is the key used in the \cite and \citeasnoun commands.

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The solution to the mysterious \enddocument problem came from Berwin A. Turlach (berwin@core.ucl.ac.be) as did the identification of a subtle problem with sorting entries in the reference list.
New intrinsic-colour calibration for \textit{uvby–β} photometry

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Abstract

A new intrinsic-colour calibration \(((b-y)_{o}-\beta)\) is presented for the \textit{uvby–β} photometric system, making use of re-calibrated Hipparcos parallaxes and published reddening maps. This new calibration for \((b-y)_{o}-\beta\), our Equation (1), has been based upon stars with \(d_{\text{Hip}}<70\) pc in the photometric catalogues of Schuster et al. (1988, 1993, 2006), provides a small dispersion, \(\pm0.009\), and has a positive “standard” \(+2.239\Delta\beta\) coefficient, which is not too different from the coefficients of Crawford (\(+1.11; 1975a\)) and of Olsen (\(+1.34; 1988\)). For 61 stars with spectra from CASPEC, UVES/VLT, and FIES/NOT databases, without detectable Na I lines, the average reddening value \(\langle E(b–y)\rangle = -0.001 \pm 0.002\) shows that any zero-point correction to our intrinsic-colour equation must be minuscule.

Key words: ISM: dust, extinction: ISM: general: stars: distances

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1 Introduction

Intrinsic-colour, metallicity and absolute magnitude calibrations from \textit{uvby–β} photometry for F-, G- and early K-type dwarf and turn-off stars are of vital importance for studying several very important astrophysical problems, such as age-metallicity relations, metallicity gradients, and interstellar reddening in the Galaxy. The \textit{uvby–β} photometric system was specifically devised by Strömgren (1951) for studying B, A, and F stars. A recent evaluation of the...
importance and capacity of the $uvby-\beta$ photometric system has been presented by Bessell (2005). For this photometry, several photometric indices, or colours, are defined: $(b-y)$, which measures the continuum slope and is sensitive to stellar temperatures for B, A, F, and G stars; $m_1 = (v-b) - (b-y)$, a colour difference designed to measure the blanketing due to metal lines near 4100Å (this index is also referred to as a metal or metallicity index); $c_1 = (u-v) - (v-b)$, a colour difference designed to measure the strength of the Balmer discontinuity; and $\beta = \beta_w - \beta_n$, an intermediate-narrow index measuring the strength of the hydrogen $\beta$ line, which is also sensitive to stellar temperatures for B, A, and F stars, and which is free of the effects of interstellar extinction and reddening.

Since the $\beta$ index is independent of interstellar reddening, $(b-y)$ is not, and both $\beta$ and $(b-y)$ measure stellar temperatures for B, A, F, and G stars, this enables us to obtain an intrinsic-colour calibration, $(b-y)_0-\beta$, which is quite important for de-reddening the photometric indices $(b-y)$, $m_1$, and $c_1$ used for deriving the astrophysical parameters $T_{\text{eff}}, M_v$, and $[Fe/H]$ from $uvby-\beta$ photometry. For dwarf and turn-off stars, some of the first calibrations for intrinsic-colour for $uvby-\beta$ photometry have been given by Crawford (1975a) (hereafter C75), and Olsen (1988) (hereafter O88). C75 presents all three types of calibration (intrinsic-colour, metallicity, and absolute magnitude) for Population I type stars in the solar neighbourhood, with spectral types F2–G0 and luminosity classes III–V. O88 gives only an intrinsic-colour $(b-y)_0-\beta$ calibration good for all F0–G2 stars of luminosity classes III–V, except perhaps the more metal-poor Population II stars. An intrinsic-colour calibration $(b-y)_0-\beta$ was also derived by Schuster & Nissen (1989) (hereafter SN89) in terms of the standard (non-differential) indices $(b-y), m_1, c_1, \text{and } \beta$.

Thanks to re-calibrated Hipparcos parallaxes (ESA 1997) by van Leeuwen (2007), the reddening maps of Schlegel, Finkbeiner & Davis (1998) (hereafter SFD98), and the large photometric data base of Schuster & Nissen (1988) (hereafter SN88), Schuster, Parrao & Contreras-Martínez (1993) (hereafter SPC93), and Schuster et al. (2006) (hereafter SMM06) a new relation for intrinsic-colour $(b-y)_0-\beta$ based on $uvby-\beta$ photometry for F-, G-, and early K-type dwarf and turn-off stars has been obtained. The calibration is updated and improved compared to those which have been available in the literature and used in $uvby-\beta$ photometric surveys to derive abundance distributions, effective temperatures, age-metallicity relations, and stellar kinematics for the Galaxy (for example, see Nissen & Schuster (1991), SPC93, SMM06, and Nordström et al. (2004)). This new intrinsic-colour calibration also has the advantage that its zero-point is tested here using stars observed spectroscopically with the CASPEC, UVES/VLT, and FIES/NOT echelle spectrographs and shown to have no interstellar Na I lines.

This paper is organized as follows: Section 2 describes the data catalogues,
parallaxes, and cleansing of binary stars. In Section 3 the de-reddening procedure is presented in detail. In Section 4 the \((b-y)_o-\beta\) relation from the Schuster et al. photometric catalogue is presented, some comparisons are made, a discussion of these, and finally the conclusions in Section 5.

2 Data, and Removal of binaries

Our new \((b-y)_o-\beta\) calibration has been based mainly on the \(uvby-\beta\) catalogues of Schuster & Nissen (1988)\(^2\) (hereafter SN88), and Schuster et al.\(^3\) (SPC93; SMM06). First, a catalogue which includes 1475 dwarf and turn-off stars from the SN88, SPC93 and SMM06 catalogues has been created, and this \(uvby-\beta\) catalogue will be referred to as the “Schuster” catalogue. Photometric ranges for this catalogue are as follows: \(0.159 \leq (b-y) \leq 0.728\), \(0.033 \leq m_1 \leq 0.757\), \(0.088 \leq c_1 \leq 0.842\), \(2.486 \leq \beta \leq 2.792\). Particular importance has been given to excluding possible binary, variable, and flare stars from the Schuster catalogue. Stars which have comments and notes, such as \((N,D)\), \((N, D^*)\), \((S, D)\), \((S, D^*)\), \((N/S, D)\), \((N/S, D^*)\), \((S, HM)\), \(R\), and \(R^?\) in the SN88 catalogue have been excluded. In general, these are stars observed with a second fainter star within or slightly outside the entrance diaphragm of the photometer (“D”), stars with \(\beta\) values taken from an outside source (“HM”), or stars near or outside the color limits of our photometric transformations (“R” or “R?”). Similarly for the catalogue of SPC93, and in addition stars labelled with “++” have been omitted; these are the redder subgiant/giant stars whose \(uvby-\beta\) photometry probably contains small systematic transformation errors. Stars with “+” from this same SPC93 catalogue are not as red, \((b-y) < 0.50\), and have been retained. Also, for the catalogue of SMM06 stars with similar binary indications in the notes, as well as “++”, have been excluded, and in addition those with the note “fainter star in diaphragm”, but stars with “fainter star (just) outside diaphragm” have been retained.

Since binaries and anomalous stars have an impact not only on the intrinsic-colour calibration, but also on the metal-abundance, and absolute-magnitude calibrations, the Schuster catalogue has been cleansed of these type of stars. SMM06 identified binaries by using various catalogues, including primarily those of Carney et al. (1994), Carney (2003), and Dommanget & Nys (1994). 235 stars which are doubled-lined spectroscopic binaries (SB2), other types of binaries, or photometrically variable stars have been removed from this

\(^2\) Based on observations collected at the H. L. Johnson 1.5m telescope at the Observatorio Astronómico Nacional at San Pedro Mártir, Baja California, México, and at the Danish 1.5m and 0.5m telescopes at La Silla, Chile.

\(^3\) Based on observations collected at the H.L. Johnson 1.5m telescope at the Observatorio Astronómico Nacional at San Pedro Mártir, Baja California, México
Re-calibrated Hipparcos parallax data by van Leeuwen (2007) and $E(B-V)$ reddening values from SFD98 have been collected for this $uvby-\beta$ Schuster catalogue. For this intrinsic-colour calibration, parallaxes ($\pi$), their associated uncertainties ($\sigma_\pi$), and Galactic coordinates ($l, b$) of stars have been taken from van Leeuwen (2007).

3 Interstellar Reddening

Understanding the local interstellar reddening is of vital importance in the derivation of the $(b-y)_o-\beta$ calibration, and likewise for stellar metallicities, distances and ages. The region which lies at 50–100 pc from the Sun is specially interesting. The nearest interstellar dust patches are at about 70 pc in some directions; this region devoid of dust is commonly identified with the Local Hot Bubble. There are several works about reddening within the limits of this Local Bubble: very weak interstellar polarization caused by magnetically aligned dust grains has perhaps been observed within $\approx$35 pc by Tinbergen (1982), but Leroy (1999) finds almost no polarization up to 50 pc. Leroy (1999) also showed that significant dust clouds appear at 70–80 pc, slightly beyond the Local Bubble boundary defined with the help of X-ray measurements. Holmberg, Nordström & Andersen (2007) consider that real reddening within 40 pc is negligible. The older intrinsic-colour calibration of SN89 was derived with a distance limit of about 80 pc, and an over-correction for interstellar reddening of about $+0.005$ was suggested by Nissen (1994) using stars without detectable interstellar Na I lines. Additionally, Vergely et al. (1998), Sfeir et al. (1999), Breitschwerdt et al. (2000), Lallement et al. (2003), Luck & Heiter (2007) state that the extinction within 65–75 pc of the Sun is essentially nil. From all these works concerning the Local Bubble, the reddening values within 70 pc are seen to be insignificant.

To derive the intrinsic-colour ($(b-y)_o-\beta$) calibration, as a first step, only stars with relative-parallax errors, $\sigma_\pi/\pi \leq 0.10$, are considered, corresponding to the near-solar vicinity, where interstellar redenings are small or negligible. To check the distribution of reddening in the solar neighbourhood, $E(B-V)(l, b)_\infty$ values for individual stars in the Schuster and Olsen catalogues are taken from the reddening maps of SFD98 via the web page of NED (NASA Extragalactic Database). The reddening $E(B-V)$ for a given star is reduced compared to the total reddening $E(B-V)(l, b)_\infty$ by a factor $\left\{ 1 - e^{\frac{-d\sin|b|}{H}} \right\}$, where $b$ and $d$ are the Galactic latitude and distance, respectively, assuming that the dust layer has a scale height $H = 125$ pc (Bonifacio, Monai & Beers 2000). However, Arce & Goodman (1999) caution that the SFD98 reddening maps overestimate the reddening values when the colour excess $E(B-V)$ is more
than about 0.15, or even as low as 0.10 (Schuster et al. 2004). Hence, according to Schuster et al. (2004), a slight revision of the SFD98 reddening estimates has been adopted via an equation, \( E(B-V)_A = 0.10 + 0.65(E(B-V) - 0.10) \) when \( E(B-V) > 0.10 \), otherwise \( E(B-V)_A = E(B-V) \), where \( E(B-V)_A \) indicates the adopted reddening estimate.

Graphs of \( E(B-V) \) versus Hipparcos distance \( (d_{Hip}) \) and versus Galactic latitude \( (b) \) for 551 stars with \( \sigma_\pi/\pi \leq 0.10 \) from the Schuster catalogue are plotted in Figs. 1(a) and 1(b), respectively, for the Galactic latitude range of \( 0^\circ \leq |b| \leq 90^\circ \). Figs. 1(a)–(b) allow us to appreciate the reddening in the solar vicinity for the derivation of the \( (b-y)_{o-\beta} \) calibration. It can be seen from Fig. 1(a) that the majority of stars have reddening values less than \( E(B-V) \approx 0.02 \) (the horizontal line), and most reddenings are small up to distances of \( d_{Hip} \approx 70 \) pc. \( E(B-V) = 0.02 \) corresponds approximately to \( E(b-y) = 0.012 \) from the relation \( E(B-V) = 1.35E(b-y) \) from Crawford (1975b). Although there are a few stars with reddenings up to \( E(B-V) \approx 0.10 \) in Figs. 1(a)–(b), the reddening values of most stars are less than 0.02 for \( 0^0 \leq |b| \leq 90^0 \). In Figs. 1(a)–(b) strict limits are put on the reddening in the solar vicinity for the derivation of our intrinsic-colour calibration. Méndez & van Altena (1998) (their figure 3) show that reddening values for three low-latitude directions are zero for distances less than about 100 pc. SN89 consider that reddening is negligible within a distance limit of 100 pc following the works of C75 and Crawford (1979); their actual distance limit may be more like 80 pc from a more exact photometric distance scale. Olsen used the criteria \( d < 70 \) pc and \( E(b-y) < 0.03 \) for his intrinsic-colour calibration.

Metal-poor stars ([Fe/H] < −1.00 dex) are of vital importance for the intrinsic-colour calibration from the Schuster catalogue, since this calibration is intended for a full range of stellar population types, from thin disk to extreme halo. Having taken into consideration the distance limit for the reddening of Local Bubble, reddening is considered to be negligible for stars with \( d_{Hip} < 70 \) pc from the distributions displayed in Figs. 1(a)–(b), and according to the references mentioned above. According to these publications concerning the Local Bubble, this \( d_{Hip} < 70 \) pc criterion, which is slightly beyond the Local Bubble boundary, can be justified as an upper limit. Also, a smaller distance limit would leave too few metal-poor stars for an adequate intrinsic-colour calibration.

In summary, the strict criteria from Figs. 1(a)–(b), plus reddening studies concerning the Local Bubble, allow us to derive an intrinsic-colour calibration using stars from the Schuster catalogue out to distances of 70 pc, with \( E(B-V) < 0.02 \).
4 The Intrinsic-colour Calibration from the Schuster Catalogue

The \((b-y)_{o}\)–\(\beta\) calibration has been carried out utilizing a mathematical package called "Minitab" which allows the regression of a dependent variable against several independent variables. From the Schuster catalogue, 405 stars with \(E(B-V) < 0.02\) and \(d_{Hip} < 70\) pc, according to panels (a) and (b) of Fig. 1, have been used for the derivation of the present intrinsic-colour calibration. (These calibration stars are assumed to be unreddened, and so \(m_1 = m_o\) and \(c_1 = c_o\).) For these 405 stars, sixteen terms from simple ones to higher-order cross terms have been tested, as follows: \(m_o, m_o^2, c_o, c_o^2, \Delta \beta, \Delta \beta^2, m_o \Delta \beta, m_o c_o, m_o c_o^2, m_o^2 c_o^2, c_o \Delta \beta, m_o \Delta \beta^2, m_o^2 \Delta \beta, c_o^2 \Delta \beta, c_o \Delta \beta^2,\) and \(m_o c_o \Delta \beta,\) where \(\Delta \beta = 2.720 - \beta.\) The t-ratios, the ratios between a coefficient and its estimated error, were used to eliminate non-significant terms. The solutions were iterated; at each step the term with the smallest t-ratio was omitted until all terms were significant. During the Minitab regression analyses, 13 stars have been removed, those with residuals greater than \(\pm 0.025,\) since they are probably slightly reddened, for the positive cases, or somewhat anomalous, for the negative. The remaining data have 375 degrees of freedom and so all coefficients are non-zero at a significance level greater than 0.982, since the solution has been iterated until all terms have t-ratios with absolute values greater than 2.59. These terms were removed while doing the subsequent iterations: \(m_o \Delta \beta, c_o^2, m_o^2 \Delta \beta, m_o, m_o^2,\) and \(m_o^2 c_o^2.\)

The final solution, with a dispersion of \(\pm 0.0088,\) is given as follows:

\[
(b - y)_{o} = +0.492(\pm 0.07) - 0.976(\pm 0.14) c_o \\
+ 2.239(\pm 0.77) \Delta \beta - 8.77(\pm 3.01) \Delta \beta^2 \\
+ 6.26(\pm 0.39) m_o c_o - 16.51(\pm 2.79) c_o \Delta \beta \\
- 4.720(\pm 0.80) m_o c_o^2 + 53.24(\pm 10.61) c_o \Delta \beta^2 \\
+ 9.39(\pm 1.65) m_o \Delta \beta^2 + 27.526(\pm 3.03) c_o^2 \Delta \beta \\
- 26.757(\pm 2.41) m_o c_o \Delta \beta
\]  

(1)

Equation (1) is valid for the ranges, \(+0.290 \leq (b-y) \leq +0.606, +0.060 \leq m_1 \leq +0.574, +0.126 \leq c_1 \leq +0.504,\) and \(2.488 \leq \beta \leq 2.668,\) has a small dispersion, \(\pm 0.0088,\) and contains a positive \(\Delta \beta\) coefficient, \(+2.239,\) which is not too different from the coefficients of Crawford (+1.11; 1975a) and of Olsen (+1.34; 1988). In Table 1 average residuals for some sub-groups of \(m_1, c_1,\) and \(\beta\) are listed for Equation (1); average residuals, numbers, and standard deviations from Equation (1) are listed in Columns 2, 3, and 4, respectively. Note that the ranges in the average residuals for \(m_1, c_1,\) and \(\beta\) for Equation (1) are \([-0.0013, +0.0007], [-0.0014, +0.0015],\) and \([-0.0022, +0.0009],\) respectively.
The intrinsic-colour calibration of SN89 was derived from 267 stars and retains nine terms, including an $m_o$ term, whereas the new calibration in Equation (1), 392 stars and 11 terms, without $m_o$, but the $m_o$ dependence is available in a more complicated form, in four cross terms: $m_oc_o$, $m_o c_o^2$, $m_o \Delta \beta^2$, and $m_o c_o \Delta \beta$; during the iterations of the calibration process, the simple $m_o$ term has been eliminated according to the empirical criteria discussed above. Here, sixteen terms have been considered while producing the new intrinsic-colour calibration as compared to only twelve terms for the one of SN89. Moreover, the number of calibration stars in Equation (1) and the metal-poor-star content is superior to that of SN89, and finally this new intrinsic-colour calibration extends to somewhat cooler stellar temperatures as shown by the applicable ranges in $(b-y)$, $m_o$, and $\beta$ for these two calibrations; stellar spectra are becoming more complicated at cooler temperatures.

$E(b-y)$ distributions for stars from the Schuster catalogue are displayed in Figs. 2(a) and (b) as calculated from Equation (1): the stars included fall in the ranges of validity given above. Panel 2(a) includes 1062 stars within the above limits of $(b-y)$, $m_1$, $c_1$, and $\beta$ in the Schuster catalogue, while 2(b) only those stars with $[Fe/H] < -1.0$. (For program stars which may be reddened, $m_1$ is substituted for $m_o$ and $c_1$ for $c_o$ in Equation (1), and then the solution is iterated to consistency in $(b-y)_o$, $m_o$, and $c_o$; see SN89.) The hatched areas of both panels in Fig. 2 fulfill the distance limit $d_{Hip} < 70$ pc, which corresponds to the near-solar vicinity and negligible reddenings, as argued above. Qualitative agreements can be seen in Figs. 2(a) and (b); all open histograms have positive tails extending to $E(b-y) \approx 0.07$, showing slightly reddened stars within distributions which are mostly symmetric about $E(b-y) = 0.00$. As expected, the hatched histograms of Fig. 2 show $E(b-y)$ distributions mostly symmetric about $E(b-y) = 0.00$, and no obvious reddening tails; this is true for both the sample of 515 stars including all stars in panel (a), and for the 21 stars with lower metallicities of panel (b). In fact, the 21 hatched, low-metallicity stars all have $E(b-y)$ less than 0.03.

For the distance $d_{Hip} < 70$ pc and metallicities $[Fe/H] < -1.0$, there are 21 stars in the Schuster catalogue; mean $\langle E(b-y) \rangle$ values for these metal-poor stars are presented in Table 2. $\langle E(b-y) \rangle$ values are +0.004 and +0.010 from Equation (1) for $[Fe/H]_{spec} < -1.0$, and $[Fe/H]_{spec} < -1.5$, respectively.

In Table 3, Column 3, $\langle E(b-y) \rangle$ values from Equation (1) are compared with those from SN89, or from O88, for different metallicity groups within the limits of these calibrations. Here, $\langle \Delta E(b-y)_{eq,(1)-SN89} \rangle = E(b-y)_{eq,(1)} - E(b-y)_{SN89}$, and correspondingly for $\langle \Delta E(b-y)_{eq,(1)-O88} \rangle$. When our $E(b-y)$ values are compared to those of SN89, the zero point in the Equation (1) of SN89 has been taken both with and without the small zero-point correction of +0.005 discussed by Nissen (1994) (hereafter N94), based on the $E(b-y)$ values of 23 stars with undetectable Na I lines; the left half of Column 3, Table 3, gives the
\[ \langle \Delta E(b-y) \rangle \] differences with this correction and the right half (in parentheses), without. The mean \[ \langle \Delta E(b-y) \rangle \] differences are quite small, as can be seen in the left half of Column 3, and are 0.005 smaller without this zero-point correction. Note that the average \[ \Delta E(b-y) \] differences show no systematic trend with \([Fe/H]\).

For the comparisons of Table 3, \(E(b-y)\) values are estimated for stars in the Schuster catalogue considering the appropriate limits of the intrinsic-colour equations of SN89 and O88. The equation of O88 is valid for the ranges of \(\delta c_1 = [-0.02, +0.25]\) and \(\delta m_1 = [-0.01, +0.135]\), whereas the relation of SN89 is valid for \((b-y) = [0.254, 0.550]\), \(m_1 = [0.033, 0.470]\), \(c_1 = [0.116, 0.540]\), and \(\beta = [2.550, 2.681]\). SN89 showed that the average difference of \(E(b-y)\) between their calibration and O88 had a systematic trend with metallicity, and confirm the need of a correction of +0.015 mag over \(-2.5 < [Fe/H] < -1.5\) for the O88 calibration. In Table 3, the trends of \(\Delta E(b-y)\) between Equation (1) and O88 agree with those in Table 4 of SN89. In the lower part of Table 3, at high metallicity, there is a non-negligible \((\approx -0.02)\) difference between the \(E(b-y)\) values of Equation (1) and those from O88, and this varies by almost 0.02 mag in passing from the metal-rich to the metal-poor regime; such a variation of about 0.02 mag is also seen in the comparison of SN89 (table 4). Both comparisons in the lower part of Table 3 have negative values, suggesting an overestimation of the reddening by O88, while the comparison to SN89 suggests a small underestimation by their calibration.

Our intrinsic-colour calibration, Equation (1), is based in part on the COBE/DIRBE, IRAS/ISSA full-sky dust maps of SFD98, by using the selection criteria of \(E(B-V) < 0.02\), plus the distance criteria of \(d < 70\) pc, derived by considering the reddening values within the Local Bubble, while the corresponding calibration of SN89 depends mostly on a distance criterion, \(d \lesssim 80\) pc. Both calibration procedures reject calibrating stars with residuals greater than \(\pm 0.025\) during the iterations. The +0.005 zero-point correction of Nissen94 is based on the histogram of his figure 2, which shows an expected rms scatter in \(E(b-y)\) of \(\pm 0.009\), the maximum bar centred at \(E(b-y) = 0.00\), but a slight asymmetry leading to a small positive \(\langle E(b-y) \rangle = +0.005\) for the 23 metal-poor stars observed with the ESO 3.6m telescope and its CASPEC echelle spectrograph and showing no interstellar Na I lines.

Such a procedure assumes that stars without interstellar Na lines are not affected by interstellar extinction, i.e. \(E(b-y) = 0.00\). Munari & Zwitter (1997)(their fig. 4) have shown there is a good correlation between \(EW(\text{Na I})\) and \(E(B-V)\) for single-lined systems. The works of Hobbs (1974), Sembach et al. (1993), Sembach & Danks (1994), and N94 have also shown correlations between the interstellar Na I gas and dust. In fact, equation (2) of Hobbs (1974), equation (1) of N94, and figure 4 of Munari & Zwitter (1997) all point to the probability that the interstellar dust abundance goes to zero together.
with the interstellar Na I gas abundance. These works point out that cold gas and dust probably occur together, and that the absence of cold interstellar gas implies the absence of dust. These results strengthen greatly our assumption that the absence of interstellar Na I lines proves the absence of interstellar dust, i.e. $E(b-y) = 0.00$.

To be able to check the zero-point of our new intrinsic-colour equation, the 23 metal-poor CASPEC stars are still available, and also UVES/VLT halo and thick disk stars, as well as FIES/NOT halo stars, as provided by Prof. P. E. Nissen. The UVES/VLT spectra have been taken from the ESO/ST-ECF Science Archive Facility, and the FIES/NOT halo stars were observed at the Observatorio del Roque de los Muchachos by Nissen and Schuster during two observing runs in 2008. A total of 61 different stars are available, all observed with echelle spectrographs, and all selected to show no interstellar Na I lines in their high-resolution spectra.

$E(b-y)$ values for the 23 CASPEC stars are presented in panel (a) of Fig. 3; these are calculated via Equation (1) using each star’s values of $(b-y)$, $m_1$, $c_1$, and $\beta$. Panel (a) gives $\langle E(b-y) \rangle = +0.004 \pm 0.002$ (mean error), which is very close to the value of +0.005, the zero-point correction of N94. The comparisons of Table 3, plus the results of Nissen (1994), would suggest that the selection criteria of these two intrinsic-colour calibrations (our Equation (1) and equation (1) of SN89), especially the rejection of calibrating stars with residuals greater than $\pm 0.025$, will tend to lead consistently to intrinsic-colour equations which slightly over-correct for the interstellar reddening. Or, that the analysis of N94, and that of our Equation (1), have perhaps been affected by small-number statistics; only about seven stars cause the asymmetry of his figure 2.

In the new UVES/VLT and FIES/NOT databases, provided by Prof. P. E. Nissen, 44 F- and G-type stars without detectable interstellar Na D lines are available with $(b-y)$, $m_1$, $c_1$, and $\beta$ photometry. These give the $E(b-y)$ distribution in panel (b) of Fig. 3, which shows an average reddening value of $\langle E(b-y) \rangle = -0.003 \pm 0.003$ (mean error) from our Equation (1), and this value is insignificantly different from $E(b-y) = 0.00$.

Combining these three samples, excluding a few overlaps in the CASPEC, UVES/VLT, and FIES/NOT databases, and including the thick-disk, spectroscopic standard stars HD 22879 and HD 76932, also without interstellar Na I lines (Nissen & Schuster 2009), the resulting $E(b-y)$ distribution for 61 stars is presented in panel (c) of Fig. 3. The average reddening value $\langle E(b-y) \rangle = -0.001 \pm 0.002$ (mean error) is obtained, which again is insignificantly different from $E(b-y) = 0.00$. These new F- and G-type metal-poor stars without interstellar Na I lines suggest that any zero-point correction to our intrinsic-colour equation must be very small.
Our new intrinsic-colour calibration has been applied to the main-sequence stars of the open clusters NGC 2548 and M67, which have CCD $uvby$–$\beta$ photometry published by Balaguer-Núñez, Jordi & Galadí-Enríquez (2005) (hereafter B05) and Balaguer-Núñez, Galadí-Enríquez & Jordi (2007) (hereafter B07). For 124 main sequence stars of the M67 cluster within the applicable limits of Equation (1), our intrinsic-colour calibration gives the average reddening $\langle E(b-y) \rangle = +0.020 \pm 0.004$. B07 give $+0.030 \pm 0.030$ for M67, derived using standard photometric relations to obtain the stellar parameters, as described in Jordi et al. (1997). Also for M67, Nissen, Twarog & Crawford (1987) (hereafter N87) obtained $\langle E(b-y) \rangle = +0.023 \pm 0.004$ from $uvby$–$\beta$ photometry of main-sequence stars, again showing very good agreement; they used several methods of C75, Crawford (1978), Crawford (1979) and of Hilditch et al. (1983), depending on the spectral range of the main sequence stars. For 21 main sequence stars of the open cluster NGC 2548, which fall within the applicable limits of our Equation (1), our calibration gives the average reddening $\langle E(b-y) \rangle = +0.060 \pm 0.011$, while B05 obtain $+0.060 \pm 0.030$, again using the method of standard photometric relations. Our estimated average reddenings for these two clusters are in good concordance with the ones found by B05 and B07, and by N87.

5 CONCLUSIONS

Our main conclusions are as follows:

(1) The intrinsic-colour calibration of our Equation (1) has a small dispersion, $\pm 0.0088$, and its $+2.239 \Delta \beta$ term is a standard positive one like those of Crawford (+1.11; 1975a) and Olsen (+1.34; 1988). Equation (1) also has the advantage of being useful over a wider range of stellar-population types, from metal-rich to quite metal-poor ($-2.72 \leq [Fe/H] \leq +0.42$).

(2) The $E(b-y)$ distribution of 23 CASPEC stars, as can be seen from panel (a) of Fig. 3, shows $E(b-y) = +0.004 \pm 0.002$, which is almost the same as the $+0.005$ zero-point correction of N94. As discussed by Nissen, this suggests that the zero point of our intrinsic-colour equation should be increased by $+0.004$.

(3) However, for 44 stars of the UVES/VLT and FIES/NOT databases without detectable interstellar Na I lines, the average reddening value $\langle E(b-y) \rangle = -0.003 \pm 0.003$, with a sign opposite to that above for the CASPEC stars, indicating that any zero-point correction to our intrinsic-colour equation is not very significant.

(4) And, in addition, as can be seen from panel (c) of Fig. 3, for the combined databases of CASPEC, UVES/VLT, and FIES/NOT, the average reddening value is $\langle E(b-y) \rangle = -0.001 \pm 0.002$, which is insignificantly different from $E(b-y) = 0.00$. These more recently observed F- and G-
type metal-poor stars help prove that any zero-point correction to our intrinsic-colour equation must be very small.

(5) For the main sequence stars of M67 and NGC 2548, the estimated average reddenings, $+0.020 \pm 0.004$ for M67 and $+0.060 \pm 0.011$ for NGC 2548, are in good concordance with the ones found by B05 and B07, and by N87.

(6) The intrinsic-colour calibration of our Equation (1) can be used for de-reddening $uvby-\beta$ photometry for measuring photometric effective temperatures, metal abundances, absolute magnitudes, distances, stellar classifications, and ages for dwarf and turn-off stars, in the field and in clusters of the Galaxy, over a wide range in metallicity.

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Table 1
Dependence of Average Residuals upon $m_1$, $c_1$, and $\beta$ for Equation (1). Col. 1: $m_1$, $c_1$, and $\beta$ intervals, Col. 2: average residuals from Equation (1), Col. 3: the number of stars in each interval, Col. 4: standard deviations from Equation (1).

| $m_1$     | Ave. residual | N   | Std.dev. |
|-----------|---------------|-----|----------|
| [0.06 0.13] | $-0.0013$     | 24  | 0.0096   |
| (0.13 0.17] | $-0.0004$     | 60  | 0.0099   |
| (0.17 0.21] | $+0.0005$     | 73  | 0.0080   |
| (0.21 0.28] | $+0.0003$     | 67  | 0.0090   |
| (0.28 0.35] | $+0.0003$     | 65  | 0.0088   |
| (0.35 0.45] | $-0.0012$     | 46  | 0.0075   |
| (0.45 0.58] | $+0.0007$     | 57  | 0.0085   |

| $c_1$     | Ave. residual | N   | Std.dev. |
|-----------|---------------|-----|----------|
| [0.12 0.25] | $+0.0000$     | 61  | 0.0104   |
| (0.25 0.28] | $-0.0006$     | 89  | 0.0085   |
| (0.28 0.31] | $+0.0015$     | 84  | 0.0084   |
| (0.31 0.34] | $-0.0014$     | 77  | 0.0074   |
| (0.34 0.40] | $+0.0004$     | 71  | 0.0087   |
| (0.40 0.51] | $-0.0005$     | 10  | 0.0108   |

| $\beta$   | Ave. residual | N   | Std.dev. |
|-----------|---------------|-----|----------|
| [2.488 2.550] | $+0.0006$     | 98  | 0.0093   |
| (2.550 2.570] | $-0.0015$     | 99  | 0.0082   |
| (2.570 2.590] | $+0.0009$     | 114 | 0.0081   |
| (2.590 2.610] | $+0.0006$     | 58  | 0.0080   |
| (2.610 2.668] | $-0.0022$     | 23  | 0.0118   |

Table 2
Mean $\langle E(b-y) \rangle$ Values for Two Metal-poor Ranges and $d < 70$ pc in the Schuster Catalogue, Calculated from Equation (1).

| $[Fe/H]$ range | $\langle E(b-y)_{eq,(1)} \rangle$ | N   |
|----------------|----------------------------------|-----|
| $[Fe/H] < -1.0$ | $+0.004$                         | 21  |
| $[Fe/H] < -1.5$ | $+0.010$                         | 8   |
Table 3
Mean $\langle \Delta E(b-y) \rangle$ Differences between Equation (1) and SN89, or O88, for Metallicity Subsets. Col. 1: $[Fe/H]$ intervals; Col. 2: the number of stars in each interval; Col. 3: first part, $\langle \Delta E(b-y) \rangle$ differences with respect to SN89, with (and without) the $+0.005$ zero-point correction of Nissen (1994); second part, with respect to O88; Col. 4: standard deviations for the comparisons.

| $[Fe/H]$ range | N   | $\langle E(b-y)_{eq.(1)} - SN89 \rangle$ | Std.dev. |
|----------------|-----|------------------------------------------|----------|
| $[+0.42, +0.00]$ | 19  | +0.0057 ($+0.0007$) | 0.0074   |
| $(-0.00, -0.25]$ | 27  | +0.0044 ($-0.0006$) | 0.0028   |
| $(-0.25, -0.50]$ | 43  | +0.0035 ($-0.0015$) | 0.0055   |
| $(-0.50, -0.75]$ | 46  | +0.0062 ($+0.0012$) | 0.0033   |
| $(-0.75, -1.00]$ | 45  | +0.0019 ($-0.0031$) | 0.0144   |
| $(-1.00, -1.50]$ | 43  | +0.0041 ($-0.0009$) | 0.0124   |
| $(-1.50, -2.00]$ | 21  | $-0.0030$ ($-0.0080$) | 0.0184   |
| $(-2.00, -2.72]$ | 10  | +0.0024 ($-0.0026$) | 0.0157   |

| $[Fe/H]$ range | N   | $\langle \Delta E(b-y)_{eq.(1)} - O88 \rangle$ | Std.dev. |
|----------------|-----|---------------------------------------------|----------|
| $[+0.32, -0.50]$ | 342 | $-0.024$ | 0.030 |
| $(-0.50, -1.22]$ | 42  | $-0.007$ | 0.007 |
Fig. 1. For the Schuster catalogue: (a) $E(B-V)$ versus $d_{\text{Hip}}$; and (b) $E(B-V)$ versus Galactic latitude. For this catalogue, the criteria, $E(B-V) < 0.02$ plus $d_{\text{Hip}} < 70$ pc have been used to define negligible reddening for the intrinsic-colour ($(b-y)_o-\beta$) calibration. See Section 4 for details.
Fig. 2. $E(b-y)$ distributions for stars from the Schuster catalogue are displayed in panels (a) and (b) as calculated from Equation (1); the stars fall within the ranges of validity: $+0.290 \leq (b-y) \leq +0.606, +0.060 \leq m_1 \leq +0.574, +0.126 \leq c_1 \leq +0.504,$ and $2.488 \leq \beta \leq 2.668.$ Panel (a) includes 1062 stars within the above limits of $(b-y), m_1, c_1,$ and $\beta,$ while (b) only those stars with $[Fe/H] < -1.0.$ In both panels the distribution is quite symmetric about $E(b-y) = 0.00.$ The hatched areas meet the restriction, $d_{Hip} < 70$ pc, which corresponds to the negligible-reddening, near-solar vicinity.
Fig. 3. $E(b-y)$ distributions for: panel (a), 23 CASPEC stars; panel (b), 44 UVES/VLT + FIES/NOT stars; and panel (c), 61 stars, the combined sample; all without detectable interstellar Na I lines. As calculated from our Equation (1), panels (a), (b), and (c) give the average reddenings of $\langle E(b-y) \rangle = +0.004 \pm 0.002$, $\langle E(b-y) \rangle = -0.003 \pm 0.003$, and $\langle E(b-y) \rangle = -0.001 \pm 0.002$, respectively.