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IRFM temperature calibrations for the Vilnius, Geneva, $RI_{(C)}$ and DDO photometric systems*

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Abstract. We have used the infrared flux method (IRFM) temperatures of a large sample of late type dwarfs given by Alonso et al. (1996a) to calibrate empirically the relations $T_{\rm eff} = f$ (colour, [Fe/H]) for the Vilnius, Geneva, $RI_{(C)}$ (Cousins) and DDO photometric systems. The resulting temperature scale and intrinsic colour-colour diagrams for these systems are also obtained. From this scale, the solar colours are derived and compared with those of the solar twin 18 Sco. Since our work is based on the same $T_{\rm eff}$ and [Fe/H] values used by Alonso et al. (1996b) to calibrate other colours, we now have an homogeneous calibration for a large set of photometric systems.

Key words. stars: fundamental parameters – stars: atmospheres – stars: general

1. Introduction

Photometric calibrations of effective temperature can be regarded as fundamental tools to compare observations with theoretical models. They are needed to transform theoretical HR diagrams into colour-magnitude diagrams (e.g. VandenBerg 2000) as well as to perform the colour synthesis of stellar populations (e.g. Bruzual & Charlot 1993). Chemical abundance studies of stars, on the other hand, use the effective temperature ($T_{\rm eff}$) as a key parameter, so that reliable methods to calculate them are widely required (e.g. Meléndez & Barbuy 2002; Nissen et al. 2002; Ramírez & Cohen 2002).

Since the first published photometric calibration of $T_{\rm eff}$ (Popper 1959) many other papers devoted to the study of the colour relations between $T_{\rm eff}$, [Fe/H] and even $\log g$ have been written (e.g. Code et al. 1976; Bell & Gustafsson 1989; Bessell et al. 1998; Houdashelt et al. 2000). Most of them, unfortunately, considered only a relatively low number of stars, the problem being more critical at the metal–poor end. To make this problem even worse we shall mention that these different calibrations used different sets of $T_{\rm eff}$ and [Fe/H] values, thus yielding inhomogeneous empirical temperature scales.

Alonso et al. (1996b; hereafter AAM96b) solved the problem partially by performing calibrations for the $BVRI_{(J)}$, $JHK_{(TCS)}$ and $uvby$-β colours with a large sample of cool dwarfs covering the ranges $-3.0 < [\rm Fe/H] < +0.5$ and 3500 K $< T_{\rm eff} <$ 8000 K. The effective temperatures for the stars of their sample were computed by means of the infrared flux method (IRFM) whilst the corresponding metallicities were taken from the Cayrel de Strobel et al. (1992) catalog and partially from previously published photometric calibrations as described in Alonso et al. (1996a; hereafter AAM96a).

Even though it is possible to obtain the effective temperature of a star by applying the calibrations mentioned above, in some cases the only colour available is $(B-V)$, which is very sensitive to metallicity, or colours that belong to photometric systems that lack a homogeneous calibration. In this sense, the aim of this work is to extend the calibrations given in AAM96b to other colours for which a large amount of photometric data exist, like the Geneva system.

In this paper, we present the calibrations for the Vilnius, Geneva, $RI_{(C)}$ and DDO photometric systems obtained with the sample in AAM96a and compare them to previously published calibrations. In Sect. 2 the sample and adopted photometry are described. The calibrations and the comparison with other works are presented in Sect. 3 leaving the discussion of the resulting temperature scale to Sect. 4. Conclusions are summarized in Sect. 5.

2. The sample

Although the atmospheric parameters $T_{\rm eff}$ and [Fe/H] of the sample used in this work are well described in AAM96a, we shall mention some extra details on these.

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* Based on data from the GCPD.

Table 1. Reddening ratios for late type dwarfs.

Colour	$E(\text{colour})/E(B-V)$	Reference
$(V-S)$	0.70	Straižys (1995)
$(Y-Z)$	0.52	Straižys (1995)
$(Z-V)$	0.29	Straižys (1995)
(B_2-V_1)	0.75	Cramer (1999)
(B_2-G)	1.01	Cramer (1999)
$(V-R)_{(C)}$	0.56	Savage & Mathis (1979)
$(R-I)_{(C)}$	0.69	Savage & Mathis (1979)
$(V-I)_{(C)}$	1.25	Savage & Mathis (1979)
$C(42{-}45)$	0.23	McClure (1979)
$C(45{-}48)$	0.31	McClure (1979)

All the stars of the sample are supposed to be late type dwarfs and subdwarfs. Nevertheless, a revision of their $\log g$ values in the Cayrel de Strobel et al. (2001) catalog and their spectral types in SIMBAD database enabled us to identify some of these stars as giants and others as early type stars. We also found some variable and double stars.

Several stars, apart from those belonging to the groups listed above, were excluded from our calibrations due to anomalies in their colours: G245-032, G009-016, G043-003, G014-039, G141-019, HD 181007, HR 8832, G190-015, G217-008 (anomalous Vilnius colours); HR 66, G026-012 (anomalous Geneva colours); vA 560 (anomalous Cousins colours); HD 45282, HR 4623, G154-021 (anomalous DDO colours). Stars with kinematical assignment of metallicity were also excluded as in AAM96b.

The photometry adopted in this work was obtained from the General Catalogue of Photometric Data (GCPD, Mermilliod et al. 1997). For the sake of completeness we compiled all of the colours available for each star but, obviously, only a subset of these proved to be sensitive to the effective temperature, while being nearly independent of metallicity. Colours satisfying this condition are: $(V-S)$ and $(Y-V)$ in the Vilnius system; (B_2-V_1) and (B_2-G) in the Geneva system; $(V-R)_{(C)}$, $(R-I)_{(C)}$ and $(V-I)_{(C)}$ in the $RI_{(C)}$ system and $C(42{-}45)$ and $C(42{-}48)$ in the DDO system. The reddening corrections E(colour) were computed from the $E(B-V)$ values given in AAM96a and the reddening ratios listed in Table 1. Unreddened $(Y-V) = (Y-Z)+(Z-V)$ colours were obtained from intrinsic $(Y-Z)$ and $(Z-V)$ colours. A similar procedure was employed to obtain unreddened $C(42{-}48)$ colours.

3. The calibrations

Following the methodology of AAM96b, we have used the parameter $\theta_{\rm eff} = 5040/T_{\rm eff}$ instead of $T_{\rm eff}$ to perform the calibrations. In general, the multi-parametric relation $\theta_{\rm eff} = f$ (colour, [Fe/H]) is a second order polynomial. Nevertheless, in order to improve our results, we have only considered those coefficients that are larger than 3σ.

The residuals of the fits as a function of colour index and metallicity are often shown to check if systematic errors are introduced by the calibration formulae and also to illustrate their ranges of applicability in colour and metallicity.

3.1. Vilnius colours

The Vilnius photometric system was originally designed to facilitate a bi-dimensional spectral classification for stars of any spectral type, luminosity class and reddening; the selection of medium-band filters being done in order to observe faint stars.

For the colour index $(V-S)$, which seems to be the best $T_{\rm eff}$ indicator in the Vilnius system, we found, using data for 120 stars, the following fit:

$$\theta_{\rm eff} = 0.248 + 1.336(V-S) - 0.354(V-S)^2 \\ -0.029[\text{Fe/H}] - 0.008[\text{Fe/H}]^2, \quad (1)$$

for which the standard deviation $\sigma(\theta_{\rm eff}) = 0.020$. In terms of $T_{\rm eff}$ this amounts to 104 K.

The application ranges of Eq. (1) are:

$$0.40 < (V-S) < 1.20 \quad \text{for } -0.5 < [\text{Fe/H}] < +0.5,$$

$$0.40 < (V-S) < 0.70 \quad \text{for } -1.5 < [\text{Fe/H}] < -0.5,$$

$$0.45 < (V-S) < 0.70 \quad \text{for } -2.5 < [\text{Fe/H}] < -1.5.$$

The stars used to obtain Eq. (1) whose temperatures calculated from the calibration formula differ by more than 2σ from their IRFM temperatures are: G273-001, G021-006, G084-029 and HR 6136.

Figure 1 shows the sample and the residuals of this fit as a function of $(V-S)$ and [Fe/H]. There is a slight tendency towards lower temperatures for stars belonging to the [Fe/H] ~ -2 group but no other trends are apparent.

The $(Y-V)$ colours, temperatures and metallicities of 134 stars allowed us to obtain the calibration formula

$$\theta_{\rm eff} = 0.330 + 0.981(Y-V) - 0.033[\text{Fe/H}] \\ -0.009[\text{Fe/H}]^2, \quad (2)$$

with $\sigma(\theta_{\rm eff}) = 0.024$ (126 K). This formula is applicable in the ranges:

$$0.40 < (Y-V) < 1.05 \quad \text{for } -0.5 < [\text{Fe/H}] < +0.5,$$

$$0.40 < (Y-V) < 0.65 \quad \text{for } -1.5 < [\text{Fe/H}] < -0.5,$$

$$0.45 < (Y-V) < 0.70 \quad \text{for } -2.5 < [\text{Fe/H}] < -1.5.$$

The following stars depart more than 2σ from the mean fit: G119-052, G217-008, G029-023, G021-006, G019-027, G014-024 and HR 6752.

Three stars with [Fe/H] < -2.5 were included in the sample used to calibrate this photometric system but since they showed a systematic tendency towards higher temperatures, we decided not to consider Eqs. (1) and (2) valid for the metal-poor end.

The high values of the residuals of these fits for the cooler stars ($T_{\rm eff} \sim 4000$ K) as shown by Figs. 1 and 2 could be associated mainly to rough estimates of the metallicity of this group.

The gradients $\Delta T_{\rm eff}/\Delta(V-S)$ and $\Delta T_{\rm eff}/\Delta(Y-V)$ corresponding to our calibrations are both nearly independent of metallicity and vary from 70 K per 0.01 mag for $T_{\rm eff} \sim 6000$ K [$(V-S) \sim 0.51$, $(Y-V) \sim 0.52$] to 25 K per 0.01 mag for

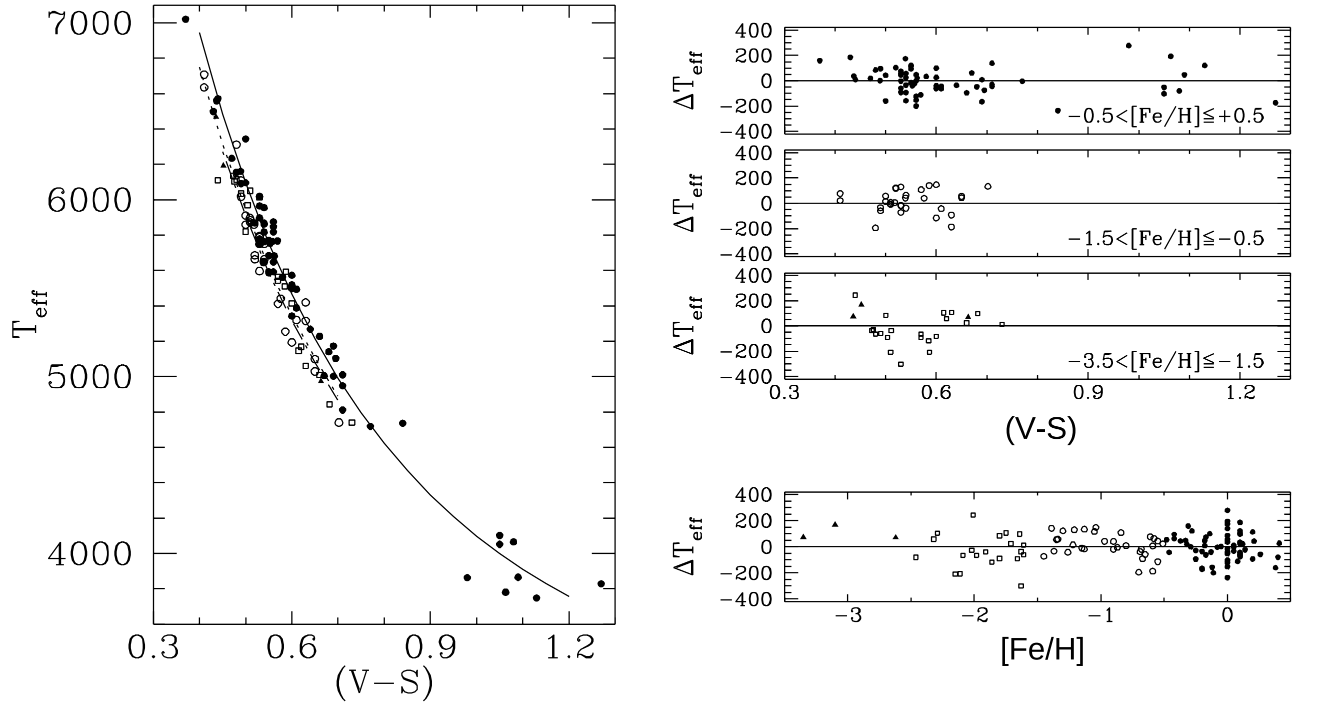

Fig. 1. Left: $T_{\rm eff}$ vs. $(V-S)$ observed for the metallicity ranges $-0.5 < [{\rm Fe/H}] \leq +0.5$ (filled circles), $-1.5 < [{\rm Fe/H}] \leq -0.5$ (open circles), $-2.5 < [{\rm Fe/H}] \leq -1.5$ (squares) and $-3.5 < [{\rm Fe/H}] \leq -2.5$ (triangles). The curves corresponding to our calibration for [Fe/H] = 0 (solid line), [Fe/H] = −1 (dotted line) and [Fe/H] = −2 (dashed line) are also shown. Right: residuals of the fit ($\Delta T_{\rm eff} = T_{\rm eff}^{\rm cal} - T_{\rm eff}^{\rm IRFM}$) as a function of $(V-S)$ (for the metallicity ranges indicated in the lower right section of the three upper panels) and [Fe/H] (bottom panel).

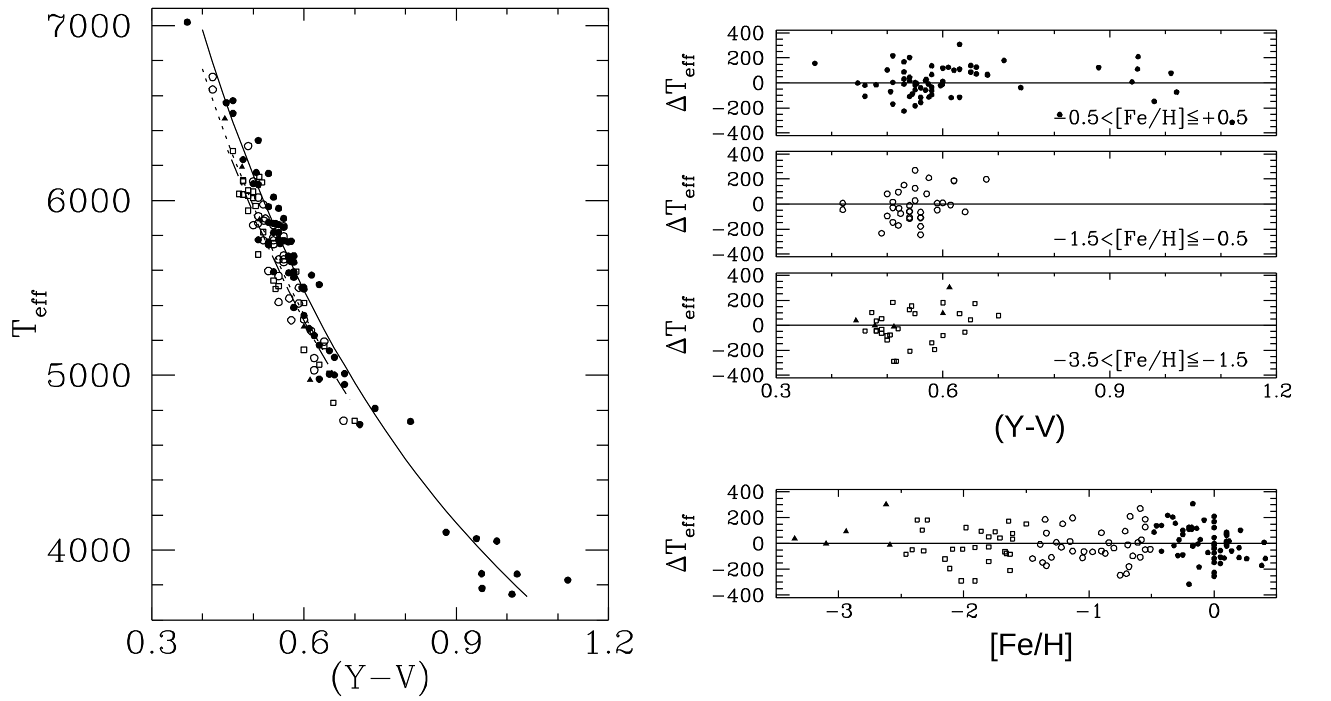

Fig. 2. The same as in Fig. 1 for $T_{\rm eff}$ versus $(Y-V)$.

$T_{\rm eff} \sim 4000$ K [$(V-S) \sim 1.05$, $(Y-V) \sim 0.95$]. As a consequence, an observational error of 0.01 mag in the photometry implies an error of about 1.2% for the hottest stars and 0.6% for the cool end when using formulae (1) and (2).

On the other hand, the variations $\Delta T_{\rm eff}/\Delta[{\rm Fe/H}]$ slightly depend on colour for both cases but the dependence of their values for a given $T_{\rm eff}$ with [Fe/H] is similar (see Table 2). For bluer colours (greater temperatures), this quantity tends to increase, especially for solar metallicities.

For both $(V-S)$ and $(Y-V)$ the gradient $\Delta T_{\rm eff}/\Delta[{\rm Fe/H}]$ approaches zero as $[{\rm Fe/H}] \longrightarrow -2$ which shows that our formulae are reliable for halo stars even if their metallicities have

Table 2. Mean variation $\Delta T_{\rm eff}/\Delta$[Fe/H] in K per 0.3 dex for $T_{\rm eff} \sim 5000$ K [$(V-S) \simeq (Y-V) \simeq 0.70$ for solar metallicity] as a function of [Fe/H].

Δ[Fe/H]	$\Delta T_{\rm eff}$ for $(V-S)$	$\Delta T_{\rm eff}$ for $(Y-V)$
$+0 \longrightarrow -0.3$	39	45
$-1 \longrightarrow -1.3$	16	18
$-2 \longrightarrow -2.3$	8	9

been roughly estimated. In addition, this effect is independent of the colour values.

3.2. Geneva colours

A large quantity of stars have been observed with this photometric system in just two observatories making the homogeneity of the data excellent. We have found that approximately 60% of the stars with *UBV* colours have also Geneva photometry. Therefore, it will be very useful to have calibrations for this system.

For the $\theta_{\rm eff}$-(B_2-V_1)-[Fe/H] relation we found the following fit:

$$\begin{aligned}\theta_{\rm eff} = &\ 0.629 + 0.644(B_2-V_1) + 0.065(B_2-V_1)^2 \\ &-0.033(B_2-V_1)[\mathrm{Fe/H}] - 0.029[\mathrm{Fe/H}] \\ &-0.010[\mathrm{Fe/H}]^2, \qquad (3)\end{aligned}$$

obtained with data for 258 stars. The corresponding standard deviation amounts to $\sigma(\theta_{\rm eff}) = 0.016$ (90 K).

From Fig. 3 it is clear that Eq. (3) is applicable only in the following intervals:

$$0.10 < (B_2-V_1) < 1.05 \quad \text{for } -0.5 < [\mathrm{Fe/H}] < +0.5,$$

$$0.10 < (B_2-V_1) < 0.60 \quad \text{for } -1.5 < [\mathrm{Fe/H}] < -0.5,$$

$$0.20 < (B_2-V_1) < 0.60 \quad \text{for } -2.5 < [\mathrm{Fe/H}] < -1.5,$$

$$0.20 < (B_2-V_1) < 0.50 \quad \text{for } -3.5 < [\mathrm{Fe/H}] < -2.5.$$

It is also evident from this figure that the formula is particularly reliable in the range $0.2 < (B_2-V_1) < 0.6$ where the star number density is high.

The stars that depart more than 2σ from the mean fit are: G237-072, HR 5901, HD 3567, G251-054, G022-024, BD +71 31, HD 111980, G126-062, G055-044, HD 101177, G076-068, G227-037 and HR 6844.

The residuals of this fit as shown by Fig. 3 suggest a slight tendency of Eq. (3) to overestimate the effective temperatures of the hottest solar-metallicity stars and those of the [Fe/H] ~ -3 group.

With the same stars used to obtain Eq. (3) we found for the (B_2-G) colour index the following formula:

$$\begin{aligned}\theta_{\rm eff} = &\ 0.838 + 0.501(B_2-G) - 0.030(B_2-G)^2 \\ &-0.044[\mathrm{Fe/H}] - 0.010[\mathrm{Fe/H}]^2, \qquad (4)\end{aligned}$$

applicable in the ranges:

$$-0.30 < (B_2-G) < 1.10 \quad \text{for } -0.5 < [\mathrm{Fe/H}] < +0.5,$$

$$-0.25 < (B_2-G) < 0.40 \quad \text{for } -1.5 < [\mathrm{Fe/H}] < -0.5,$$

$$-0.20 < (B_2-G) < 0.40 \quad \text{for } -2.5 < [\mathrm{Fe/H}] < -1.5,$$

$$-0.20 < (B_2-G) < 0.30 \quad \text{for } -3.5 < [\mathrm{Fe/H}] < -2.5.$$

The standard deviation $\sigma(\theta_{\rm eff}) = 0.014$ (86 K).

The following stars depart more than 2σ from the mean fit: G021-022, HD 3567, HD 111980, HR 7386, G076-068, G251-054, HD 181007, HD 101177, G227-037 and HR 6844.

The sample and residuals of this fit are both shown in Fig. 4. Here we find that Eq. (4) gives higher temperatures (by ~100 K) for solar-metallicity stars with $T_{\rm eff} > 6400$ K.

There is only a slight dependence on [Fe/H] for the $\Delta T_{\rm eff}/\Delta(B_2-G)$ values, which vary from 50 K per 0.01 mag at $(B_2-G) \sim -0.2$ to 15 K per 0.01 mag at $(B_2-G) \sim 0.8$. In contrast with this behavior, the gradient $\Delta T_{\rm eff}/\Delta$[Fe/H] is higher for the hottest stars (it could be as high as 130 K per 0.3 dex at $(B_2-G) \sim -0.2$ for solar metallicities) and lower for the coolest ones (it is only about 50 K per 0.3 dex for $(B_2-G) \sim 0.8$ and [Fe/H] ~ 0). Almost for any value of (B_2-G), the gradient $\Delta T_{\rm eff}/\Delta$[Fe/H] approaches zero as [Fe/H] $\longrightarrow -2$.

Following Straižys (1995, p. 372) we have also performed a calibration for the parameter $t \equiv (B_2-G)-0.39(B_1-B_2)$, which is almost independent of [Fe/H] for F, G and early K stars. Data for 245 stars belonging to this last group allowed us to obtain the following fit:

$$\begin{aligned}\theta_{\rm eff} = &\ 0.768 + 0.578t + 0.426t^2 - 0.020[\mathrm{Fe/H}] \\ &-0.007[\mathrm{Fe/H}]^2, \qquad (5)\end{aligned}$$

with $\sigma(\theta_{\rm eff}) = 0.012$ (75 K). This equation is restricted to the ranges:

$$-0.10 < t < 0.45 \quad \text{for } -0.5 < [\mathrm{Fe/H}] < +0.5,$$

$$-0.05 < t < 0.40 \quad \text{for } -1.5 < [\mathrm{Fe/H}] < -0.5,$$

$$+0.00 < t < 0.45 \quad \text{for } -2.5 < [\mathrm{Fe/H}] < -1.5,$$

$$+0.00 < t < 0.30 \quad \text{for } -3.5 < [\mathrm{Fe/H}] < -2.5.$$

The following stars deviate more than 2σ from the mean fit: G014-024, G021-022, G076-068, G048-039, HR 159, G227-037, G126-062, HD 3567, HD 111980 and HD 101177.

Unlike formulae (3) and (4), the present calibration does not produce systematic effects on any metallicity or colour intervals as shown in Fig. 5. From this figure it is also clear that the range $0 < t < 0.4$ provides good estimates of $T_{\rm eff}$ almost for any [Fe/H] value.

The calibration formula (5) introduces a shift of about 50 K for an error of 0.01 mag in t if $-0.1 < t < 0.2$ for any value of the metallicity. This effect decreases monotonically as cooler stars are considered. On the other hand, the gradient $\Delta T_{\rm eff}/\Delta t$ vanishes for [Fe/H] ~ -1.5 independently of the t value and increases its absolute value up to 80 K per 0.01 mag for the hottest stars going towards both solar and very low metallicities.

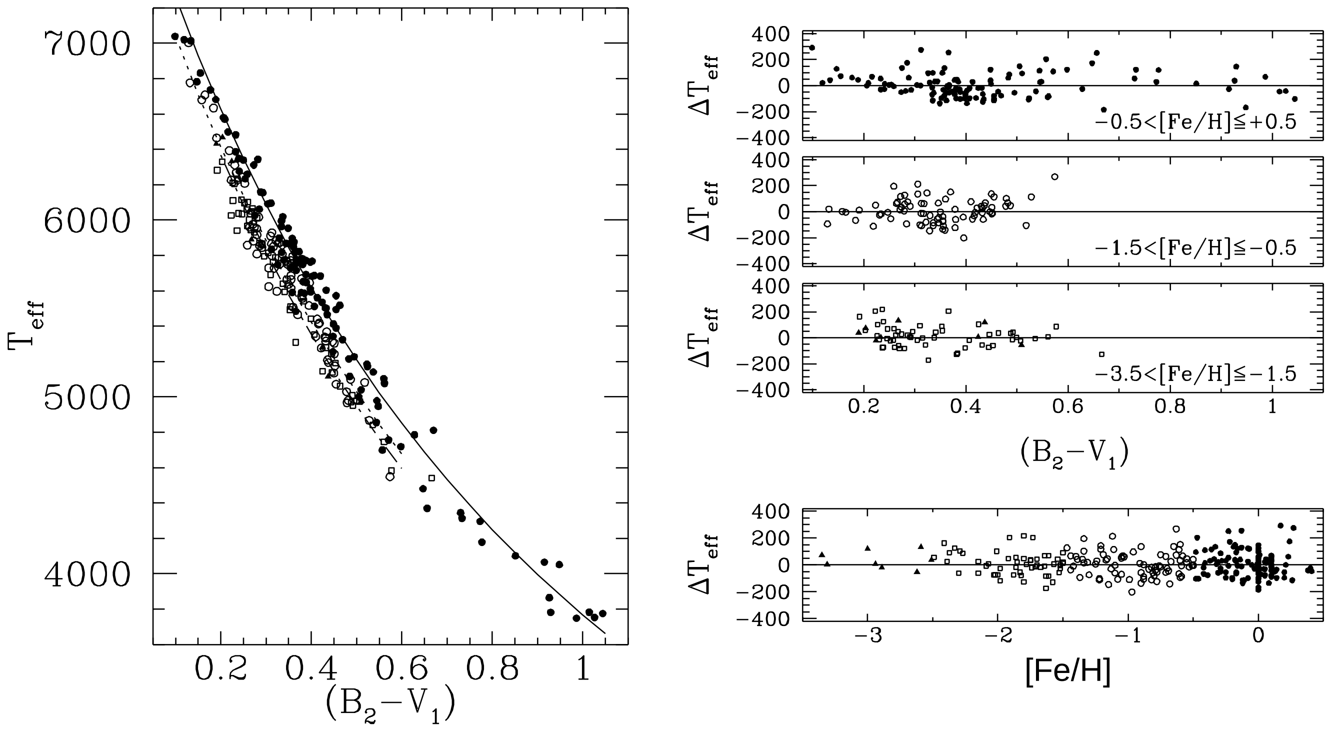

Fig. 3. The same as in Fig. 1 for $T_{\rm eff}$ versus $(B_2 - V_1)$.

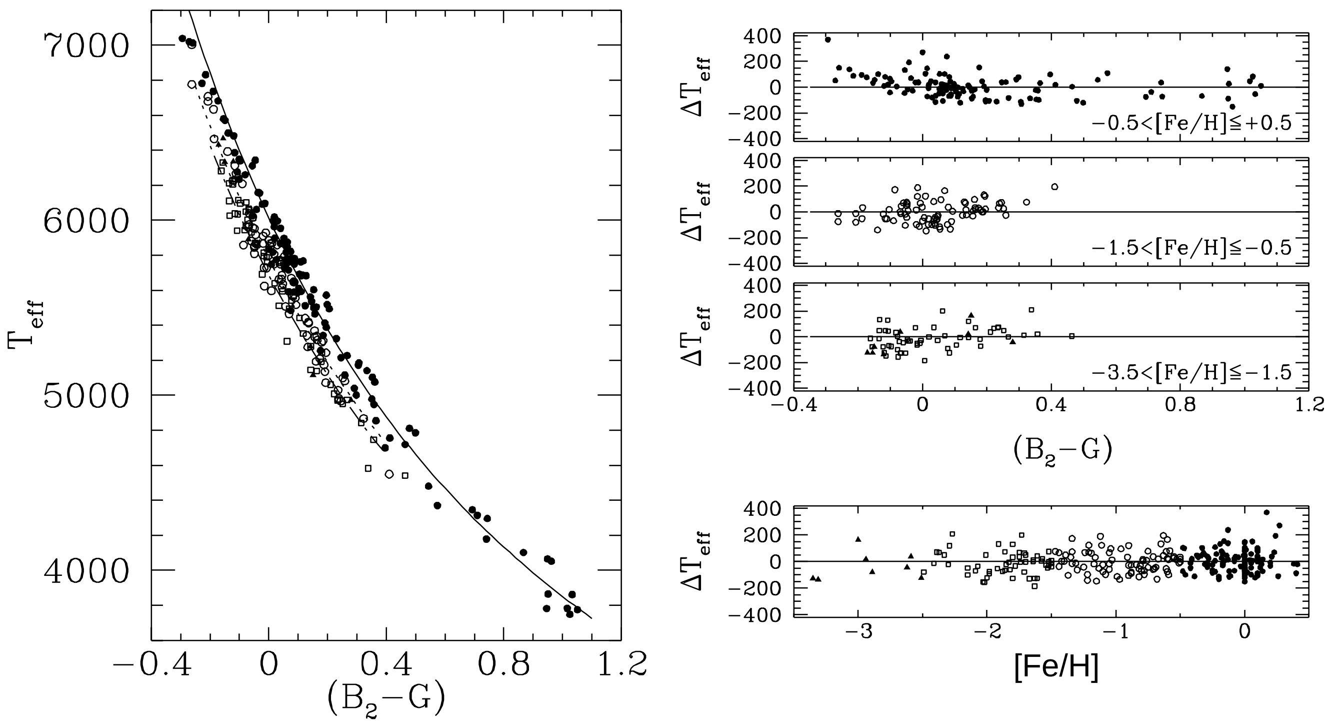

Fig. 4. The same as in Fig. 1 for $T_{\rm eff}$ versus $(B_2 - G)$.

3.3. Cousins colours

Since spectra of late type stars are dominated by emission at long wavelengths, it is relatively easy to observe them with infrared filters. In addition, infrared colours are good temperature indicators because there are only slight blanketing effects in this region of the spectrum.

For the $(V - R)_{\rm (C)}$-$\theta_{\rm eff}$ – [Fe/H] relation we found:

$$\theta_{\rm eff} = 0.516 + 1.085(V-R)_{\rm (C)} - 0.203(V-R)^2_{\rm (C)} -0.120(V-R)_{\rm (C)}[{\rm Fe/H}] + 0.025[{\rm Fe/H}], \quad (6)$$

using data for 97 stars. The standard deviation $\sigma(\theta_{\rm eff}) = 0.016$, which is equivalent to 91 K.

Equation (6) is applicable in the ranges

$0.20 < (V - R)_{(C)} < 0.90$ for $-0.5 < [Fe/H] < +0.5$,

$0.20 < (V - R)_{(C)} < 0.50$ for $-1.5 < [Fe/H] < -0.5$,

$0.25 < (V - R)_{(C)} < 0.45$ for $-2.5 < [Fe/H] < -1.5$;

which are the colour index and metallicity intervals covered by the sample, as shown in Fig. 6. Note that we have not considered the $-3.5 < [Fe/H] \leq -2.5$ interval because the only three stars with $[Fe/H] < -2.5$ actually have $[Fe/H] \sim -2.6$.

The stars whose IRFM T_{eff} depart more than 2σ from the mean fit are: G180-058, G021-022, HD 157089, HR 159 and G251-054.

Errors in the metallicity estimative are not so important when using Eq. (6) if we are dealing with F stars since $\Delta T_{eff}/\Delta[Fe/H] < 20$ K per 0.3 dex. The gradient itself is independent of [Fe/H] for any value of the colour index and reaches a maximum of 50 K per 0.3 dex for K dwarfs.

On the other hand, observational errors on $(V - R)_{(C)}$ do affect the temperature estimate for F stars since the variations $\Delta T_{eff}/\Delta(V - R)_{(C)}$ can be as high as 90 K per 0.01 mag for $(V - R)_{(C)} \sim 0.22$. For the coolest stars this effect can be reduced to 30 K per 0.01 mag. The metallicity dependence of this quantity is only slight.

We have 104 stars with measured $(R - I)_{(C)}$ colours which satisfy the following formula:

$$\theta_{eff} = 0.422 + 1.557(R - I)_{(C)} - 0.563(R - I)^2_{(C)} - 0.140(R - I)_{(C)}[Fe/H] + 0.055[Fe/H], \quad (7)$$

and cover the application ranges:

$0.20 < (R - I)_{(C)} < 0.80$ for $-0.5 < [Fe/H] < +0.5$,

$0.30 < (R - I)_{(C)} < 0.45$ for $-1.5 < [Fe/H] < -0.5$,

$0.30 < (R - I)_{(C)} < 0.50$ for $-2.5 < [Fe/H] < -1.5$.

The corresponding standard deviation $\sigma(\theta_{eff}) = 0.013$ which amounts to 80 K.

The stars whose temperatures obtained from this fit differ by more than 2σ with their IRFM temperatures are: G089-014, HD 193901, HD 74000, G026-012, HR 159, G105-050, G088-027 and HD 3567.

The relation between T_{eff} and $(R - I)_{(C)}$ is not affected by the star metallicity in the range $0.35 < (R - I)_{(C)} < 0.45$ where the variation $\Delta T_{eff}/\Delta[Fe/H] \sim 10$ K per 0.3 dex, which means an error lower than 0.25% in the estimated T_{eff}. For $(R - I)_{(C)} < 0.35$ and $(R - I)_{(C)} > 0.45$ this gradient increases to 30 K per 0.3 dex.

Except for the coolest stars, the gradient $\Delta T_{eff}/\Delta(R - I)_{(C)}$ depends strongly on [Fe/H], increasing its absolute value from 90 K per 0.01 mag for $[Fe/H] \sim 0$ to 120 K per 0.01 mag for $[Fe/H] \sim -2$ at $(R - I)_{(C)} \sim 0.3$ for instance. For $(R - I)_{(C)} \sim 0.4$ an observational error of 0.01 mag would produce an error of 70 K when using Eq. (7) which means 1.3%, whilst for $(R - I)_{(C)} \sim 0.7$ this reduces to 30 K (0.75%).

The best temperature indicator for the Cousins system is the $(V - I)_{(C)}$ colour. Data for 97 stars satisfy the relation:

$$\theta_{eff} = 0.483 + 0.617(V - I)_{(C)} - 0.072(V - I)^2_{(C)} - 0.066(V - I)_{(C)}[Fe/H] + 0.023[Fe/H] - 0.008[Fe/H]^2, \quad (8)$$

in the ranges:

$0.40 < (V - I)_{(C)} < 1.70$ for $-0.5 < [Fe/H] < +0.5$,

$0.40 < (V - I)_{(C)} < 1.00$ for $-1.5 < [Fe/H] < -0.5$,

$0.55 < (V - I)_{(C)} < 0.90$ for $-2.5 < [Fe/H] < -1.5$.

The standard deviation corresponding to Eq. (8) is $\sigma(\theta_{eff}) = 0.011$, which means the lowest dispersion obtained in this work (64 K).

The following stars depart more than 2σ from the mean fit: G021-022, HD 3567, G105-050, HR 159, G026-012.

The gradient $\Delta T_{eff}/\Delta[Fe/H]$ depends strongly on colour and metallicity. Just to give an example, for $(V - I)_{(C)} \sim 0.7$, where the star number density is high (Fig. 8), $\Delta T_{eff}/\Delta[Fe/H]$ vanishes for $[Fe/H] \sim -1.5$ but can be as high as 60 K per 0.3 dex for solar metallicities. If we go to $(V - I)_{(C)} \sim 0.4$ the gradient now vanishes for solar metallicities and is higher than 100 K per 0.3 dex for $[Fe/H] \sim -2$.

The ratio $\Delta T_{eff}/\Delta(V - I)_{(C)}$ monotonically decreases in absolute value from 60 K per 0.01 mag to 15 K per 0.01 mag depending on the mean value of $(V - I)_{(C)}$. For $(V - I)_{(C)} \sim 0.7$ this amounts to 35 K per 0.01 mag.

We should mention that from Figs. 6–8 there is a slight tendency towards lower temperatures if they are obtained from the corresponding calibration formulae for the hottest solar-metallicity stars. Despite this fact, we have found that our calibrations for the Cousins colours do not introduce considerable systematic errors.

3.4. DDO colours

Although data in this system were available for only 89 stars and even though DDO colours are very sensitive to the star metallicity, the need for an empirical DDO temperature scale encouraged us to perform the following calibrations.

For the $C(42–45)$ colour we found the following fit:

$$\theta_{eff} = 0.492 + 0.635\,[C(42–45)] - 0.067\,[C(42–45)]^2 - 0.073[Fe/H] - 0.018[Fe/H]^2, \quad (9)$$

applicable in the ranges:

$0.40 < C(42–45) < 1.50$ for $-0.5 < [Fe/H] < +0.5$,

$0.40 < C(42–45) < 0.74$ for $-1.5 < [Fe/H] < -0.5$,

$0.42 < C(42–45) < 0.76$ for $-2.5 < [Fe/H] < -1.5$.

Its standard deviation $\sigma(\theta_{eff}) = 0.018$ (103 K).

Stars whose IRFM temperatures depart more than 2σ from the fit are: HR 5447, HR 5568, HD 111980 and HD 140283.

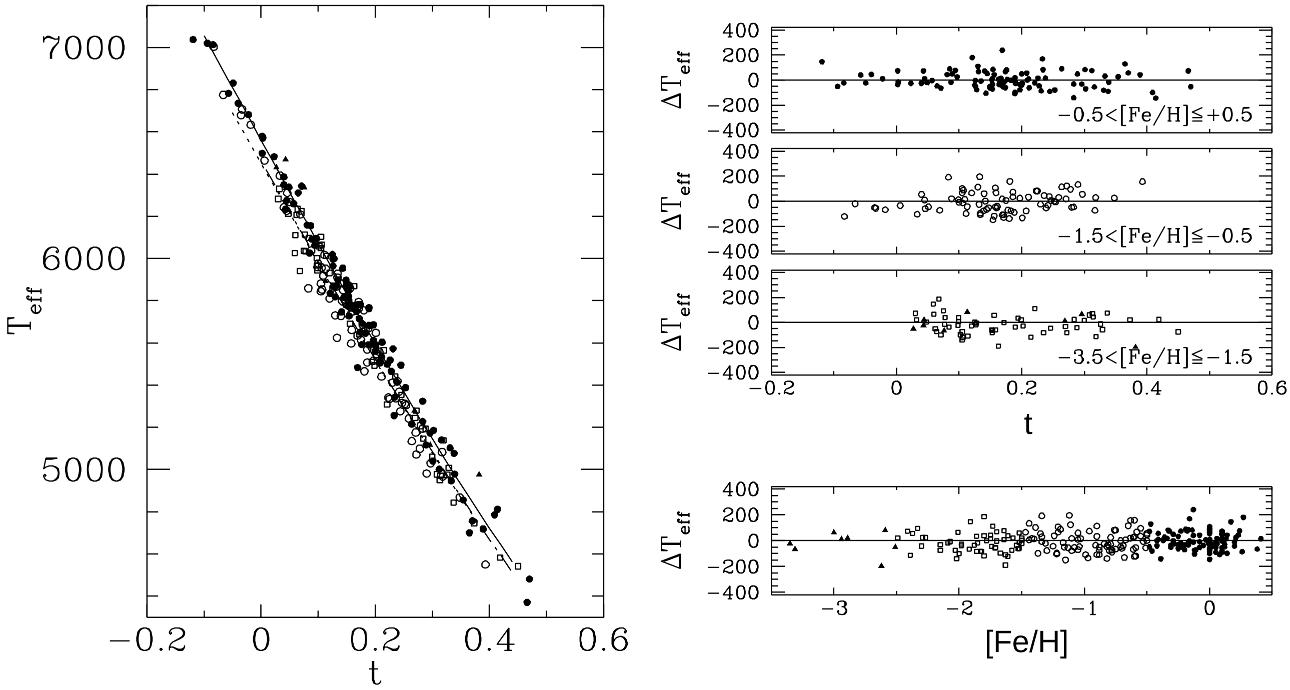

Fig. 5. The same as in Fig. 1 for $T_{\rm eff}$ versus t.

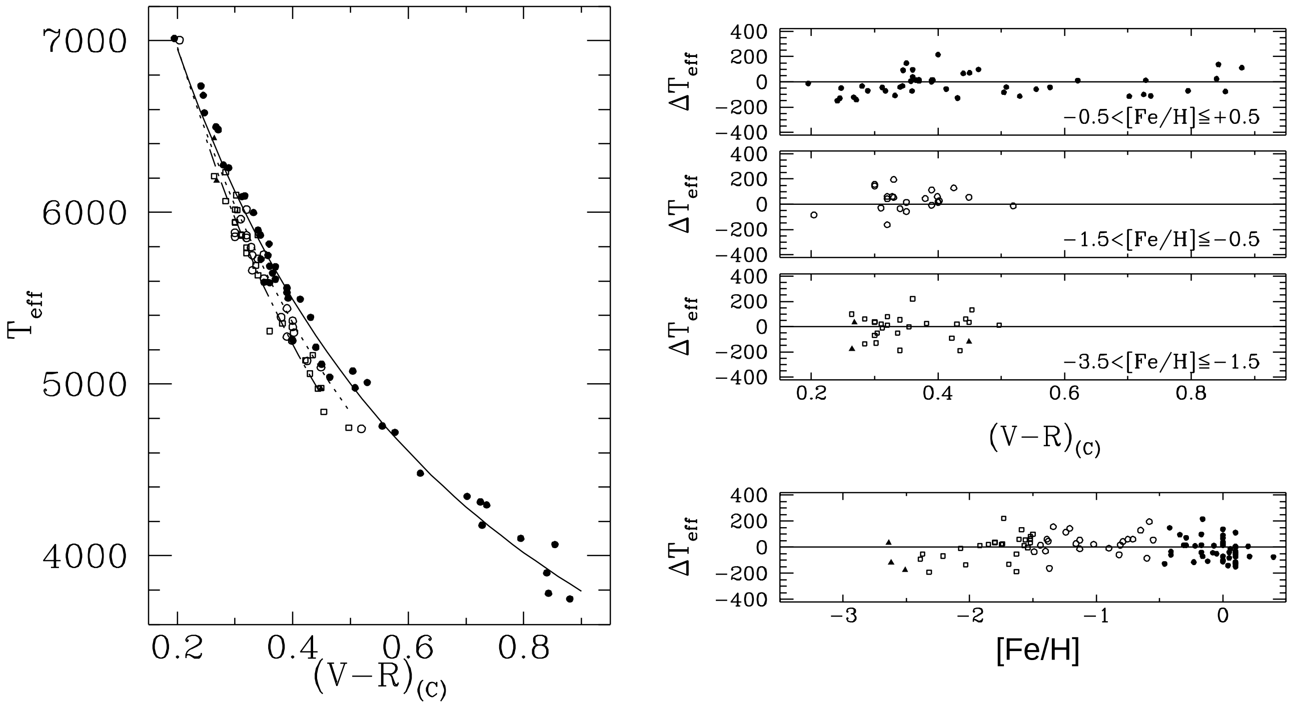

Fig. 6. The same as in Fig. 1 for $T_{\rm eff}$ versus $(V-R)_{\rm (C)}$.

Finally, for the $C(42{-}48)$ colour, we obtained:

$$\theta_{\rm eff} = 0.189 + 0.413\,[C(42{-}48)] - 0.060[{\rm Fe/H}] - 0.015[{\rm Fe/H}]^2, \quad (10)$$

whose application ranges are:

$1.30 < C(42{-}48) < 2.70$ for $-0.5 < [{\rm Fe/H}] < +0.5$,

$1.32 < C(42{-}48) < 1.82$ for $-1.5 < [{\rm Fe/H}] < -0.5$,

$1.32 < C(42{-}48) < 1.82$ for $-2.5 < [{\rm Fe/H}] < -1.5$.

The standard deviation of Eq. (10) amounts to $\sigma(\theta_{\rm eff}) = 0.015$ (83 K) and only three stars depart more than 2σ from the fit: HR 5568, HD 111980 and HD 140283.

The general behavior of the gradients $\Delta T_{\rm eff}/\Delta C(42{-}45)$ and $\Delta T_{\rm eff}/\Delta C(42{-}48)$ is very similar. Their absolute values decrease for lower values of [Fe/H] and $T_{\rm eff}$, and they both reach a minimum between 10 and 20 K per 0.01 mag for

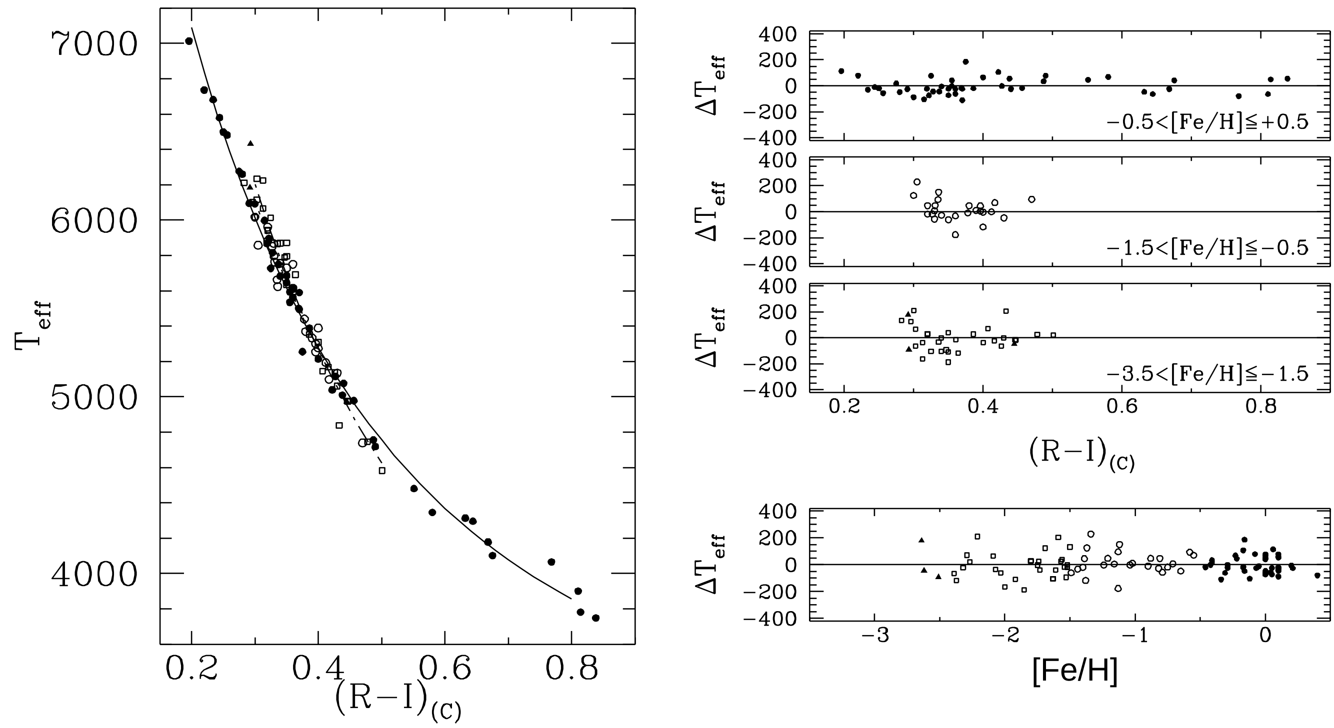

Fig. 7. The same as in Fig. 1 for $T_{\rm eff}$ versus $(R-I)_{\rm (C)}$.

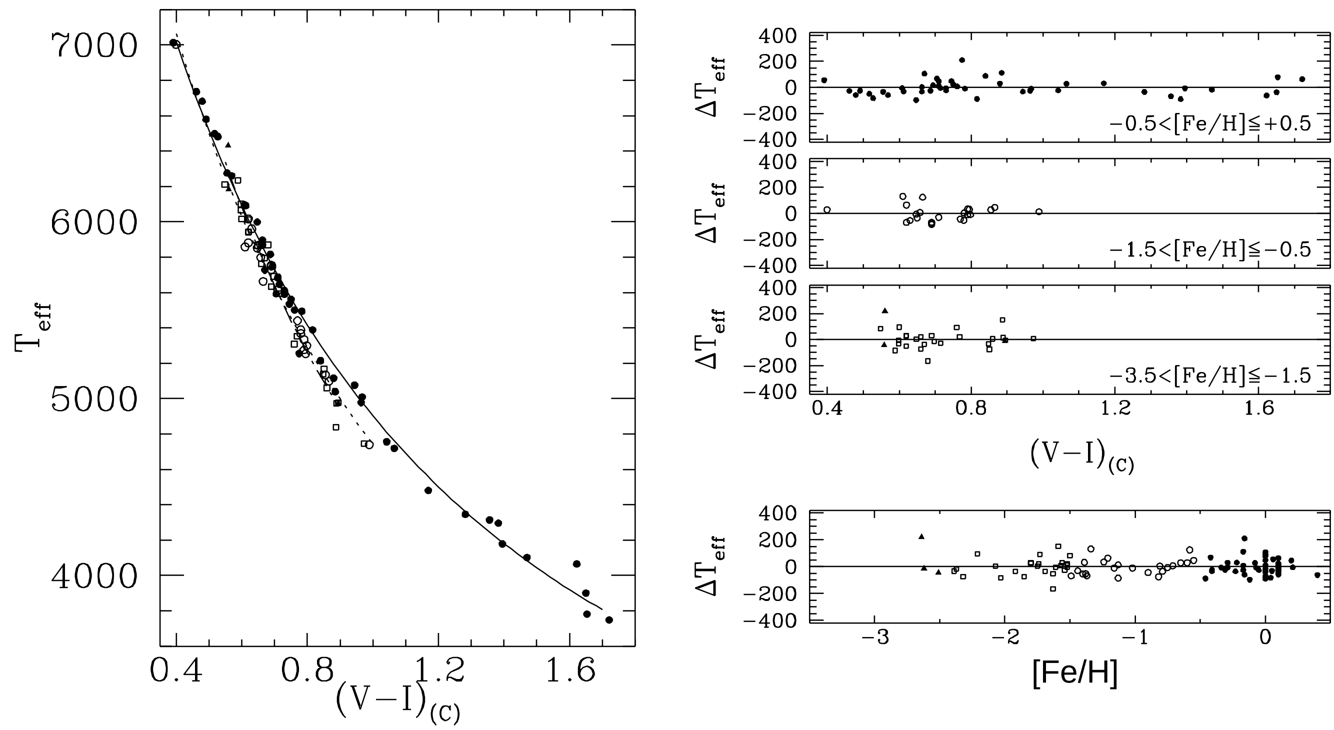

Fig. 8. The same as in Fig. 1 for $T_{\rm eff}$ versus $(V-I)_{\rm (C)}$.

late K stars ($C(42{-}45) > 1.2$, $C(42{-}48) > 2.2$). For the hottest stars these quantities depend slightly on metallicity, and are about 40 K and 30 K per 0.01 mag for $C(42{-}45)$ and $C(42{-}48)$, respectively.

The high values found for the mean variations $\Delta T_{\rm eff}/\Delta[{\rm Fe/H}]$ corresponding to Eqs. (9) and (10) confirm the strong metallicity dependence of DDO colours, which is also evident from the values of the coefficients for [Fe/H] and $[{\rm Fe/H}]^2$ in the calibration formulae. For $T_{\rm eff} \sim 6200$ K and solar metallicities, for example, $\Delta T_{\rm eff}/\Delta[{\rm Fe/H}] \sim 200$ K and 160 K per 0.3 dex for $C(42{-}45)$ and $C(42{-}48)$, respectively. For $[{\rm Fe/H}] \sim -1$ these variations reduce to

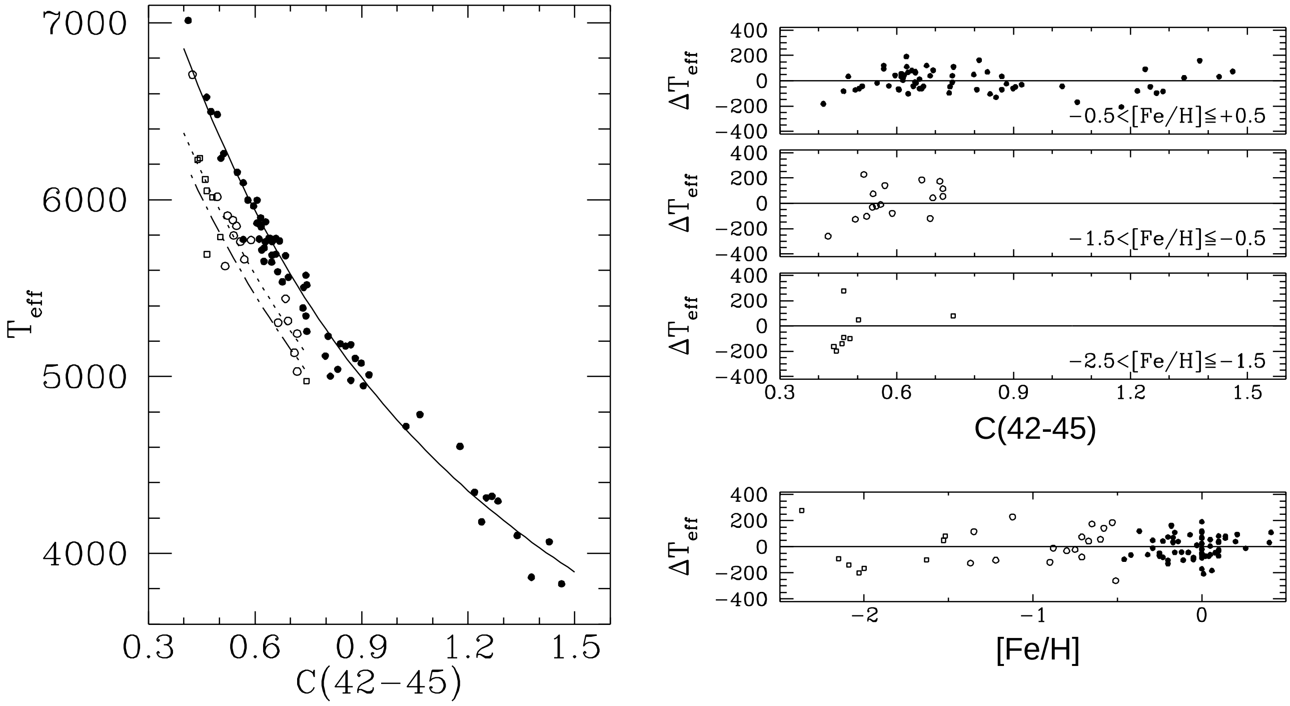

Fig. 9. The same as in Fig. 1 for $T_{\rm eff}$ versus $C(42{-}45)$.

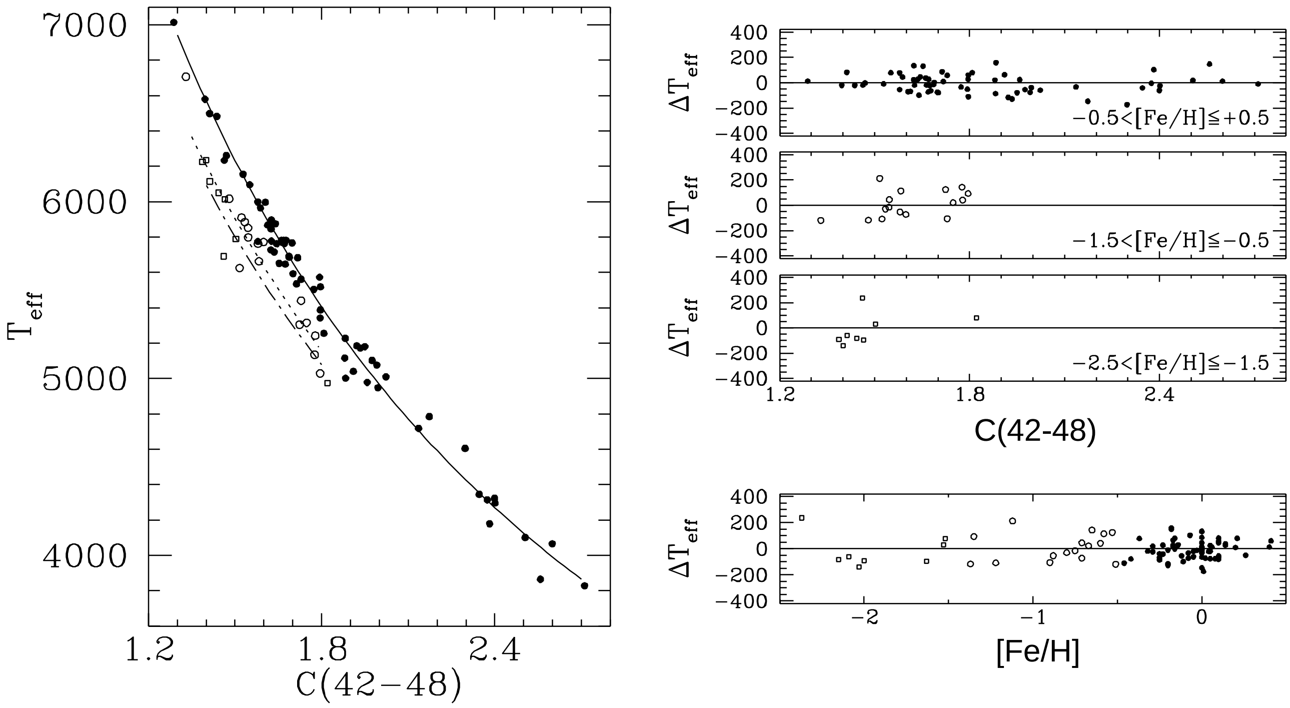

Fig. 10. The same as in Fig. 1 for $T_{\rm eff}$ versus $C(42{-}48)$.

aproximately 70 K. For lower temperatures $\Delta T_{\rm eff}/\Delta[{\rm Fe/H}]$ decreases monotonically so that for $T_{\rm eff} \sim 5300$ K and solar metallicity it is about 140 K and 100 K per 0.3 dex for $C(42{-}45)$ and $C(42{-}48)$, respectively.

3.5. Comparison with other calibrations

In Figs. 11 to 13 the present calibrations for [Fe/H] = 0 and [Fe/H] = −1 (solid lines) are compared to previously published theoretical and empirical calibrations as described below.

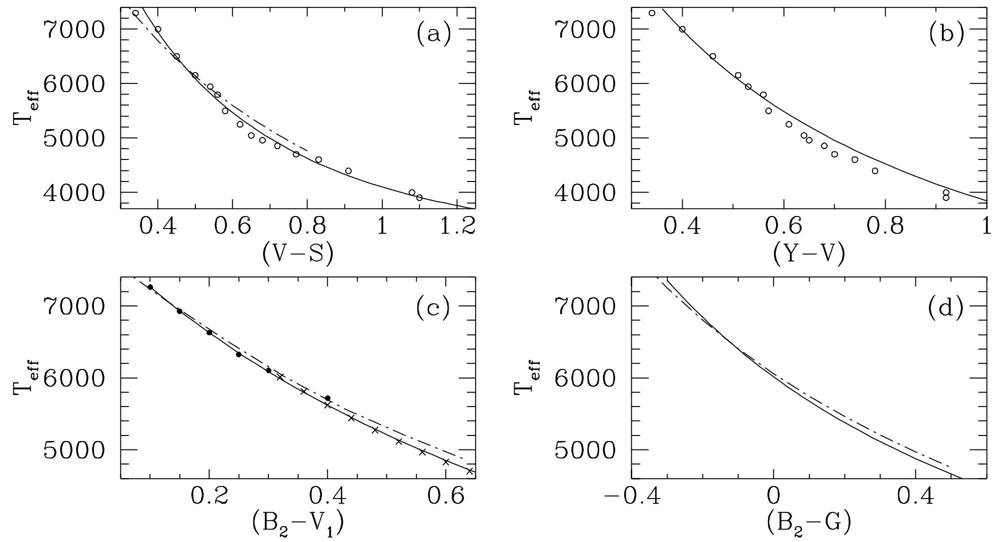

Fig. 11. a–b) Comparison of our calibrations (solid lines) with those of Hauck & Künzli (1996) (dashed line) and Straižys (1995, p. 438) (open circles) for [Fe/H] = 0; **c–d)** Comparison of Eqs. (3) and (4) for [Fe/H] = 0 (solid lines) to other calibrations: Kobi & North (1990) (filled circles), Hauck & Künzli (1996) (dashed line) and Blackwell & Lynas-Gray (1998) (crosses).

3.5.1. Vilnius system

The empirical work of Hauck & Künzli (1996; hereafter HK96) for the relation between $T_{\rm eff}$ and $(V-S)$ (shown in Fig. 11a as a dashed line) is based on effective temperatures obtained by several authors using direct and semi-direct methods (including the IRFM). They fitted a linear function of $(V-S)$ on $\theta_{\rm eff}$ with 66 stars, some of them out of the range covered in this work (namely, stars hotter than 7000 K). Since HK96 did not consider metallicity effects on their calibration formula, we have assumed [Fe/H] = 0 for the comparison.

For the hottest stars ($(V-S) \sim 0.40$) the difference in derived effective temperatures in our work and in HK96 is higher than 150 K, for the coolest ones ($(V-S) \sim 0.80$) it is about −140 K (these differences amount to 2.2% and 2.9% respectively) whilst it vanishes for $(V-S) \sim 0.50$ so that the slopes are quite different. This can be attributed to the calibration formulae used in each work; the observed curvatures in our fits, for example, are due mainly to the (colour)^2 term.

In Figs. 11a,b we also show the intrinsic colour indices determined for luminosity class V stars of various spectral types by averaging observed indices of unreddened and dereddened stars of the same MK spectral type (Straižys 1995, p. 438). The calibration of $T_{\rm eff}$ in terms of spectral type is also provided in Straižys (1995). The agreement is good in the range 5800 K $< T_{\rm eff} <$ 7000 K for both $(V-S)$ and $(Y-V)$ while at cooler temperatures the maximum difference in $(V-S)$ is about 150 K (2.9%). For the calibration in $(Y-V)$ there is a shift of aproximately −250 K for the Straižys (1995) work with respect to ours in the range $0.56 < (Y-V) < 0.92$ but both slopes are rather similar.

3.5.2. Geneva system

The calibration given by Kobi & North (1990) is based on synthetic Geneva colours obtained from older versions of Kurucz models. It is compared to our calibration for the colour index (B_2-V_1) in Fig. 11c. As usual, they corrected the synthetic colours using standard stars so that they could be able to reproduce the observed colours, especially for cool stars. This correction was calculated only for [Fe/H] = 0 but they assumed that it was also valid for lower metallicities. Nevertheless, their published results for [Fe/H] < 0 are ambiguous and have not been considered here.

Some of the standard stars mentioned above were used by HK96 to calibrate this colour index and also the (B_2-G), hence the better agreement between Kobi & North (1990) and HK96 works for the coolest stars. In total, HK96 used more than 140 stars for the empirical calibrations shown in Figs. 11c,d. The tendency of both calibrations with respect to ours are similar. They give higher temperatures than ours for the coolest stars whilst around $T_{\rm eff}$ = 6800 K the difference vanishes. The maximum difference amounts to 150 K for the (B_2-V_1) colour index and 120 K for (B_2-G). In both cases this maximum is achieved at $T_{\rm eff} \sim$ 4800 K and is equivalent to 3.0 and 2.5%, respectively.

In a recent work, Blackwell & Lynas-Gray (1998) used the IRFM temperatures of a large sample of ISO (Infrared Space Observatory) flux calibration stars and their Geneva colours (B_2-V_1) corrected by interstellar extinction using Hipparcos parallaxes and an average interstellar extinction law coupled with extinction maps to calibrate the relation $T_{\rm eff} = f(B_2-V_1)$ where f is a second order polynomial. Their results are shown in Fig. 11c as crosses. The agreement between our work and theirs is excellent. We should also mention that the effect of metallicity is considered in Blackwell & Lynas-Gray (1998) but apparently valid only for [Fe/H] > −0.6.

3.5.3. $RI_{\rm (C)}$ system

Houdashelt et al. (2000) have obtained colour-temperature relations with improved MARCS stellar atmosphere models

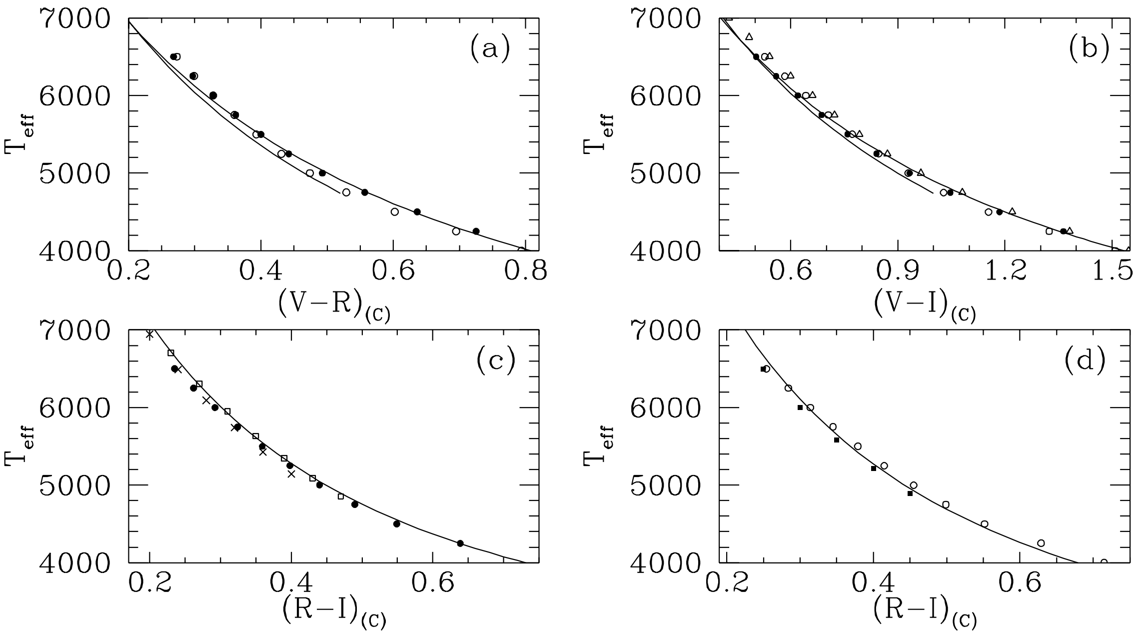

Fig. 12. a–d) Comparison of our calibrations for [Fe/H] = 0, −1 (solid lines) with those of Houdashelt et al. (2000) for [Fe/H] = 0 (filled circles) and [Fe/H] = −1 (open circles), Bessell et al. (1998) for [Fe/H] = 0 (triangles), Hauck & Künzli (1996) for [Fe/H] = 0 (open squares) and Carney et al. (1994) for [Fe/H] = 0 (crosses) and [Fe/H] = −1 (filled squares).

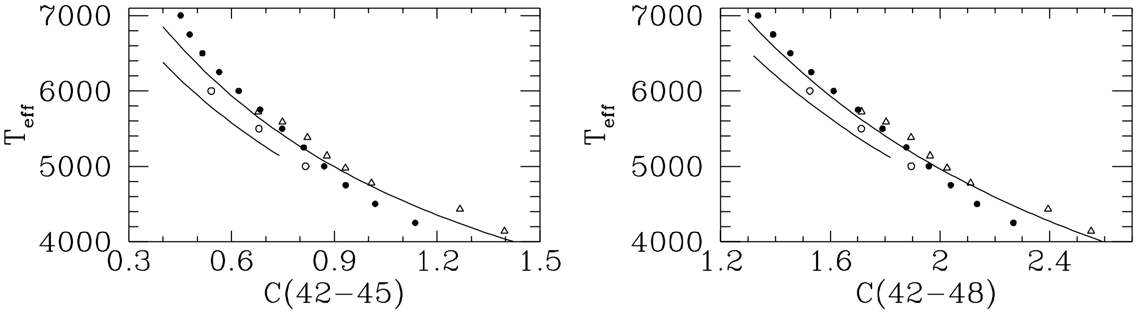

Fig. 13. Comparison of our calibrations for [Fe/H] = 0, −1 (solid lines) with those given by Tripicco & Bell (1991) for [Fe/H] = 0 (filled circles) and [Fe/H] = −1 (open circles) and Clariá et al. (1994) for [Fe/H] = 0 (triangles).

(Gustafsson et al. 1975; Bell et al. 1976) after putting synthetic colours onto the observational systems by means of a sample of field stars with IRFM temperatures determined and a model for Vega, whose colours fix the zero point corrections. These relations are shown in Figs. 12a–d as filled circles for [Fe/H] = 0 and open circles for [Fe/H] = −1. It is worth mentioning that the colour calibrations were derived for [Fe/H] = 0 stars so that their results for lower metallicities are less reliable. Their calibrations for solar metallicities seem to agree with ours for $T_{\rm eff} < 6000$ K and for the whole range of temperatures in the case of $(V-I)_{\rm (C)}$. For the hottest stars the $(V-R)_{\rm (C)}$ colours derived by Houdashelt et al. (2000) are too red whilst the $(R-I)_{\rm (C)}$ colours are too blue. The maximum difference with our work is about 150 K.

In Fig. 12b we show as open triangles the relation between temperature and synthetic colours computed from spectra obtained from overshoot (for $T_{\rm eff} > 6000$ K) and no-overshoot (for $T_{\rm eff} < 6000$ K) Kurucz models as given by Bessell et al. (1998). The selection of overshoot and no-overshoot models for the different ranges of temperatures alowed us to improve the agreement with our work although it showed to be very small. For effective temperatures below 5000 K our empirical calibration is very close to this one but for the hottest stars Bessell et al. (1998) provide $(V-I)_{\rm (C)}$ colours that are too red (the difference is about 0.03 mag). The agreement is also good, though it is not shown, for the $(V-I)_{\rm (C)}$ colours of the late K dwarfs calculated on the basis of NMARCS models.

We also show in Fig. 12c the empirical calibration of HK96 (open squares), which, though being based on the effective temperatures of only 26 solar-metallicity stars, agrees perfectly well with the results of this work.

In their survey of proper motion stars, Carney et al. (1994) derived the metallicity dependent relation between $T_{\rm eff}$ and $(R-I)_{\rm (C)}$ that is shown in Fig. 12c for [Fe/H] = 0 (crosses) and Fig. 12d for [Fe/H] = −1 (filled squares). Their temperature scale was based upon "a comparison of spectrophotometric scans of the Paschen continuum with surface flux distributions computed with the same model atmospheres used to calculate

Table 3. Intrinsic colours in the Vilnius system as a function of [Fe/H].

	$(V-S)$			$(Y-V)$		
$T_{\rm eff}$	[Fe/H] = 0	−1	−2	[Fe/H] = 0	−1	−2
3750	1.205	-	-	1.034	-	-
4000	1.049	-	-	0.948	-	-
4250	0.932	-	-	0.872	-	-
4500	0.839	-	-	0.805	-	-
4750	0.763	-	-	0.745	-	-
5000	0.698	0.673	0.667	0.691	0.667	0.661
5250	0.642	0.619	0.613	0.642	0.618	0.612
5500	0.594	0.571	0.566	0.598	0.573	0.567
5750	0.551	0.529	0.524	0.557	0.533	0.527
6000	0.513	0.491	0.486	0.520	0.495	0.489
6250	0.479	0.458	0.453	0.486	0.461	0.455
6500	0.448	0.427	-	0.454	0.430	-
6750	0.420	0.400	-	0.425	-	-

Table 4. The same as in Table 3 for the Geneva system.

	(B_2-V_1)			(B_2-G)			t		
$T_{\rm eff}$	[Fe/H] = 0	−1	−2	[Fe/H] = 0	−1	−2	[Fe/H] = 0	−1	−2
3750	1.008	-	-	1.080	-	-	-	-	-
4000	0.898	-	-	0.890	-	-	-	-	-
4250	0.800	-	-	0.726	-	-	-	-	-
4500	0.711	-	-	0.583	-	-	0.456	-	0.443
4750	0.631	0.578	0.555	0.458	0.386	0.357	0.393	0.379	0.380
5000	0.557	0.507	0.487	0.347	0.276	0.247	0.333	0.318	0.319
5250	0.490	0.442	0.424	0.247	0.178	0.149	0.276	0.260	0.261
5500	0.428	0.382	0.367	0.158	0.089	0.061	0.221	0.204	0.205
5750	0.370	0.327	0.314	0.077	0.009	−0.019	0.167	0.149	0.150
6000	0.317	0.276	0.265	0.004	−0.064	−0.091	0.115	0.095	0.097
6250	0.268	0.229	0.220	−0.063	−0.130	−0.157	0.063	0.043	0.044
6500	0.222	0.185	-	−0.124	−0.191	-	0.013	−0.010	-
6750	0.179	0.144	-	−0.180	−0.247	-	−0.038	−0.062	-
7000	0.139	0.105	-	−0.232	-	-	−0.089	-	-

Table 5. The same as in Table 3 for the $RI_{\rm (C)}$ system.

	$(V-R)_{\rm (C)}$			$(R-I)_{\rm (C)}$			$(V-I)_{\rm (C)}$		
$T_{\rm eff}$	[Fe/H] = 0	−1	−2	[Fe/H] = 0	−1	−2	[Fe/H] = 0	−1	−2
3750	0.922	-	-	-	-	-	-	-	-
4000	0.808	-	-	0.732	-	-	1.534	-	-
4250	0.712	-	-	0.638	-	-	1.353	-	-
4500	0.631	-	-	0.563	-	-	1.201	-	-
4750	0.561	-	-	0.501	-	-	1.071	-	-
5000	0.500	0.466	0.439	0.449	0.443	0.438	0.958	0.899	0.879
5250	0.447	0.419	0.397	0.405	0.403	0.402	0.859	0.814	0.803
5500	0.399	0.377	0.360	0.366	0.369	0.371	0.772	0.737	0.735
5750	0.356	0.339	0.326	0.332	0.338	0.343	0.694	0.669	0.673
6000	0.317	0.305	0.296	0.301	0.311	0.319	0.624	0.607	0.617
6250	0.283	0.274	0.268	0.274	-	-	0.561	0.551	0.567
6500	0.251	0.246	-	0.249	-	-	0.503	0.500	-
6750	0.222	0.220	-	0.227	-	-	0.451	0.453	-
7000	0.195	-	-	0.207	-	-	0.403	0.410	-

Table 6. The same as in Table 3 for the DDO system.

	$C(42-45)$			$C(42-48)$		
$T_{\rm eff}$	[Fe/H] = 0	−1	−2	[Fe/H] = 0	−1	−2
4000	1.423	-	-	2.593	-	-
4250	1.260	-	-	2.414	-	-
4500	1.122	-	-	2.254	-	-
4750	1.002	-	-	2.112	-	-
5000	0.898	0.792	0.756	1.983	1.874	1.838
5250	0.805	0.702	0.667	1.867	1.758	1.722
5500	0.724	0.623	0.588	1.761	1.652	1.616
5750	0.650	0.551	0.517	1.665	1.556	1.519
6000	0.584	0.486	0.453	1.576	1.467	1.431
6250	0.524	0.428	0.395	1.495	1.386	1.350
6500	0.470	-	-	1.420	-	-
6750	0.420	-	-	1.350	-	-

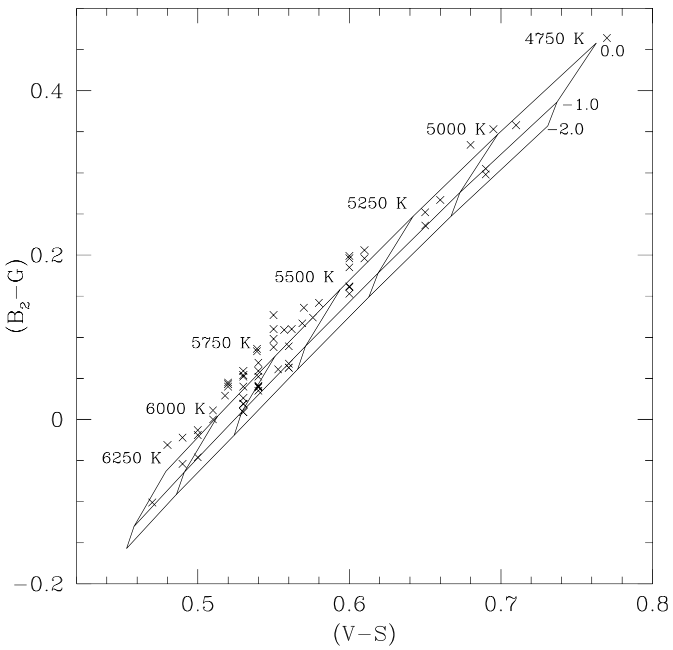

Fig. 14. $(V-S)$ versus (B_2-G), colour-colour diagram showing lines of equal $T_{\rm eff}$ and metallicity for [Fe/H] = 0, −1 and −2. Crosses correspond to observed colours for stars with −0.5 < [Fe/H] < +0.5.

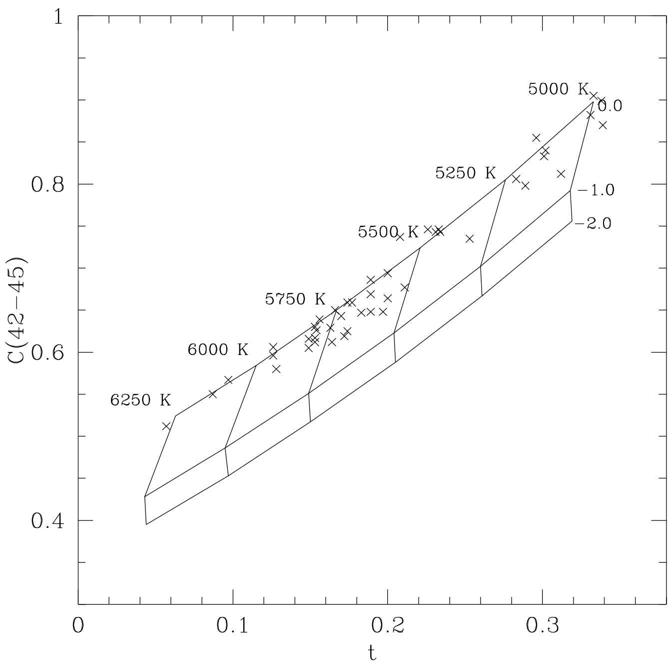

Fig. 15. The same as in Fig. 14 for t versus $C(42-45)$.

the synthetic spectra". In general, their temperatures are lower than those calculated from our formulae.

3.5.4. DDO system

Finally, in Fig. 13 is shown the comparison between our calibrations for the DDO colours and those given by Tripicco & Bell (1991) and Clariá et al. (1994). The former of these (which is shown in Fig. 13 as filled and open circles for [Fe/H] = 0 and [Fe/H] = −1, respectively) was based on MARCS models and used spectrophotometric scans for several stars to put the synthetic colours onto the observational system, thus allowing a model independent treatment. Tripicco & Bell (1991) argue that the effect of metallicity on DDO colours is so strong that "DDO system is primarily a measure of line, rather than continuum effects". This is something that can be easily seen in Figs. 9 and 10 and was already discussed in Sect. 3.4. For a given $T_{\rm eff}$ in the range 5200–6200 K, the effect of metallicity is such that a change from [Fe/H] = 0 to [Fe/H] = −1 produces a decrease of 0.08 mag in $C(42-45)$ and 0.09 mag in $C(42-48)$ in the Tripicco & Bell (1991) work. For the present calibration, the decrease amounts to 0.1 mag in both cases. In this range there is a reasonably good agreement but large systematic differences start to appear as we go both to lower and higher temperature ranges. In general, the slopes are not similar but the effect of [Fe/H] on DDO colours is well reproduced.

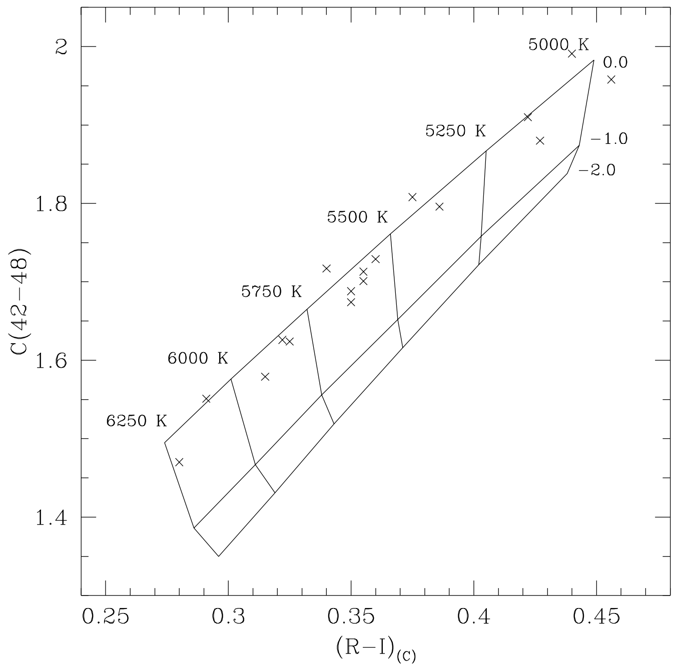

Fig. 16. The same as in Fig. 14 for $(R-I)_{(C)}$ versus $C(42{-}48)$.

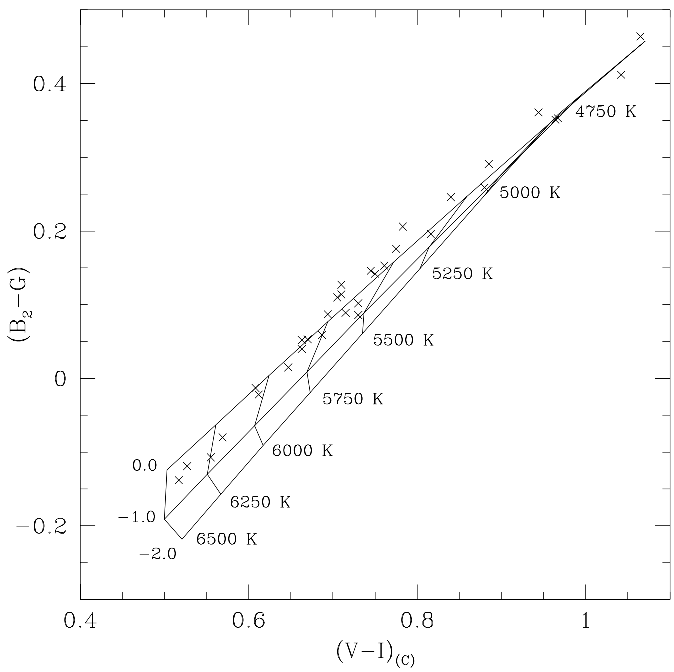

Fig. 17. The same as in Fig. 14 for $(V-I)_{(C)}$ versus (B_2-G).

Spectroscopic observations of field and open cluster stars allowed Clariá et al. (1994) to calibrate the relation $C(45{-}48)$ vs. $C(42{-}45)$ for [Fe/H] $\sim$ 0. This colour-colour diagram was then used to determine the mean values of DDO colours as a function of spectral type so that the mean DDO effective temperature-MK spectral type relation provided them the $T_{\rm eff}$: DDO colours calibration. The triangles in Fig. 13 show that our temperatures are always lower than those derived by Clariá et al. (1994), the maximum difference being about 200 K for K5 stars. There is a reasonable agreement around 5000 K.

4. The empirical temperature scale

Solving Eqs. (1) to (10) for the colour index as a function of $T_{\rm eff}$ and [Fe/H] we obtained a set of intrinsic colours for late type dwarfs. They are listed in Tables 3 to 6 for various metallicities. Because of their usefulness, these results have been used to plot the colour-colour diagrams shown in Figs. 14 to 17. Also shown in these figures are the observed colours for stars with $-0.5 <$ [Fe/H] $< +0.5$. The agreement is rather good since the observed dispersion can be attributed primarily to the amplitude of the metallicity range considered.

For the sun ($T_{\rm eff}$ = 5777 K, [Fe/H] = 0), our temperature scale yields: $(V-S)_\odot = 0.547$, $(Y-V)_\odot = 0.553$, $(B_2-V_1)_\odot = 0.365$, $(B_2-G)_\odot = 0.069$, $t_\odot = 0.161$, $(V-R)^\odot_{(C)} = 0.352$, $(R-I)^\odot_{(C)} = 0.328$, $(V-I)^\odot_{(C)} = 0.686$, $C(42{-}45)_\odot = 0.643$ and $C(42{-}48)_\odot = 1.655$. These results are in good agreement with the solar colours compiled in HK96 and almost with every calibration mentioned in Sect. 3.5 for it is clear from Figs. 11 to 13 that the differences vanish for $T_{\rm eff} \sim 5800$ K. It is also interesting to note that these solar colours are similar to the colours of the "solar twin" 18 Sco (Porto de Mello & da Silva 1997): $(V-S) = 0.54$, $(Y-V) = 0.57$, $(B_2-V_1) = 0.385$, $(B_2-G) = 0.089$, $t = 0.17$, $(V-R)_{(C)} = 0.353$, $(R-I)_{(C)} = 0.335$, $(V-I)_{(C)} = 0.686$, $C(42{-}45) = 0.651$ and $C(42{-}48) = 1.674$.

5. Conclusions

We have derived the relation between $T_{\rm eff}$, [Fe/H] and several colours for different photometric systems and have found good agreement with previously published calibrations. We have given detailed information about the application ranges and made several warnings on the use of our calibration formulae. The standard deviations amount from 64 K for $(V-I)_{(C)}$ to 126 K for $(Y-V)$ and stars whose IRFM effective temperatures depart by more than 2σ from the mean fit have always been listed.

The solar colours derived in this work have proved to be similar to the colours of the solar twin 18 Sco so now these colours can be used to look for new solar twins.

Along with AAM96b work, our calibrations provide an homogeneous (IRFM) temperature scale for cool dwarfs which can be used to explore the capability of models to reproduce the observations. A similar extension for giants is also necessary.

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