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The determination of $T_{\rm eff}$ for metal-poor A-type stars using V and 2MASS J, H and K magnitudes[⋆,⋆⋆]

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Abstract. Effective temperatures ($T_{\rm eff}$) can be determined from $(V-J)_0$, $(V-H)_0$ and $(V-K)_0$ colours that are derived from 2MASS magnitudes. This gives another way to estimate the $T_{\rm eff}$ of faint blue halo stars ($V \lesssim 15$) whose temperatures are now usually deduced from $(B-V)_0$. Transformations (adapted from Carpenter 2001b) are used to change colours derived from the 2MASS data to the Johnson system. $T_{\rm eff}$ is then derived from these colours using an updated Kurucz model. Tables are given to derive $T_{\rm eff}$ as a function of $(V-J)_0$, $(V-H)_0$ and $(V-K)_0$ for a variety of metallicities and $\log g$ suitable for blue horizontal branch and main sequence stars. The temperatures obtained in this way are compared with those in the recent literature for various stars with $5 \le V \le 15$ and $T_{\rm eff}$ in the range 6500 to 9500 K; systematic differences are ∼100 K. An exception is the sample of BHB stars observed by Wilhelm et al. (1999) whose $T_{\rm eff}$ are significantly cooler than those we derive by an amount that increases with increasing temperature.

Key words. stars: fundamental parameters (temperatures) – stars: horizontal-branch

1. Introduction

The determination of an effective temperature $T_{\rm eff}$ is an essential preliminary to deriving the chemical abundances in a stellar atmosphere. If a moderately high resolution ($\lambda/\Delta\lambda \gtrsim 15\,000$) spectrum is available, several independent methods may be used to derive $T_{\rm eff}$ from the spectra, and their inter-agreement can be used to assess their accuracy (e.g. see Kinman et al. 2000, Table 7). For fainter stars, only a single broad-band colour such as $(B-V)$ may be available to give an observational constraint on $T_{\rm eff}$. The relation between $(B-V)$ and $T_{\rm eff}$ has recently been discussed by Castelli (1999) for dwarfs and giants and also by Sekiguchi & Fukugita (2000, hereafter SF00) primarily for stars with $T_{\rm eff}$ cooler than 7000 K. For hotter stars, $(B-V)_0$ becomes increasingly insensitive to $T_{\rm eff}$ and the $(B-V)$ vs. $T_{\rm eff}$ relation is also quite sensitive to $\log g$ (see Table 1). Caution is needed therefore in the use of the $(B-V)$ vs. $T_{\rm eff}$ relation for stars hotter than 7000 K; not only must $\log g$ be well determined but the accuracy of the method decreases rapidly with increasing temperature (see Table 1).

We therefore need another way to estimate $T_{\rm eff}$ which can be used to check that derived from $(B-V)$. A particular application is for metal-poor A-type halo stars with $V \lesssim 15$. An extensive discussion of empirical $T_{\rm eff}$ calibrations has been given by Bessell et al. (1998). For earlier type stars, they prefer optical colour-indices to derive $T_{\rm eff}$ because "the lower precision of much $(V-K)$ photometry (from independent observations of V and K magnitudes) produces larger uncertainties in the $T_{\rm eff}$ – colour relations". The 2MASS sky survey provides near-IR magnitudes in the J, H, and $K_{\rm s}$ (K-short) wavebands for stars as faint as 15th magnitude and so in principle can provide another way to estimate $T_{\rm eff}$ *providing a sufficiently accurate V-magnitude is available.* Obviously the stars must also not be variable or be composite. In this paper we investigate how well the 2MASS magnitudes can be used to derive $T_{\rm eff}$ for fainter hot stars for which the use of $(B-V)$ lacks accuracy.

In Sect. 2 we present the synthetic grids of colour indices used in this paper, which are based on the ATLAS9 (Kurucz 1993) models.

In Sect. 3 we compare the computed $T_{\rm eff}$ vs. $(V-K)_0$ relation with the best-determined data for several nearby stars. This includes the "reference" $T_{\rm eff}$ given by Smalley & Dworetsky (1995) and also the recent $(V-K)_0$ and $T_{\rm eff}$ data published by Di Benedetto (1998, hereafter Di B98), Blackwell & Lynas-Gray (1998, hereafter BL98) and Alonso et al. (1996, hereafter AAMR96) for main-sequence stars of solar metallicity. The assumptions that these authors have made

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[⋆⋆] Tables 2 and 3 are only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/391/1039`

Table 1. Comparison of $(B-V)_0$ and $(V-K)_0$ colour vs. $T_{\rm eff}$ relations for various $T_{\rm eff}$.

$T_{\rm eff}$	Change in $T_{\rm eff}$ for $(B-V)_0$ relation for colour change of 0.01 mag[a]	$(B-V)_0$ relation for log g change of 1.0[b]	$(V-K)_0$ relation for colour change of 0.01 mag[a]	$(V-K)_0$ relation for log g change of 1.0[b]	$(V-K)_0$ relation for [M/H] change of 1.0[c]
(1)	(2)	(3)	(4)	(5)	(6)
7000 K	52 K	178 K	20 K	104 K	60 K
8000 K	59 K	488 K	27 K	123 K	50 K
9000 K	100 K	630 K	49 K	78 K	60 K
10 000 K	172 K	655 K	78 K	16 K	100 K

[a] For $\log g = 4.0$ and [M/H] = 0.0.
[b] From $\log g = 3.0$ to $\log g = 4.0$ and [M/H] = 0.00.
[c] From $\log g = 4.0$ and [M/H] = −1.0 to [M/H] = −2.0

about the interstellar extinction affect both their $T_{\rm eff}$ and $(V-K)_0$.

In Sect. 4, we investigate the problem of transforming the 2MASS magnitudes to the Bessell-Brett (1988) homogenized system, so that they will be compatible with the $T_{\rm eff}$ vs. colour relations from Bessell et al. (1998) (hereafter BCP) that are computed in the same photometric system. Finally, in Sect. 5, we compare the $T_{\rm eff}$ that are obtained from $(V-J)_0$, $(V-H)_0$ and $(V-K)_0$ colours (using 2MASS data) with those obtained in previous investigations. We considered the hotter Hyades dwarfs extracted from the sample studied by de Bruijne et al. (2001) (Sect. 5.1); field blue horizontal branch (BHB) stars already studied by Kinman et al. (2000) in the optical region and by Castelli & Cacciari (2001) in the ultraviolet region (Sect. 5.2); a small number of blue metal-poor (BMP) stars taken from the sample studied by Preston & Sneden (2000) and Wilhelm et al. (1999) (Sect. 5.3); the BMP and BHB stars in the high-latitude field BS 15621 field among those studied by Wilhelm et al. (1999) (Sect. 5.4) and six of the outlying BHB stars in the globular cluster M 13 that were studied by Peterson et al. (1995) and for which reliable 2MASS data are available (Sect. 5.5).

2. The grids of synthetic colors

The synthetic grids of $VJHK$ colours used in this paper are based on the ATLAS9 Kurucz models computed by Castelli with the overshooting option for the convection switched off (NOVER grids, Castelli et al. 1997).

When $(V-K)$ colours in the Johnson (J) system are considered, the NOVER $RIJKL$ grids available at `http://kurucz.harvard.edu` were used, while when $(V-J)$, $(V-H)$, and $(V-K)$ colours in the Bessell-Brett (BB) homogenized system are considered, the BCP NOVER grid of colours were used. We recall that for $(V-K)$, the conversion from the J system to the BB system is (Bessell & Brett 1988):

$$(V-K)_{\rm J} = 1.007[(V-K)_{\rm BB} - 0.01]. \quad (1)$$

We used the BCP colours to generate two tables of synthetic indices $(V-J)_{\rm BB}$, $(V-H)_{\rm BB}$, and $(V-K)_{\rm BB}$ vs. $T_{\rm eff}$. Table 2 gives $T_{\rm eff}$ vs. colour relations *specifically for BHB stars* in the interval 7000 to 10 500 K for [M/H] = −1.0, −1.5, and −2.0. The $T_{\rm eff}$ vs. colour relations were set up by assuming that $\log g$ satisfies the empirical relation:

$$\log g = 4.375 \log T_{\rm eff} - 13.967 \quad (2)$$

which we derived from the field BHB stars studied by Kinman et al. (2000). This relation is compatible with the data for cluster BHB stars with $T_{\rm eff} \lesssim 10\,000$ K discussed by Moehler (2001). The colours versus $T_{\rm eff}$ relations of Table 2 were obtained by interpolating in the synthetic indices for a given $T_{\rm eff}$ and the specific $\log g$ derived from the above linear relation.

Table 3 gives $T_{\rm eff}$ for $(V-J)_{\rm BB}$, $(V-H)_{\rm BB}$, and $(V-K)_{\rm BB}$ in the interval 6500 to 10 500 K for metallicities [M/H] = 0.0, −1.0, −1.5 and −2.0. This table is in two parts; the first for $\log g = 4.0$ and the second for $\log g = 4.5$. In both Tables 2 and 3 the step in $T_{\rm eff}$ is 10 K.

Figures 1 and 2 show the effect of gravity and the effect of the metallicity respectively on the relations $T_{\rm eff}$ vs. $(V-J)_{\rm BB}$, $T_{\rm eff}$ vs. $(V-H)_{\rm BB}$, and $T_{\rm eff}$ vs. $(V-K)_{\rm BB}$. Table 1 shows the effect of gravity on the $T_{\rm eff}$ vs. $(V-K)_{\rm BB}$ relation indicating that it is at a maximum at 8000 K with $\Delta T_{\rm eff} = 123$ K for $\Delta \log g = 1.0$. Figure 1 shows that this effect is of the same order as for the $T_{\rm eff}$ vs. $(V-J)_{\rm BB}$ and $T_{\rm eff}$ vs. $(V-H)_{\rm BB}$ relations. The effect of errors in the metallicity on the $T_{\rm eff}$ vs. colour relations are not larger than those caused by gravity. Table 1 shows that, for $(V-K)$, the largest difference in $T_{\rm eff}$ produced by a [M/H] change of 1.0 is about 100 K. Figure 2 shows that this behaviour is similar for all the three colour indices.

Houdashelt et al. (2000) have used updated MARC-SSG models to obtain colours on the Johnson-Glass system for stars with 4000 K $\leq T_{\rm eff} \leq$ 6500 K. Their hottest model (6500 K) is somewhat cooler than the temperatures with which we are concerned in this paper. Nevertheless, it may be interesting to note that at this temperature, for $\log g = 4.0$, [Fe/H] = 0.0, their relation gives a $V-K = 1.047$ compared with 1.079 for the BCP colors. Thus, at 6500 K, their model gives a $T_{\rm eff}$ which is ∼56 K cooler than that given by BCP. Such systematic differences do not seem unreasonable considering the use of different atmospheric models and the different calibrations for the colours.

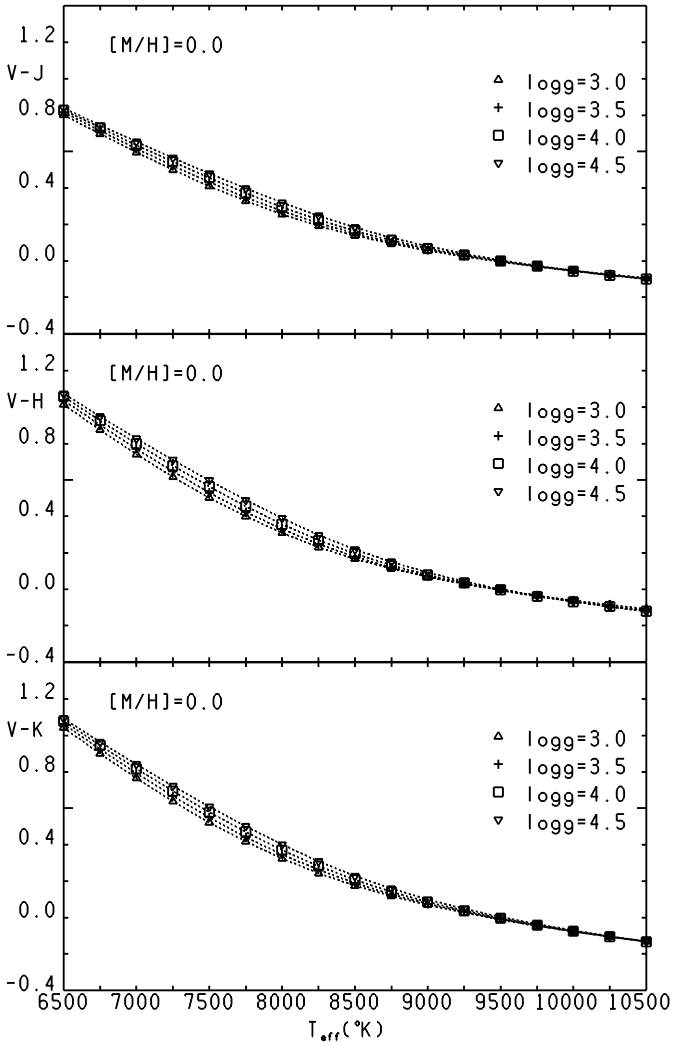

Fig. 1. Computed $T_{\rm eff}$ vs. colour relations for different $\log g$ and [M/H] = 0.0.

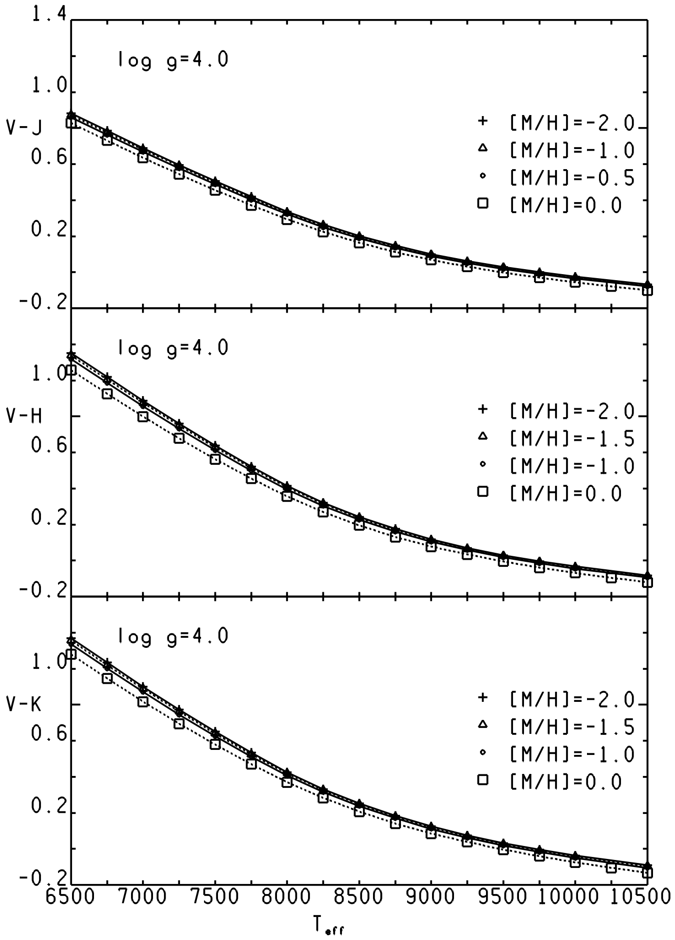

Fig. 2. Computed $T_{\rm eff}$ vs. colour relations for different metallicities and $\log g = 4.0$.

3. Computed and empirical $T_{\rm eff}$ vs. $(V-K)$ relations for dwarfs of solar metallicity. The effect of the interstellar extinction

Any determination of $T_{\rm eff}$ *from a colour index depends crucially on how well we know the interstellar extinction* A_V*, which is required for de-reddening* $(V-K)$*.* In this section we discuss the effect of the interstellar extinction on the determinations of $T_{\rm eff}$ from $(V-K)$ for dwarfs of solar metallicity and compare $T_{\rm eff}$ from models with the $T_{\rm eff}$ from other determinations.

$E(V-K)$ was determined from the relation

$E(B-V) = E(V-K)/2.76$ (Mathis 1999).

3.1. $T_{\rm eff}$ from $(V-K)$ for bright stars with "reference" $T_{\rm eff}$

The effective temperature is obtained most directly from the Stefan-Boltzmann equation which relates $T_{\rm eff}$ to the angular diameter θ and the total integrated flux at the earth ($f_\oplus$) of a star:

$$f_\oplus = \frac{1}{4}\sigma\theta^2 T_{\rm eff}^4.$$

The number of stars for which angular diameters are available and from which "reference" $T_{\rm eff}$ can be obtained is quite limited. A compilation of these "reference" $T_{\rm eff}$ has been given by Smalley & Dworetsky (1995)[1]; these include several stars with luminosity class V and IV–V and spectral types A and F. The "reference" $T_{\rm eff}$ for these stars are given in Table 4 (Col. 4) and are compared with those derived from the *RIJKL* grids (Col. 5) using $(V-K)_0$ taken from Di B98 (Col. 8). We adopted the metallicity listed in Col. 7 and the gravity given in Col. 6. The agreement is generally good; the mean difference between the $T_{\rm eff}$ from the synthetic colors and the "reference" $T_{\rm eff}$ is -21 ± 50 K.

The two stars with the largest departures from the model predictions are α CMa and ϵ Sgr. We see from Cols. 9 and 10 in Table 4 that these stars have the largest differences between the $E(B-V)$ estimated by two different methods; this suggests that the correction of $(V-K)$ for the interstellar extinction may be a significant source of uncertainty in determining

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[1] Their $T_{\rm eff}$ are very similar to those given by SF00.

Table 4. Data for bright luminosity class V stars with reference $T_{\rm eff}$.

Name	θ^a	$f_\oplus{}^b$	$T_{\rm eff}$		$\log g^b$	[M/H]	$(V-K)_0{}^a$	$E(B-V)$	
	$10^{-3}('')$	10^{-6} erg cm^{-2} s^{-1}	Reference	Model^c				Pol.^{d}	(Di B98)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
α CMa[1]	5.92 ± 0.09	112.899 ± 7.106	9916 ± 174	10 033	4.33	+0.5^e	−0.099	0.0018 ± 0.0013	0.006
α Lyr[2]	3.24 ± 0.07	29.737 ± 1.820	9602 ± 180	9558	3.95	−0.5^e	−0.001	0.0005 ± 0.0009	0.002
ϵ Sgr[3]	1.44 ± 0.06	5.436 ± 0.316	9418 ± 337	9240	4.5	0.0	0.047	0.0006 ± 0.0008	0.012
β Leo[4]	1.33 ± 0.10	3.644 ± 0.197	8867 ± 355	8761	4.1	0.0	0.140	0.0019 ± 0.0016	0.004
α PsA[5]	2.10 ± 0.14	8.638 ± 0.459	8756 ± 315	8760	4.2	0.0	0.144	0.0008 ± 0.0004	0.002
α CMi[6]	5.51 ± 0.05	18.638 ± 0.868	6551 ± 82	6634	4.06	0.0	1.010	0.0005 ± 0.0005	0.000

[1] BS 2491, [2] BS 7001, [3] BS 6879, [4] BS 4534, [5] BS 8728, [6] BS 2943.
[a] Di Benedetto (1998) (Di B98). [b] Smalley & Dworetsky (1995). [c] $T_{\rm eff}$ from *RIJKL* grids using $(V-K)$ from Col. 8.
[d] Derived from polarization (see Appendix). [e] Qiu et al. (2001).

Table 5. Data for F dwarfs that lie within ~50 pc.

HIP	HD	Dist. (pc.)	$T_{\rm eff}{}^a$ (K)	$(V-K)^a$	$(V-K)_0{}^a$	$E(B-V)^a$	$E(B-V)^b$	$(V-K)_0$ (adopted)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
2832	3268	38	6 087	1.295	1.268	0.010	0.0040	1.284
14594	19445	39	6 014	1.340	1.311	0.010	0.0018	1.335
28644	40832	50	6 551	1.038	1.001	0.013	0.0034	1.029
54383	96574	50	6 113	1.288	1.251	0.013	0.0015	1.284
60098	107213	50	6 303	1.174	1.138	0.013	0.0022	1.168
76568	139798	36	6 756	0.924	0.897	0.010	0.0016	0.920
81800	151044	30	6 061	1.305	1.284	0.008	0.0043	1.293
91058	171620	52	6 129	1.281	1.243	0.014	0.0015	1.277
95492	182807	28	6 105	1.277	1.257	0.007	0.0027	1.270
98946	191096	52	6 783	0.922	0.885	0.014	0.0025	0.915

[a] Taken from Di B98.
[b] Derived from polarization (see Appendix A).

$T_{\rm eff}$. Column 10 is derived from the $E(V-K)$ correction taken from Di B98, who assumes $A_v = 0.8$ mag kpc^{-1} (or $E(B-V) = 0.25$ mag kpc^{-1}). Column 9 gives $E(B-V)$ derived from polarization data, as described in Appendix A. The $E(B-V)$ derived from the polarizations (Col. 9) are essentially zero while those assumed by Di B98 tend to be larger.

3.2. $T_{\it eff}$ from $(V-K)$ for stars nearer than 50 pc.

Evidence is given in the Appendix A that the extinction for stars within 50 pc is generally quite low ($E(B-V) = 0.0025$). There are twelve F stars that are nearer than 50 pc (mean distance 25 pc)[2] whose $T_{\rm eff}$ have been determined by *both* Di B98 and AAMR96. The mean difference between their estimates (Di B98 minus AAMR96) is very small (14 ± 10 K). Thus these mean extinction corrections applied by Di B98 and AAMR96 ($E(B-V) = 0.006$ and 0.000 respectively) are too small to have a large effect on their calculated $T_{\rm eff}$.

We now consider another group of F stars that are closer than 52 pc (Table 5) for which we were able to derive $E(B-V)$ from their polarizations (as explained in Appendix A). The $E(B-V)$ of these stars is sufficently small so that the $T_{\rm eff}$ derived by Di B98 should be little affected by his adopted $E(B-V)$. We have taken the $(V-K)$ from Di B98 and corrected it by the extinction derived from the polarization (Table 5, Col. 8). These $T_{\rm eff}$ and $(V-K)_0$ are plotted in Fig. 3; the case where the extinction is that used by Di B98 is shown by filled circles and the case where the extinction is derived from the polarization by open circles. The latter case agrees better with the colour vs. temperature relation given by the synthetic colors. Figure 3 shows that $T_{\rm eff}$ from the synthetic $(V-K)$ differs by less than 100 K from that given by the empirical relations taken from Di B98. However, the $T_{\rm eff}$ from the models is systematically larger than the empirical $T_{\rm eff}$. The discrepancy between the $T_{\rm eff}$ from the models and that obtained by BL98 using the Infrared flux method is somewhat larger.

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[2] HIP 39780, 40843, 50384, 57629, 57757, 60098, 71284, 72567, 73996, 75971, 76568 & 86032.

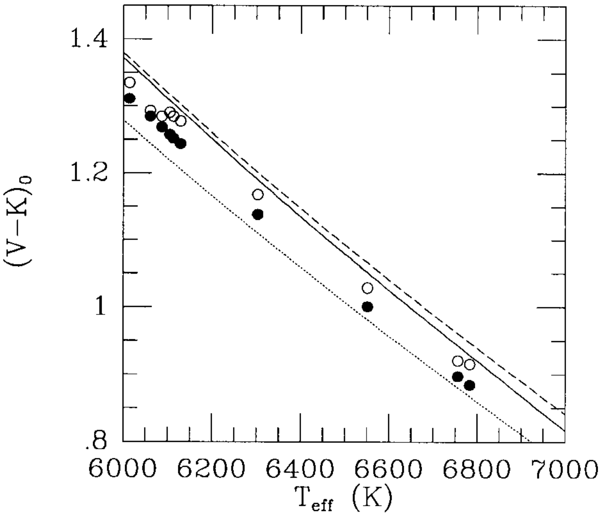

Fig. 3. The ordinate is $(V-K)_0$ and the abscissa is $T_{\rm eff}$ (K). The filled circles are ISO standards within 52 pc (for details see Table 6 and text). The filled circles correspond to the extinction used by Di B98 and the open circles to the extinction derived from the polarization. The lines show the relations derived from the *RIJKL* synthetic grid for solar metallicity and $\log g = 4.0$ (full line) and 4.5 (dashed line). The dotted line is an empirical relation given by BL98.

It is also interesting that the difference between the two empirical $T_{\rm eff}$ vs. $(V-K)$ relations given by BL98 and DiB98 increases with decreasing temperature.

Bearing in mind the uncertainties in the extinction, we conclude that the relation between $T_{\rm eff}$ and $(V-K)_0$ given by the models is consistent within 100 K with the best data that we have at this time for dwarf stars of solar metallicity.

4. Transformation of 2MASS magnitudes to the Bessell-Brett (BB) homogenized system

The 2MASS data used in this paper are from the Second Incremental Data Release (Cutri et al. 2000). Thirty nine of the stars with $(V-K) < 1.50$ for which Di B98 gives K magnitudes on the TCS system have 2MASS $K_{\rm s}$ magnitudes. For 18 stars with $(V-K)_{\rm J} < 0.50$, $K_{\rm s}$ minus $K_{\rm TCS} = -0.075 \pm 0.007$ mag. For the 21 stars with $0.50 \le (V-K)_{\rm J} \le 1.50$, $K_{\rm s}$ minus $K_{\rm TCS} = -0.064 \pm 0.006$ mag. We conclude that there is no significant colour term in the transformation and for all 39 stars we obtain:

$$K_{\rm TCS} = K_{\rm s} + 0.069 \pm 0.005. \qquad (3)$$

The differences between the 2MASS and Di B98 magnitudes are shown in Fig. 4 where the error bars are those given for the 2MASS data alone; the differences seem reasonable since the Di B98 magnitudes have errors of about ±0.02 mag. In this plot, it seems that the differences are greater for the very brightest stars. No similar effect was found in a larger sample of these stars (Carpenter 2001a) and so no systematic magnitude effect is likely to be present.

Carpenter (2001b) gives colour transformations for the 2MASS Second Incremental Data Release to various other photometric systems, including the Bessell & Brett (BB) homogenized system (Bessell & Brett 1988). Carpenter (Eq. (A1)) finds:

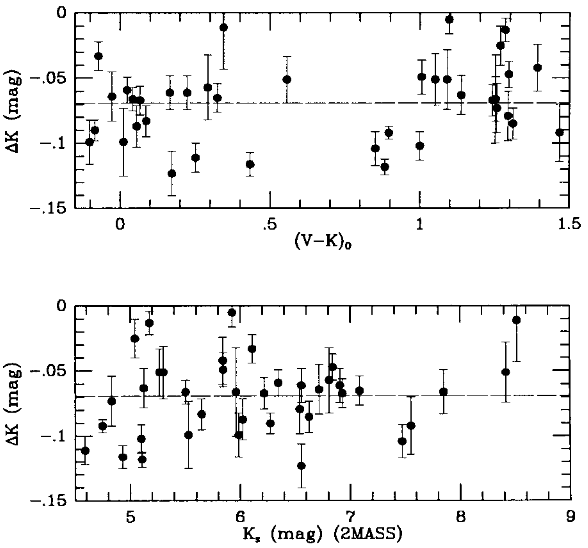

Fig. 4. The difference (ΔK) (2MASS $K_{\rm s}$ minus K magnitude on the TCS system (Di Benedetto 1998) as function of $(V-K)_0$ (above) and $K_{\rm s}$ (below).

$$(K_{\rm s})_{\rm 2MASS} = K_{\rm BB} + (0.000 \pm 0.005)(J-K)_{\rm BB} + (-0.044 \pm 0.003). \qquad (4)$$

The difference between the constants in Eqs. (4) and (5) is greater than their quoted errors. We assume that this is an indication of the looseness of the definition of the Johnson system for hot stars (e.g. Fig. 1 of Di B98). In this paper we have chosen to adopt Eq. (4) and so have:

$$K_{\rm BB} = (K_{\rm s})_{\rm 2MASS} + 0.044. \qquad (5)$$

Using Carpenter's Eqs. (A4) and (A3), we further obtain:

$$H_{\rm BB} = H_{\rm 2MASS} + 0.016 \qquad (6)$$

$$J_{\rm BB} = J_{\rm 2MASS} + 0.029(J-K_{\rm s})_{\rm 2MASS} + 0.055. \qquad (7)$$

Hawarden et al. (2001) have given a list of faint IR standard stars on the *UKIRT* system. Seven of these are blue $(-0.01 \le (B-V) \le 0.020)$ and have $9.9 < K < 13.5$ and have 2MASS magnitudes. The mean differences in the sense 2MASS minus *UKIRT* magnitudes for these seven stars are:

$$\Delta J = -0.022 \pm 0.015 \qquad (-0.007 \pm 0.007) \qquad (8)$$

$$\Delta H = +0.008 \pm 0.013 \qquad (+0.019 \pm 0.006) \qquad (9)$$

$$\Delta K = -0.009 \pm 0.011 \qquad (+0.002 \pm 0.004) \qquad (10)$$

where the quantities in parentheses were calculated from Carpenter's transformation Eqs. (38), (40) and (41). The agreement is satisfactory and shows that the 2MASS magnitudes for fainter and bluer stars are on the same system as for the brighter stars and that their quoted errors are realistic for these relatively faint stars.

Table 6. Data for the Hyades Dwarf stars discussed in Sect. 5.1.

HD (1)	HIP (2)	$T_{\rm eff}{}^{a}$ (K) (3)	$\log g^{a}$ (4)	V^{b} (5)	$J_{\rm 2MASS}$ (6)	$H_{\rm 2MASS}$ (7)	$K_{\rm 2MASS}$ (8)	$(V-J)_{\rm BB}{}^{c}$ (9)	$(V-H)_{\rm BB}{}^{c}$ (10)	$(V-K)_{\rm BB}{}^{c}$ (11)
24098	17950	6624	4.431	6.473	5.711	5.552	5.470	0.700	0.905	0.959
		±51.8	±0.029	±0.006	±0.023	±0.064	±0.033	±0.024	±0.064	±0.034
26345	19504	6660	4.336	6.612	5.822	5.622	5.557	0.727	0.974	1.011
		±44.4	±0.036	±0.007	±0.057	±0.039	±0.041	±0.057	±0.040	±0.042
26737	19789	6674	4.334	7.049	6.225	6.091	5.999	0.762	0.942	1.006
		±44.4	±0.037	±0.004	±0.078	±0.043	±0.037	±0.078	±0.043	±0.037
27524	20349	6628	4.340	6.807	5.968	5.791	5.741	0.777	1.000	1.022
		±67.2	±0.039	±0.022	±0.036	±0.032	±0.039	±0.042	±0.039	±0.045
27534	20350	6598	4.345	6.791	5.951	5.802	5.727	0.779	0.973	1.020
		±62.3	±0.038	±0.021	±0.036	±0.032	±0.037	±0.042	±0.038	±0.043
27731	20491	6507	4.361	7.175	6.253	6.117	6.072	0.862	1.042	1.059
		±29.9	±0.039	±0.009	±0.022	±0.025	±0.025	±0.024	±0.027	±0.027
28406	20948	6554	4.352	6.915	6.066	5.901	5.786	0.786	0.998	1.085
		±43.7	0.039	±0.007	±0.039	±0.053	±0.038	±0.040	±0.053	±0.039
28911	21267	6651	4.337	6.619	5.757	5.635	5.528	0.800	0.968	1.047
		±53.6	±0.039	±0.004	±0.027	±0.036	±0.030	±0.027	±0.036	±0.030
29225	21474	6593	4.346	6.647	5.785	5.608	5.552	0.800	1.023	1.051
		±78.9	±0.043	±0.010	±0.054	±0.030	±0.046	±0.055	±0.032	±0.047
31845	23214	6558	4.352	6.753	5.818	5.645	5.617	0.874	1.092	1.092
		±66.5	±0.041	±0.005	±0.032	±0.035	±0.040	±0.032	±0.035	±0.040
33400	24116	6580	4.348	7.856	7.003	6.852	6.797	0.792	0.988	1.015
		±66.8	±0.048	±0.031	±0.033	±0.034	±0.044	±0.045	±0.046	±0.054

[a] Data taken from de Bruijne et al. (2001).

[b] Data taken from Hipparcos Input Catalogue (Turon et al. 1992).

[c] On the Bessell-Brett system.

5. $T_{\rm eff}$ from the 2MASS color indices and comparison with other determinations

In this section we take a number of recent determinations of $T_{\rm eff}$ and compare them with those obtained from colours determined from the 2MASS magnitudes after transformation to the Bessell-Brett system using Eqs. (5)–(7) in Sect. 4. In making comparisons with other determinations of $T_{\rm eff}$ we have chosen cases in which the correction for interstellar extinction is not a major source of uncertainty (in general, $E(B-V) \leq 0.05$ mag).

5.1. $T_{\rm eff}$ for Hyades dwarfs

The Hyades cluster is sufficiently close (mean distance ~45 pc) that we can assume that $E(B-V) = 0.0$. In their Hipparcos study of this cluster, de Bruijne et al. (2001) have given $T_{\rm eff}$ for main sequence stars ($4.33 \leq \log g \leq 4.36$) which are based on two recent calibrations of the $T_{\rm eff}$ versus $(B-V)$ relation: (1) Bessell et al. (1998) in combination with Alonso et al. (1996) and (2) Lejeune et al. (1997, 1998). We have used the eleven hottest of these Hyades stars ($T_{\rm eff} > 6500$ K) for which 2MASS magnitudes are available. Table 6 lists the stars and their $T_{\rm eff}$ and $\log g$ according to de Bruijne et al. (2001). Their V magnitudes were taken from the Hipparcos Input Catalogue (Turon et al. 1992) and the 2MASS magnitudes were transformed to the Bessell-Brett system with Eqs. (5)–(7). The quoted errors of both the V and the 2MASS magnitudes were used to determine the errors of the colours. These data, given in Table 6, are compared in Fig. 5 with the computed $T_{\rm eff}$ vs. colour relations for $\log g = 4.0$ and 4.5 that are given in Table 3; the agreement is generally satisfactory. The mean difference between the observed and the synthetic colours for the temperatures adopted by de Bruijne et al. are $+0.002 \pm 0.013$, -0.009 ± 0.014 and $+0.010 \pm 0.009$ for $(V-J)_0$, $(V-H)_0$ and $(V-K)_0$ respectively. The mean differences between the $T_{\rm eff}$ given by de Bruijne et al. and those derived from the synthetic and the observed colours are -5 ± 33 K, $+23 \pm 36$ K and -26 ± 23 K for $(V-J)_0$, $(V-H)_0$ and $(V-K)_0$ respectively.

5.2. $T_{\rm eff}$ for nearby Blue Horizontal Branch stars

2MASS magnitudes are available for thirteen out of the twenty nine nearby BHB stars that were discussed by Kinman et al. (2000) (KCCBHV); these thirteen stars are listed in Table 7.

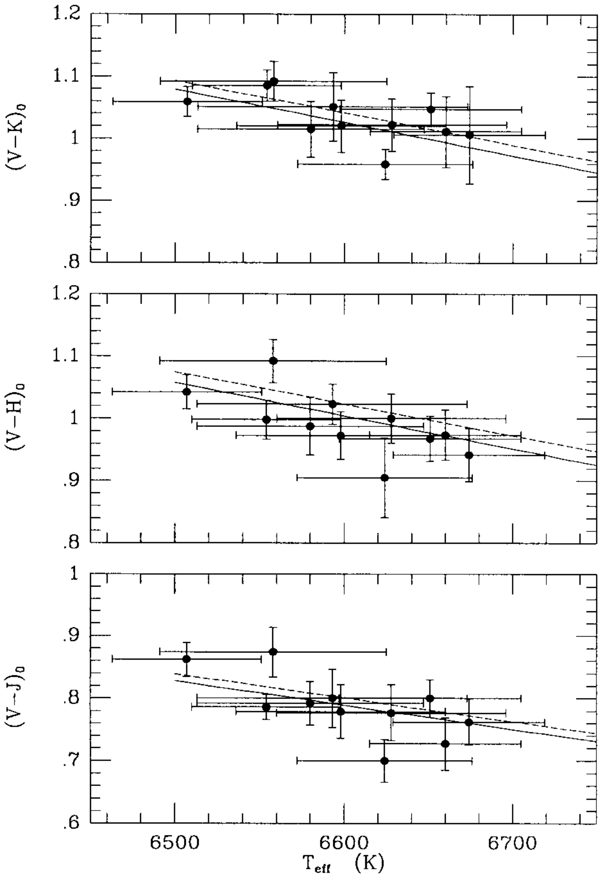

Fig. 5. Hyades members whose $T_{\rm eff}$ is taken from de Bruijne et al. (2001). The colours (ordinates) were determined from 2MASS magnitudes using the transformations in Sect. 4. The full and dashed lines show the computed $T_{\rm eff}$ vs. colour relations from Table 3 for $\log g$ = 4.0 and $\log g$ = 4.5, respectively.

The observed dereddened colour indices $(V-J)_{\rm BB0}$, $(V-H)_{\rm BB0}$ and $(V-K)_{\rm BB0}$ given in Cols. 7, 9, and 11 were obtained from the observed 2MASS magnitudes (Cols. 3–5) using the the transformation equation given in Sect. 4, the reddening $E(B-V)$ given in Col. 6 and the following reddening relations obtained from Mathis (1999) for $A_v = 3.1\ E(B-V)$: $E(V-J) = 2.23E(B-V)$, $E(V-H) = 2.55E(B-V)$ and $E(V-K) = 2.76E(B-V)$.

We used Table 2 to derive $T_{\rm eff}$ from the dereddened colour indices. According to KCCBHV the abundances of the α-elements are enhanced by about 0.4 dex over the iron in these stars. Since the red colour-indices of these stars have a weak dependance on their metallicity (Fig. 2), we adopted the synthetic colours of Table 2 which were computed from non-α-enhanced models. We also adopted the metallicities listed in Col. 2 of Table 7; these are close to those obtained by KCCBHV.

In Fig. 6 we compare the $T_{\rm eff}$ derived from $(V-J)_{\rm BB0}$, $(V-H)_{\rm BB0}$ and $(V-K)_{\rm BB0}$ (using Table 2) with the $T_{\rm eff}$ from the literature taken from KCCBHV, Adelman & Philip (1990 1994 and 1996) and Gray et al. (1996). All these temperatures are summarized in Table 13 of KCCBHV. If T_J is the effective temperature derived from Table 2 for a BHB star of known $(V-J)_0$ and [M/H], then we define the difference ΔT_J as the $T_{\rm eff}$ for the BHB star given in the literature minus T_J. The differences ΔT_H and ΔT_K are defined similarly. These differences are shown plotted against T_{JHK} in Fig. 6, where T_{JHK} is the weighted mean of T_J, T_H and T_K[3]. In the case of the KCCBHV temperatures, these differences are shown by filled circles and the mean values of ΔT_J, ΔT_H and ΔT_K are are $+58 \pm 44$ K, $+110 \pm 45$ K and $+79 \pm 40$ K respectively. The corresponding rms deviations are 153 K, 157 K and 137 K. The error bars of ΔT_J, ΔT_H and ΔT_K in Fig. 6 take into account the quoted errors of $T_{\rm eff}$ given by KCCBHV and the quoted photometric errors of the 2MASS observations.

The open circles in Fig. 6 are similarly derived from the $T_{\rm eff}$ given by Adelman & Philip (1990, 1994, 1996) and Gray et al. (1996). In this case, the mean values of ΔT_J, ΔT_H and ΔT_K are -122 ± 95 K, -25 ± 119 K and -66 ± 92 K respectively and the corresponding rms deviations are 286 K, 356 K and 277 K. When $T_{\rm eff}$ from Castelli & Cacciari (2001, hereafter CC) are considered the mean values of ΔT_J, ΔT_H and ΔT_K are $+90 \pm 50$ K, $+158 \pm 50$ K and $+129 \pm 37$ K respectively and the corresponding rms deviations are 167 K, 165 K and 121 K.

Table 8 compares T_{JHK} with the $T_{\rm eff}$ from KCCBHV (which is based mostly on optical data) and those from CC (based on IUE ultraviolet energy distributions). The mean of the differences (Col. 5) between the KCCBHV $T_{\rm eff}$ and the weighted mean T_{JHK} is $+93 \pm 37$ K with an rms deviation of 127 K. The mean of the differences (Col. 6) between the CC $T_{\rm eff}$ and the weighted mean T_{JHK} is $+138 \pm 37$ K with an rms deviation of 122 K.

These BHB stars are at distances of several hundred parsecs and at various galactic latitudes, so the uncertainty in their $E(B-V)$ is at least 0.01 mag. This corresponds to an uncertainty of about 50 K at 7500 K and 180 K at 9000 K in the derived temperatures. Bearing this in mind, the agreement between previously derived values of $T_{\rm eff}$ for BHB stars and those derived from the 2MASS data seems satisfactory.

5.3. $T_{\rm eff}$ for blue metal-poor stars ($12 \le V \le 14$)

The blue metal-poor (BMP) stars were originally defined by Preston et al. (1994) as having $0.15 \le (B-V) \le 0.36$, $\log g \approx 4$ and [Fe/H] < -1. They are presumed to be the same as the "Class A" stars found by Kinman et al. (1994). Preston & Sneden (2000) have obtained echelle spectra of sixty-two of their BMP stars and shown that a high proportion are single-line binaries and likely to be blue stragglers; only 44 of their sample have [Fe/H] < -1. Preston & Sneden derived a preliminary effective temperature from a $T_{\rm eff}$ vs. $(B-V)$, [Fe/H] relation and then adjusted it so as to minimize the variation of the calculated abundance with respect to excitation potential. We picked five of their hottest stars for which 2MASS data are currently available; they are listed in Table 9 and also in Table 10 which gives their $\log g$, [Fe/H] and V from Preston & Sneden (2000). We used the procedure described in Sect. 5.2 to obtain T_J, T_H, T_K for each star from the 2MASS data using

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[3] The $T_{\rm eff}$ derived from each colour was given a weight that is proportional to the inverse square of its error (in K); these errors in $T_{\rm eff}$ were determined from the error in the colour using the $T_{\rm eff}$ vs. colour relation in Table 2.

Table 7. Temperatures T_J, T_H, and T_K for BHB stars derived from Table 2 and 2MASS colours.

HD/BD	V^a [M/H]	$J_{\rm 2M}$	$H_{\rm 2M}$	$K_{\rm 2M}$	$E(B-V)$	$(V-J)_{\rm BB0}$	T_J	$(V-H)_{\rm BB0}$	T_H	$(V-K)_{\rm BB0}$	T_K
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
2857	9.99	9.495	9.351	9.305	0.022	0.385	7665	0.567	7459	0.580	7467
	−1.5	±0.030	±0.025	±0.033			±92		±50		±70
14829	10.31	10.120	10.044	10.033	0.018	0.088	9001	0.200	8553	0.179	8673
	−2.0	±0.029	±0.026	±0.028			±190		±100		±113
60778	9.10	8.742	8.629	8.651	0.028	0.241	8179	0.387	7908	0.331	8103
	−1.5	±0.028	±0.043	±0.027			±110		±115		±80
74721	8.71	8.537	8.526	8.507	0.012	0.093	8945	0.140	8792	0.129	8876
	−1.5	±0.044	±0.034	±0.029			±275		±150		±138
86986	8.00	7.540	7.515	7.485	0.022	0.354	7777	0.413	7838	0.410	7884
	−1.5	±0.030	±0.028	±0.039			±95		±72		±100
87047	9.72	9.321	9.273	9.229	0.006	0.333	7855	0.421	7828	0.435	7831
	−2.0	±0.033	±0.056	±0.041			±109		±140		±102
109995	7.63	7.295	7.275	7.262	0.010	0.257	8134	0.314	8131	0.296	8222
	−1.5	±0.028	±0.022	±0.021			±107		±65		±62
130095	8.13	7.828	7.856	7.818	0.072	0.084	9002	0.072	9171	0.067	9210
	−1.5	±0.038	±0.070	±0.034			±250		±450		±195
167105	8.97	8.736	8.738	8.725	0.024	0.121	8777	0.151	8741	0.131	8869
	−1.5	±0.025	±0.029	±0.020			±140		±130		±96
202759	9.09	8.431	8.347	8.221	0.072	0.437	7522	0.543	7526	0.626	7390
	−2.0	±0.036	±0.063	±0.050			±100		±140		±101
252940	9.10	8.455	8.370	8.301	0.048	0.476	7401	0.590	7412	0.621	7384
	−1.5	±0.045	±0.031	±0.046			±122		±65		±93
+25 2602	10.12	9.826	9.855	9.829	0.008	0.221	8289	0.229	8428	0.225	8475
	−2.0	±0.032	±0.030	±0.031			±130		±110		±106
+42 2309	10.77	10.554	10.583	10.498	0.013	0.131	8715	0.139	8795	0.193	8594
	−1.5	±0.034	±0.036	±0.022			±190		±170		±90

[a] Data taken from KCCBHV.

Table 3 and thus derived T_{JHK}. The colours of these stars were de-reddened using the $E(B-V)$ of SFD (Table 9, Col. 6).

Table 10 compares the T_{JHK} temperature with those from Preston & Sneden (2000) and with those from Wilhelm et al. (1999) who also observed the same BMP stars using UBV photometry and low resolution spectra.

The mean difference between the Preston and Sneden $T_{\rm eff}$ and our T_{JHK} is −63 ± 119 K and the rms deviation of these differences is 237 K. The mean difference between the $T_{\rm eff}$ of Wilhelm et al. and our T_{JHK} is +137 ± 157 K; the rms deviation of these differences is 314 K. The mean difference between the Preston & Sneden $T_{\rm eff}$ and those of Wilhelm et al. is −200 ± 168 K and the rms deviation of these differences is 335 K.

The agreement between the T_{JHK} and these previous $T_{\rm eff}$ is satisfactory, if we take into account their binary nature and that they are probably all photometric variables. Their V-amplitudes (when known) are given in the footnotes to Table 10. Our use of non-simultaneous optical and infrared magnitudes will clearly produce errors in our temperatures and we have tried to take these and other *photometric* errors into account in calculating the errors for our T_{JHK}. We have not taken into account any other errors such as those in our estimated $E(B-V)$. The *random* errors of both our $T_{\rm eff}$ and those of Preston & Sneden are probably about 150 K, while for Wilhem et al. they are probably ~300 K. The systematic difference between our temperatures and those of Preston & Sneden is not significant.

5.4. $T_{\rm eff}$ for BMP and BHB stars observed by Wilhelm et al. (1999) in field BS 15621

Wilhelm et al. (1999) have given $T_{\rm eff}$ for large numbers of both BMP and BHB stars. We have chosen one of their fields (BS 15621) for which both $E(B-V)$ is low and 2MASS data are available. We evaluated T_J, T_H, T_K and the weighted T_{JHK} for the BMP and BHB stars in this field as described in Sect. 5.2; the results are shown in Table 11. Our adopted $\log g$ and metallicity [M/H] are given in Table 11, Col. 2. The adopted $E(B-V)$ (Table 11, Col. 6) are taken from SFD and do not differ greatly from those assumed by Wilhelm et al. (Table 12, Col. 5). We interpolated in Table 3 for the BMP stars and in Table 2 for the BHB stars. Wilhelm et al. give an uncertain [Fe/H] of 0.0 for the BHB star BS 15621-0039. We interpolated in Table 3 for this star, since a metallicity [M/H] = 0.0 is not available for BHB stars in Table 2. If we had used Table 2

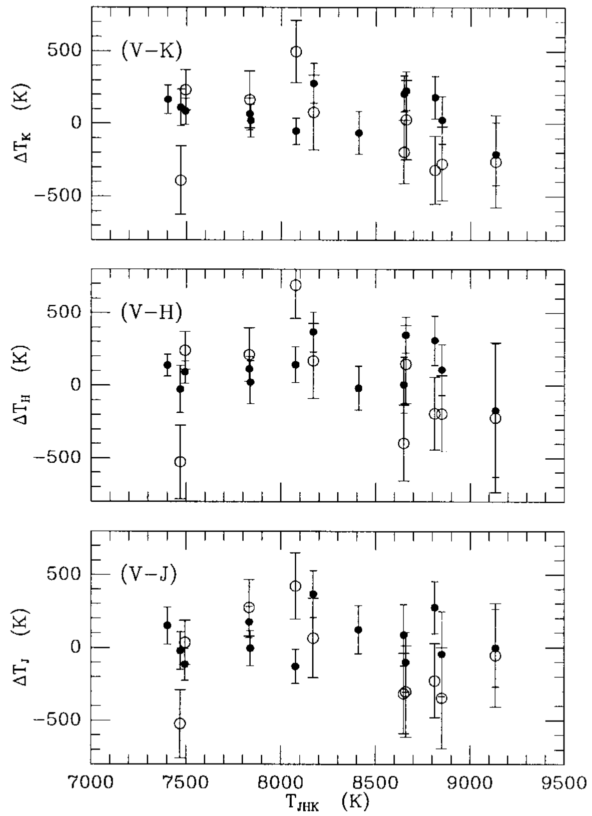

Fig. 6. Differences between the $T_{\rm eff}$ of BHB stars given in the literature and those derived from 2MASS data and the $T_{\rm eff}$-colours relations for BHB stars given in Table 2. For further details see the text in Sect 5.2.

and [M/H] = −1.0, the resulting temperature would have been 137 K higher. Our results are given in Table 11 (Cols. 8, 10, 12) and in Table 12 (Col. 6). The errors quoted for T_J, T_H and T_K are derived from the errors in the photometry while those quoted for the weighted T_{JHK} are derived from the errors of T_J, T_H and T_K.

Table 12 compares our T$_{JHK}$ with the $T_{\rm eff}$ from Wilhelm et al. (1999). The difference ΔT between the $T_{\rm eff}$ of Wilhelm et al. and our T_{JHK} is shown plotted against T_{JHK} in Fig. 7. The errors for ΔT in this plot assume an error of 300 K for the $T_{\rm eff}$ of Wilhelm et al.. The mean difference $< \Delta T >$ for the BMP stars is +249 ± 74 (K) which is comparable with the difference found for the other BMP star data of Wilhelm et al. (1999) and which we discussed in Sect. 5.3.

In the case of the BHB stars the mean difference $< \Delta T >$ is −504 ± 211 (K) and ΔT becomes increasingly negative as T_{JHK} increases. We note that in the case of the four BHB stars whose T_{JHK} exceeds 8000 K, the $\log g$ assumed by Wilhelm et al. (1999) are significantly less than those predicted by Eq. (9) for the T_{JHK}.

An inspection of the $T_{\rm eff}$ that Wilhem et al. derive for BHB stars show that they are cooler than might be expected; thus 9% are less than 7000 K, 50% between 7000 and 8000 K, 36% between 8000 and 9000 K and 5% greater than 9000 K. Also, the $(B-V)_0$ of a few of the coolest of these stars suggests that they may be RR Lyrae stars or even (e.g. CS 16027-0049 with $(B-V)_0 = 0.54$ and $T_{\rm eff} = 6200$ K) that they belong to to the red horizontal branch. We would expect the BHB stars to have $T_{\rm eff}$ that range from 7600 K corresponding to $(B-V)_0 \sim +0.20$ at the blue end of the instability strip to temperatures greater than 10 000 K. It therefore seems that systematic errors may be present in the $T_{\rm eff}$ of their whole BHB sample. A further investigation of this is published elsewhere (Kinman & Miller 2002) and shows that the trend shown for the BHB stars in Fig. 7 is present in a much larger sample and is related to the difference between the $\log g$ used by Wilhelm et al. (1999) and that predicted from T_{JHK} and Eq. (2).

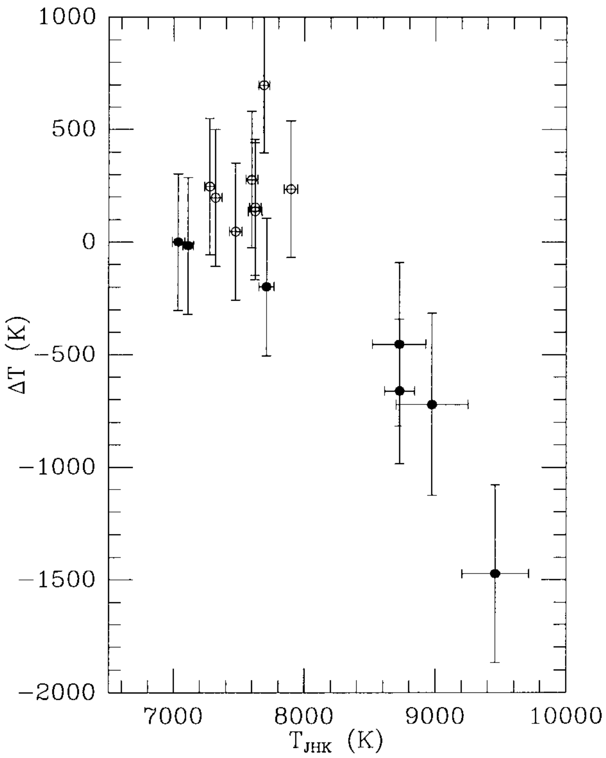

Fig. 7. Difference ΔT between Wilhelm et al. $T_{\rm eff}$ and T_{JHK} given in Table 13. Filled circles are BHB stars and open circles are BMP stars.

5.5. The BHB stars in the globular cluster M 13

Peterson et al. (1995) have determined $T_{\rm eff}$ for BHB stars in the globular cluster M 13. 2MASS data are available for these stars but the errors in the 2MASS $K_{\rm s}$ magnitudes are too large for reliable colours to be derived from them. We used the V magnitudes of Cudworth & Monet (1979) and $E(B-V)$ from SFD and assumed [Fe/H] = −1.5 to derive $T_{\rm eff}$ using Table 2. These $T_{\rm eff}$ are compared with those of Peterson et al. in Table 13. The errors for T_J and T_H were derived by assuming an error of 0.03 mag in V and the quoted errors for the 2MASS magnitudes. The difference between the $T_{\rm eff}$ of Peterson et al. and the mean of T_J and T_H is given as $\Delta T_{\rm eff}$ in Col. 9. Its mean value $< \Delta T_{\rm eff} > = +152 \pm 154$ and the rms deviation of these differences is 344 K. Considering the faintness of these stars and consequently the relatively large errors in the colours and derived temperatures, this agreement is satisfactory. As Peterson et al. point out, there is significant uncertainty in the V-magnitudes of these stars which could produce a systematic

Table 8. Comparison of $T_{\rm eff}$ from 2MASS colours for BHB stars with the parameters from KCCBHV[a] and CC[b].

HD/BD	T_{JHK}/log g/[M/H] This paper	$T_{\rm eff}$/log g/[Fe/H] KCCBHV[a]	$T_{\rm eff}$/log g/[M/H] CC[b]	$\Delta T_{\rm eff}$ from KCCBHV[a]	$\Delta T_{\rm eff}$ from CC[b]
2857	7495 ± 37/3.00/−1.5	7550/3.00/−1.73	7600/2.8/−1.75a	+55	+105
14829	8659 ± 70/3.20/−2.0	8900/3.20/−2.39	8900/3.1/−2.5a	+241	+241
60778	8076 ± 56/3.10/−1.5	8050/3.10/−1.49	8250/2.9/−1.50a	–26	+174
74721	8850 ± 95/3.30/−1.5	8900/3.30/−1.42	8800/3.2/−1.50a	+50	–50
86986	7833 ± 50/3.20/−1.5	7950/3.20/−1.81	8100/2.8/−1.75a	+117	+267
87047	7839 ± 66/3.10/−2.0	7850/3.10/−2.47	7900/2.8/−2.50a	+11	+61
109995	8172 ± 41/3.10/−1.5	8500/3.10−1.72	8500/3.0/−1.75a	+328	+328
130095	9135 ± 145/3.30/−1.5	9000/3.30/−1.87	9100/3.2/−1.75a	–135	–35
167105	8813 ± 68/3.30/−1.5	9050/3.30/−1.56	9000/3.1/−1.50a	+237	+187
202759	7471 ± 63/3.05/−2.0	7500/3.05/−2.16	7500/2.8/−2.00a	+29	+29
252940	7403 ± 49/2.95/−1.5	7550/2.95/−1.77	7650/2.7/−1.75a	+147	+247
+25 2602	8410 ± 66/3.20/−2.0	8410/3.17/−1.98	· · ·	0	· · ·
+42 2309	8649 ± 73/3.20/−1.5	8800/3.20/−1.63	8750/3.0/−1.75a	+151	+101

[a] Kinman et al. (2000).
[b] Castelli & Cacciari (2001).

Table 9. Temperatures T_J, T_H, and T_K for blue metal poor stars derived from Table 3 and 2MASS colours.

ID CS– (1)	log g [M/H] (2)	$J_{\rm 2M}$ (3)	$H_{\rm 2M}$ (4)	$K_{\rm 2M}$ (5)	$E(B-V)$ (6)	$(V-J)_{\rm BB0}$ (7)	T_J (8)	$(V-H)_{\rm BB0}$ (9)	T_H (10)	$(V-K)_{\rm BB0}$ (11)	T_K (12)
22871-040	4.2	12.147	12.041	12.001	0.101	0.289	8185	0.406	8047	0.396	8100
	−1.5	±0.026	±0.031	±0.031		±0.030	±105	±0.034	±90	±0.034	±90
29497-017	4.2	13.571	13.435	13.459	0.016	0.495	7512	0.668	7416	0.613	7558
	−1.0	±0.032	±0.037	±0.044		±0.035	±100	±0.040	±85	±0.046	±100
22966-043	3.7	13.011	12.852	12.825	0.017	0.451	7605	0.649	7425	0.644	7464
	−2.0	±0.032	±0.030	±0.037		±0.068	±190	±0.067	±140	±0.070	±150
29497-030	4.2	11.960	11.760	11.730	0.016	0.592	7291	0.832	7140	0.831	7163
	−2.0	±0.031	±0.031	±0.029		±0.034	±95	±0.034	±70	±0.033	±65
29499-057	4.5	13.356	13.315	13.226	0.023	0.384	7954	0.462	7993	0.517	7882
	−2.0	±0.033	±0.030	±0.041		±0.045	±139	±0.042	±106	±0.051	±118

Table 10. Comparison of $T_{\rm eff}$ for blue metal poor stars from various sources.

ID	Preston & Sneden[a]				Wilhelm et al.[b]			This paper
CS−	V	$T_{\rm eff}$ (K)	log g	[Fe/H]	$T_{\rm eff}$ (K)	log g	[Fe/H]	$T_{\rm JHK}$ (K)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
22871-040[c]	12.72 ± 0.015	7880	4.2	−1.66	7722	3.7	−2.1	8103 ± 54
29497-017[d]	14.16 ± 0.015	7500	4.2	−1.19	7768	4.9	−0.5	7486 ± 54
22966-043[e]	13.56 ± 0.060	7300	3.7	−1.96	7577	4.1	−1.4	7480 ± 90
29497-030	12.65 ± 0.015	7500	4.2	−2.16	7426	3.9	−2.5	7180 ± 43
29499-057[f]	13.85 ± 0.030	7700	4.2	−2.33	8386	4.3	−2.9	7946 ± 69

[a] Data taken from Preston & Sneden (2000).
[b] Data taken from Wilhelm et al. (1999).
[c] Light amplitude ΔV ~ 0.01 mag (Preston & Landolt 1999).
[d] Light amplitude ΔV < 0.01 mag (Preston & Landolt 1999).
[e] Light amplitude ΔV = 0.12 mag (Preston & Landolt 1999).
[f] Light amplitude ΔV = 0.04 mag (Preston & Landolt 1999).

Table 11. Temperatures T_J, T_H, T_K for a sample of BMP and BHB stars† in BS 15621 by using Tables 2, 3 and 2MASS colours.

BS 15621 V^a (1)	$\log g^a$ [M/H] (2)	J_{2M} (3)	H_{2M} (4)	K_{2M} (5)	$E(B-V)$ (6)	$(V-J)_{\mathrm{BB0}}$ (7)	T_J (8)	$(V-H)_{\mathrm{BB0}}$ (9)	T_H (10)	$(V-K)_{\mathrm{BB0}}$ (11)	T_K (12)
−0002	3.8	11.421	11.236	11.207	0.018	0.318	7981	0.542	7620	0.539	7657
11.84	−1.0	±0.034	±0.030	±0.029		±0.034	±110	±0.030	±67	±0.029	±64
−0012	3.8	11.765	11.654	11.628	0.017	0.408	7700.	0.557	7587	0.551	7631
12.27	−1.0	±0.034	±0.029	±0.034		±0.034	±100	±0.029	±65	±0.034	±75
−0022	4.3	12.211	12.087	12.047	0.022	0.560	7295	0.721	7267	0.728	7277
12.88	−0.5	±0.036	±0.033	±0.031		±0.036	±103	±0.033	±60	±0.031	±65
−0037	3.7	11.053	10.973	10.950	0.037	0.447	7569	0.557	7569	0.544	7630
11.64	−1.0	±0.035	±0.036	±0.029		±0.035	±100	±0.036	±80	±0.029	±65
−0040	4.2	13.327	13.159	13.193	0.050	0.313	8071	0.508	7769	0.435	7968
13.81	−1.0	±0.030	±0.031	±0.034		±0.030	±112	±0.031	±73	±0.034	±85
−0041	4.0	12.120	11.937	11.946	0.026	0.362	7835	0.581	7523	0.538	7649
12.60	−0.5	±0.034	±0.040	±0.041		±0.039	±122	±0.034	±75	±0.040	±90
−0048	3.0	11.640	11.531	11.531	0.020	0.457	7470	0.602	7387	0.570	7494
12.20	0.0	±0.036	±0.057	±0.028		±0.036	±110	±0.057	±123	±0.028	±60
−0072	3.8	12.221	12.085	12.046	0.030	0.482	7400	0.653	7277	0.657	7307
12.83	0.0	±0.031	±0.033	±0.047		±0.031	±87	±0.033	±70	±0.047	±100
− 0009	2.9	13.265	13.104	13.069	0.022	0.555	7177	0.754	7072	0.756	7106
13.93	−1.5	±0.032	±0.034	±0.037		±0.032	±83	±0.034	±65	±0.037	±70
−0015	3.0	11.841	11.715	11.693	0.020	0.325	7856	0.488	7640	0.478	7700
12.27	−2.0	±0.034	±0.035	±0.049		±0.034	±114	±0.035	±81	±0.049	±120
−0025	3.3	15.031	14.928	14.929	0.023	0.030	9479	0.167	8654	0.134	8839
15.17	−2.0	±0.047	±0.071	±0.110		±0.047	±460	±0.071	±390	±0.110	±710
−0031	2.9	13.800	13.561	13.517	0.030	0.560	7194	0.837	6951	0.846	6970
14.49	−2.0	±0.033	±0.040	±0.052		±0.033	±85	±0.040	±73	±0.052	±100
−0032	3.3	14.592	14.713	14.699	0.031	0.147	8603	0.052	9368	0.031	9493
14.86	−2.0	±0.040	±0.068	±0.106		±0.040	±220	±0.068	±624	±0.106	±950
−0039	3.3	13.369	13.360	13.256	0.049	0.064	8938	0.099	8824	0.165	8509
13.60	0.0	±0.031	±0.035	±0.038		±0.031	±220	±0.035	±200	±0.038	±180
−0043	3.4	14.251	14.234	14.214	0.039	0.016	9633	0.061	9306	0.044	9404
14.41	−2.0	±0.040	±0.050	±0.068		±0.040	±410	±0.050	±430	±0.068	±500

† The ID of BHB stars are shown in boldface.

[a] Adopted values for interpolation in Tables 2 and 3.

error in the resulting temperatures. There is no indication, however, of differences ΔT_{eff} as large as those found for the field BHB stars observed by Wilhelm et al.

6. Conclusion

The "reference" temperatures taken from Smalley & Dworetsky (1995) for six stars are compatible within the errors with T_{eff} derived from the T_{eff} vs. $(V-K)_0$ relation taken from the grids of synthetic colours *RIJKL* computed by Castelli and available at the Kurucz web-site. For four out of the six stars the differences between the reference T_{eff} and T_{eff} from $(V-K)_0$ is less than 100 K. The same is true for a sample of ISO standards which have temperatures that Di Benedetto (1998) derived with empirical methods. The accuracy is limited by the uncertainty in the correction for interstellar extinction (see Appendix A) and by the looseness of the definition of the Johnson photometric system for hot stars.

We give T_{eff} as a function of the colours $(V-J)_0$, $(V-H)_0$ and $(V-K)_0$ (Bessell-Brett system) for various metallicities and $\log g$ appropriate for (a) BHB stars and (b) main sequence stars in Tables 2 and 3 respectively. The data in Table 3 are appropriate for the BMP (or class A) stars that make up a substantial fraction of the blue stars in the galactic halo.

We give relations by which the colours derived from V and the 2MASS magnitudes may be converted to the Johnson system so that the transformed colours may be used (with Tables 2 or 3) to derive T_{eff}. Satisfactory agreement was found between these T_{eff} and those found for (a) Hyades dwarfs (b) local BHB stars (c) BMP stars and (d) BHB stars in the globular cluster M 13. *We therefore conclude that this use of the 2MASS data affords a practical way of getting* T_{eff} *for blue halo stars in the magnitude range* $5 \le V \le 15$. The accuracy is at least as good as that obtainable from $(B-V)_0$.

While the T_{eff} derived by Wilhelm et al. (1999) for their BMP stars are in reasonable agreement with ours, the T_{eff} which they derive for their (generally hotter) BHB stars are

Table 12. Comparison of $T_{\rm eff}$ from 2MASS colours for BMP and BHB stars in field BS 15621 with $T_{\rm eff}$ from Wilhelm et al. (1999).

ID[†]	Wilhelm et al.				2MASS
15621- (1)	$T_{\rm eff}$ (K) (2)	$\log g$ (3)	[Fe/H] (4)	$E(B-V)$ (5)	T_{JHK} (K) (6)
0002	8390	3.8	−1.2	0.01	7691 ± 43
0012	7778	3.8	−0.9	0.00	7624 ± 44
0022	7521	4.3	−0.6	0.01	7275 ± 41
0037	7875	3.7	−1.1	0.04	7598 ± 45
0040	8131	4.2	−0.9	0.04	7896 ± 50
0041	7759	4.0	−0.4	0.01	7622 ± 52
0048	7520	3.8	0.0	0.02	7473 ± 48
0072	7517	3.8	−0.1	0.01	7321 ± 48
0009	7093	2.9	−1.4	0.01	7110 ± 41
0015	7511	2.9	−2.2	0.00	7710 ± 58
0025	8254	2.9	−2.6:	0.01	8975 ± 274
0031	7034	3.0	−1.9:	0.01	7034 ± 48
0032	8271	2.9	−2.2:	0.01	8724 ± 203
0039	8066	2.6	0.0:	0.04	8728 ± 114
0043	7984	2.8	−3.0:	0.03	9458 ± 255

[†] The ID of BHB stars are shown in boldface.

Table 13. $T_{\rm eff}$ for BHB stars in M 13.

ID (1)	r[‡] (arcsec) (2)	V_0 (3)	$(B-V)_0$ (4)	$E(B-V)$ (5)	T_J (K) (6)	T_H (K) (7)	$T_{\rm eff}$ (Peterson et al.[†]) (K) (8)	$\Delta T_{\rm eff}$ (K) (9)
I-64	214	14.94	0.093	0.017	7720 ± 160	7800 ± 160	7970	+210
IV-83	225	15.02	0.114	0.016	8385 ± 250	8330 ± 310	8962	+604
II-68	233	14.93	0.031	0.019	8680 ± 340	8605 ± 385	8595	−48
J 52	395	15.03	0.084	0.016	8650 ± 275	8650 ± 420	8244	−406
J 11	398	14.94	0.054	0.016	7520 ± 150	7450 ± 135	7784	+299
SA 368	414	15.08	0.042	0.018	8515 ± 270	8150 ± 260	8586	+254

[‡] Radial distance from cluster centre.
[†] From Table 6 of Peterson et al. (1995).

significantly smaller than ours and the difference increases with increasing temperature. The distribution of the $T_{\rm eff}$ in their sample of BHB stars suggests that such differences are present in their whole sample of BHB stars. This is confirmed by Kinman & Miller (2002) who find that the differences between their $T_{\rm eff}$ and T_{JHK} are related to their choice of $\log g$. As a consequence, the [Fe/H] that Wilhelm et al. derive for their BHB stars are, on average, ~0.4 dex too metal-poor.

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Appendix A: The interstellar extinction for nearby stars

The distribution of interstellar material in the solar neighborhood is quite complex (Frisch 1994). Studies based on the colour excesses of early type stars (e.g. Lucke 1978) showed that there is a relatively clear region within 100 pc of the Sun.

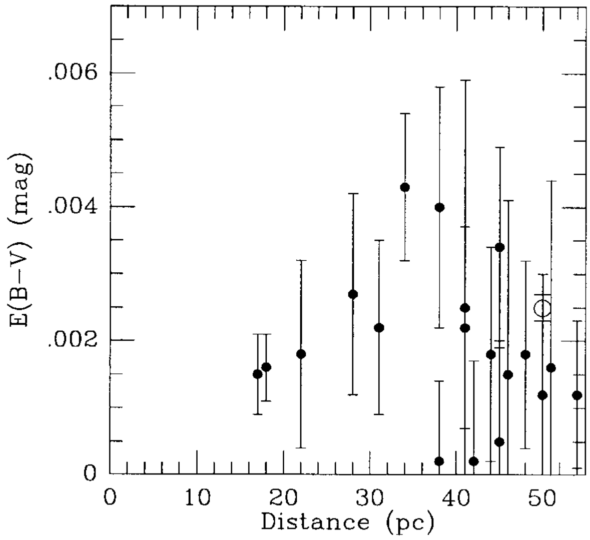

Fig. A.1. Colour excesses $E(B-V)$ derived from their polarizations for stars within 50 pc (filled circles) as a function of distance. The open circle is the mean value derived from the polarizations of 92 stars at distances between 45 and 55 pc.

The accuracy of the $E(B-V)$ determined from the intrinsic colours of hot stars is limited by the intrinsic spread in the colours of these stars (e.g., the dependence of colour on rotational velocity, Gray & Garrison 1987).

Interstellar dust can also be detected by the polarization that it produces. The precise polarization measurements of Tinbergen (1982) of 180 stars within 35 pc showed that *in general* the visual extinction (A_v) is 0.002 mag or less within this region. He did find relatively strong polarization (indicating $A_v \approx 0.01$ mag), however, in stars in a region out to 20 pc in the direction bounded by galactic coordinates $l = 350°$ to $20°$ and $b = -40°$ to $-5°$ and a few other isolated directions. This generally low extinction has been confirmed by Leroy (1993b) whose catalogue (Leroy 1993a) gives the polarizations of stars within about 50 pc. The 92 stars in this catalogue with distances between 45 and 55 pc[4] have a mean percentage polarization of $23 \pm 2 \times 10^{-5}$. Using Tinbergen's conversion factor, this corresponds to a $E(B-V)$ of 0.0025 ± 0.0002 mag.

In Sect. 3.3, we consider ten F dwarfs that lie within 52 pc. Polarizations are given for two of these stars (HD 3268 and HD 182807) in Leroy (1993a). For the remainder, the polarizations were assumed to be similar to stars at a comparable distance and as closely as possible the same part of the sky. These polarizations were converted to $E(B-V)$ and are shown plotted against distance in Fig. A.1. These $E(B-V)$ are comparable with the mean value at 50 pc (discussed above) which is shown by the open circle. We conclude that none of these F dwarfs are in regions of unusually high extinction and that it is reasonable to derive their extinctions (Col. 8 in Table 5) from their polarizations. These $E(B-V)$ are significantly less than those adopted by Di B98 (Col. 7, Table 5).

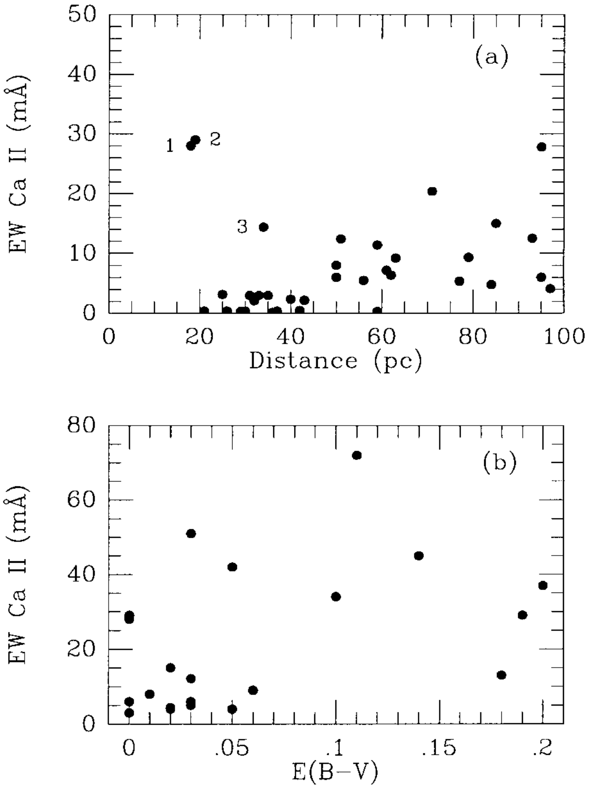

Fig. A.2. Equivalent widths of Ca II K-line (mÅ) vs. **a)** distance in parsecs and **b)** $E(B-V)$. The numbered stars in **a)** are (1) α Oph, (2) 2 And and (3) ι Oph. See text for reference to sources.

The interstellar Ca II K-line is also an indicator of interstellar material, but its equivalent width correlates only weakly with $E(B-V)$ as is shown in Fig. A.2b where the data is taken from Welty et al. (1996). Some of the scatter may well be caused from errors in the $E(B-V)$ which were calculated assuming intrinsic colors. The scale height of the Ca II K-line equivalent widths is of the order of 1 kpc (Beers 1990) which is significantly greater than that of the optical extinction and so a tight correlation is not expected. The plot of the Ca II K-line equivalent width against distance shown in Fig. A.2a (using data from Welty et al. 1996 and Vallerga et al. 1993) shows that the line only appears in strength for stars at distances greater than 50 kpc. The only exceptions to this are stars in Ophiuchus and 2 And for which Tinbergen found significant polarization; presumably these are behind isolated local clouds. Thus the evidence from the Ca II K-line also suggests that the region out to 50 pc is relatively clear.

Far UV lines such as those of Mg II are also observable in such nearby stars as Sirius and Procyon in which the Ca II K-line is not observed. Frisch (loc. cit.) uses this Mg II strength to show that the N(H I + H II) column densities in front of Sirius and Procyon are 3.0×10^{17} and 1.1×10^{18} cm^{-2} respectively. This assumes the same N(Mg II)/ N(H I + H II) ratio as for η UMa (42 pc) for which the hydrogen column density is known. If we assume that N(H I + H II)/$E(B-V)$= 4.9×10^{21} cm^{-2} mag^{-1} (Diplas & Savage 1994), then the $E(B-V)$ for Sirius and Procyon are 0.00006 and 0.00022

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[4] Excluding stars where the error in their percentage polarization exceeds 30×10^{-5} and five stars with intrinsic percentage polarizations that exceed 125×10^{-5}.

respectively. Frisch notes that data on the EUV spectrum of the white dwarf companion to Sirius give a hydrogen column density that is an order of magnitude greater than that derived above. Even so, the $E(B-V)$ of Sirius would be ≈0.001. The $E(B-V)$ of Sirius and Procyon that are derived from their polarization are 0.0018 ± 0.0013 and 0.0005 ± 0.0009 respectively which are consistent with the low extinctions derived from the Mg II line estimate. It has therefore seemed reasonable to use the $E(B-V)$ derived from their polarizations for the bright stars (Sirius, Procyon etc.) described in Table 2.

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