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The missing opacity and the temperature calibration of solar-type stars

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Summary. A new temperature calibration of some colour indices is established for F and G dwarfs. It is based on the infrared flux method and extends the work of Saxner and Hammerbäck to the Population II stars. The disagreement between the empirical colours and some model predictions is discussed and showed to be most naturally interpreted in terms of the so-called "missing opacity".

Key words. stellar atmospheres – stellar colours – stellar temperatures – Population II stars

1. Introduction

In a recent paper, Saxner and Hammarbäck (1985, hereafter SH) have presented an empirical temperature calibration for F and early G type dwarfs. They used the so-called "infrared flux method" (Blackwell and Shallis, 1977) which is based on the comparison of the flux measured at some infrared wavelength with the integrated flux. They obtained effective temperatures for about 30 Population I dwarfs, which allowed them to calibrate some widely used colour indices, such as $B - V$ or $b - y$, in terms of effective temperature.

An interesting outcome of their analysis is that there are still significant discrepancies between theoretical and observed colour-temperature relations for solar-type stars. In particular, Kurucz (1979) models seem too red for the early F stars and too blue for solar temperature stars. A similar problem was reported by Böhm-Vitense (1981) who attributed this discrepancy to the influence of convection. Moreover, Gustafsson and Bell (1979) discussed a similar effect in the case of cooler giants. Although the new colours of VandenBerg and Bell (1985) are in better agreement with the empirical calibration than previous model colours, the same kind of discrepancy remains.

The aim of the present paper is twofold. First, we extend the work of SH to the Population II dwarfs, in order to cover the whole range of metallicities. Secondly, we want to investigate in more detail the discrepancy between the theoretical and empirical temperature calibrations.

Before turning to the computations, however, we would like to summarize some earlier discussions of that problem. Since the review paper of Böhm-Vitense, convection is most often advocated as responsible for that discrepancy. We recall that convection is included in the models only in the framework of the mixing-length approximation. In particular, temperature inhomogeneities are neglected. As pointed out by Böhm-Vitense, this may introduce systematic errors in the continuous flux. On the other hand, Magain (1983) argued that the discrepancy should rather be attributed to the so-called "missing opacity", i.e. to a veil of faint metal lines present in the blue and ultraviolet regions of the spectra of solar-type (and cooler) stars, but not included in the models. He showed that the inclusion of such a veil improves significantly the agreement between the observed and computed colours for mid F to late G dwarfs of different metallicities and concluded that the most natural and successful interpretation of the discrepancy was in terms of such a veil. This has been confirmed by Kurucz (1986), who showed that including a huge number of additional Fe lines in the models led to improved fluxes in the ultraviolet.

2. The effective temperature calibration

The method we use is very similar to that of SH, most of the differences being dictated by the fact that we analyse different stars, with a different observational material at hand. The essence of the infrared flux method is summarized in Eqs. (1) to (4) of SH. What is needed is (1) the integrated stellar flux measured outside the earth atmosphere and (2) the flux measured at some infrared wavelength(s).

(1) The integrated flux from 337 to 983 nm is computed from the 13 colour photometry (Johnson and Mitchell, 1975; Schuster, 1979), with the absolute calibration adopted by SH. From 983 nm to 2.2 μm, we use the J and K magnitudes (Carney, 1983) with, again, the calibration of SH. The ultraviolet flux shortwards of 337 nm is extrapolated with the help of Kurucz (1979) models, while the infrared flux longwards of 2.2 μm is extrapolated by assuming a $1/\lambda^4$ behaviour. These last two contributions amount respectively to some 9% (UV) and 4% (IR) of the total flux, so that any reasonable uncertainty on these quantities has a negligible effect on the deduced effective temperature (e.g. a 20% error on the extrapolated UV flux would correspond roughly to a 25 K error on the deduced effective temperature). Moreover, it has been shown by Magain (1984) that the extrapolation of the UV flux with the help of Kurucz models gives practically the same result as the use of the IUE fluxes in the case of HD 19445, the temperature difference amounting to 10 K. Our estimates also agree, within 2% of the total flux, with the measurements of Bell (1986) for HD 19445 and HD 84937.

(2) The monochromatic infrared fluxes are computed from the J and K magnitudes of Carney (1983), with the use of the absolute calibration of SH and of their "q-factors" to convert the mean flux in the filter passband to the monochromatic flux at

Table 1. Program stars

Star	log(g)	[Fe/H]	T_J	T_K	T_e	$B-V$	$b-y$	$V-K$
HD 19445	4.0	−2.3	5875	5990	5933	0.46	0.354	1.39
HD 64090	4.5	−1.9	5300	5440	5370	0.61	0.431	1.73
HD 74000	4.5	−1.8	6087	6183	6135	0.42	0.312	1.26
HD 84937	4.0	−2.0	6149	6271	6210	0.39	0.303	1.21
HD 94028	4.0	−1.5	5682	5872	5777	0.48	0.345	1.39
HD 108177	4.1	−1.6	5969	6082	6026	0.43	0.323	1.32
HD 132475	4.0	−1.2	5570	5658	5614	0.555	0.388	1.625
HD 140283	3.2	−3.0	5506	5708	5607	0.48	0.377	1.59
BD + 42°2667	3.7	−1.3	5917	5993	5955	0.46	0.338	1.36
HD 201891	4.5	−1.4	5674	5847	5761	0.51	0.349	1.42
HD 219617		−1.4	5854	6981	5918	0.48	0.337	1.39

the effective wavelength of the band (see Fig. 2 of SH). Note that no measurement of the L magnitude is available for most of our stars.

Our stellar sample was selected from the [Fe/H] catalogue of Cayrel et al. (1984). Only the stars with [Fe/H] < -1 and with published 13 colour and JK photometry were retained. The resulting sample contains 11 dwarfs and subgiants (Table 1). The effective temperature, surface gravity and metal abundance are taken from the catalogue, except for HD 19445 and HD 140283 for which the more recent determinations of Magain (1985) are used. The colours are from Carney (1983). As in SH, a systematic difference appears between the effective temperatures determined from the $J(T_J)$ and $K(T_K)$ magnitudes. This is probably due to errors in the absolute calibrations of the J and K magnitudes. The final effective temperatures are the means of T_J and T_K and, so, are not exactly on the same scale as the effective temperatures of SH.

In Figs. 1, 2 and 3 are shown plots of the empirical effective temperatures T_e versus the colour indices $B-V$, $b-y$ and $V-K$. Least squares linear fits, taking into account uncertainties in both coordinates, lead to the following relations:

$$T_e = 7720 - 3910(B-V) \tag{1}$$

$$T_e = 8190 - 6670(b-y) \tag{2}$$

$$T_e = 8060 - 1550(V-K) \tag{3}$$

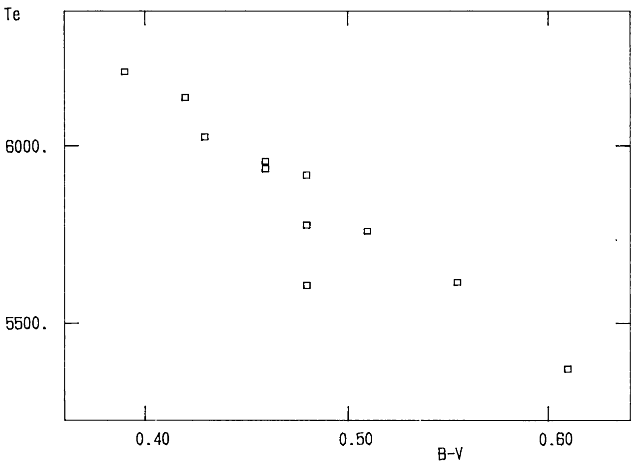

Fig. 1. Empirical effective temperatures against $B-V$ colour index

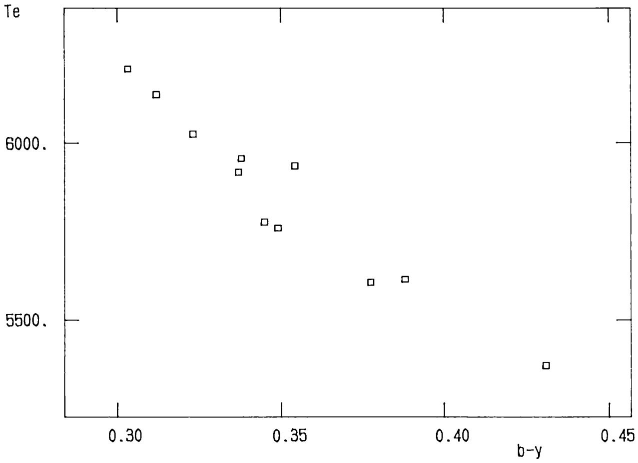

Fig. 2. Empirical effective temperatures against $b-y$ colour index

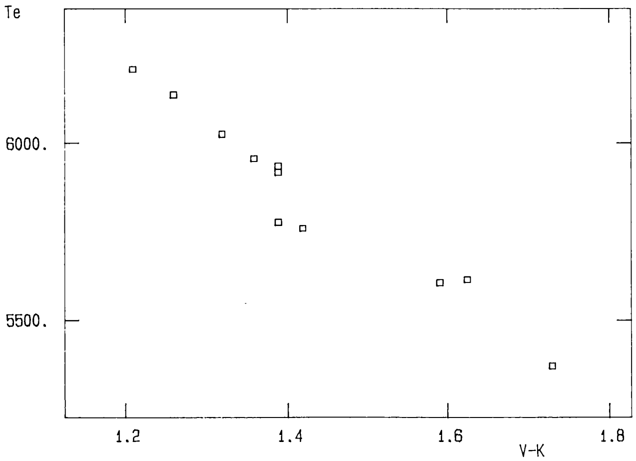

Fig. 3. Empirical effective temperatures against $V-K$ colour index

These relations should be valid for dwarfs and subgiants with [Fe/H] < -1 and $0.39 < B-V < 0.61$, $0.30 < b-y < 0.43$, $1.2 < V-K < 1.7$, which corresponds to the range covered by the calibrating stars. The scatter around these relations amounts to some 60 K for $b-y$ and $V-K$, and 80 K in the case of $B-V$. This is similar to the scatter around the SH calibrations, after inclusion of an [Fe/H] dependency.

Our first result is thus an effective temperature calibration for Population II dwarfs, similar to the SH calibration for Population I dwarfs, although, by necessity, based on a smaller number of stars. The consistency of our results, however, as illustrated by the small scatter, implies that the internal accuracy of our calibration should be roughly comparable to that of SH. The uncertainty of the zero-point depends very much on that of the absolute calibration of the infrared colours. It is thus much more difficult to estimate, but we feel that the zero-point should not be in error by more than 100 K, and probably by significantly less than that. This is confirmed by the remarkable agreement with the new theoretical calibration of Bell and Oke (1986, see their Table 5), especially in the case of $(b-y)$.

3. Comparison with theoretical calibrations

Some insight may be gained by simply comparing the empirical (SH, this paper) and theoretical (Relyea and Kurucz, 1978, hereafter RK; VandenBerg and Bell, 1986, hereafter VB) calibrations of the $b-y$ colour index (Table 2). The most striking results are the following.

(1) The slope of the $T_e(b-y)$ relation is well reproduced by the theoretical models for the Population II stars, the zero-point being also in agreement in the case of the VB calibration.

(2) There is a disagreement in the slope of the $T_e(b-y)$ relation for the Population I stars, especially for the RK calibration: between 6000 and 7000 K, the empirical $b-y$ index varies by 0.161 mag, while the theoretical predictions are 0.114 (RK) and 0.129 (VB). Note, moreover, that in both cases, the discrepancy (or agreement) for the hotter Population I stars is roughly the same as for the Population II stars.

It is difficult to interpret such a behaviour in terms of convection. Indeed, convection is predicted to be more important in the cooler Population I stars and in the Population II stars. On the basis of this interpretation, we would certainly not expect the Population II stars to behave like the hotter Population I stars. It is equally difficult to understand why the effect would not change with temperature in the Population II stars. The only reasonable (?) interpretation of these trends would be that convection plays no role in the Population II dwarfs, at variance with all theoretical predictions.

As we have just indicated, examination of Table 2 suggests that no discrepancy is present in the Population II and hotter Population I stars, and that it increases with decreasing temperature of the Population I stars. This interpretation would require a 0.02 mag offset in the calibration of RK, which we feel is consistent with the various uncertainties affecting their zero-point. The resulting behaviour would then be in perfect agreement with the interpretation in terms of a veil of weak metal lines, which would decrease with increasing temperature and decreasing metal abundance. This hypothesis will be analysed in more detail in the following section.

Table 2. Comparison of theoretical and empirical $T(b-y)$ calibrations

	$b-y$ ([Fe/H) = 0)			$b-y$ ([Fe/H] = −2)		
T	RK	VB	Emp.	RK	VB	Emp.
5500	0.407	0.430	(0.450)	0.423	0.405	0.403
6000	0.345	0.350	0.369	0.347	0.330	0.328
6500	0.287	0.286	0.289	0.283	0.267	(0.253)
7000	0.231	0.221	0.208			

Note: The theoretical calibrations of Relyea and Kurucz (1978, RK) and VandenBerg and Bell (1986, VB) reported here correspond to a surface gravity $\log(g) = 4.0$

4. More on the missing opacity

Since there is some systematic difference between the effective temperature determined from the J magnitude (T_J) and the other ones (T_K and T_L), we will, in order to obtain an approximately consistent set of empirical temperatures for Population I and Population II stars, disregard the T_L determination of SH and take the mean of their T_J and T_K. This change will affect the zero-point of their calibration, but not significantly its variation with effective temperature or with metallicity, which is of concern here. This will thus change none of our conclusions.

For each star in the sample of SH and our sample, we compute the "theoretical effective temperature" T_t from the observed $b-y$ index, using each theoretical calibration at the appropriate surface gravity and metallicity, and compare it with the "empirical effective temperature" $T_e = 0.5(T_J + T_k)$. We thus obtain a set of "temperature errors" $\delta T = T_t - T_e$ as a function of T_e and [Fe/H], that we can compare to the predictions of a simple model.

Let us assume, as in Magain (1983), that the discrepancy is due to a veil of faint neutral metallic lines. The flux absorbed by that veil in a given wavelength band may be approximated by:

$$W = 1 - F/F_0 \sim \kappa_v/\kappa_c = k\,10^{[\mathrm{Fe/H}]+(\theta-1)(I-\chi-0.75)} \tag{4}$$

where W is the "total equivalent width" of the veil in that wavelength band, F_0 the flux in the absence of the veil, F the actual flux, κ_v and κ_c the veil and continuous opacities (the latter being dominated by H^-), I and χ the ionization and excitation potentials of the "mean line" characteristic of the veil and $\theta = 5040/T$. The constant k is an unknown parameter which represents the strength and density of the veil lines (see Magain, 1983).

Since $W \ll 1$, the magnitude difference due to the veil is given by:

$$\delta m = -2.5\log(F/F_0) = -2.5\log(1-W) \simeq 1.086W \tag{5}$$

If the veil is present in the b band, but not in the y band, we may write:

$$\delta(b-y) \simeq \delta m \simeq 1.086k\,10^{[\mathrm{Fe/H}]+(\theta-1)(I-\chi-0.75)} \tag{6}$$

To convert $\delta(b-y)$ in δT, we assume that the stellar flux may be approximated by a black body:

$$F(\lambda) \simeq c_1\lambda^{-5}(e^{c_2/\lambda T}-1)^{-1} \tag{7}$$

so that

$$b-y = -2.5\log(F_b/F_y) \simeq -2.5\log\frac{\lambda_y^5(e^{c_2/\lambda_y T}-1)}{\lambda_b^5(e^{c_2/\lambda_b T}-1)} \tag{8}$$

where c_1 and c_2 are universal constants (Gray, 1976), λ_b and λ_y the effective wavelengths of the b and y passbands, F_b and F_y the fluxes in these bands. Differentiation of Eq. (8) thus gives the approximate variation of $b-y$ with temperature:

$$\delta(b-y) \simeq 1.086 c_2 T^{-2}(\lambda_y^{-1} - \lambda_b^{-1}) \quad (9)$$

With $\lambda_b = 467$ nm and $\lambda_y = 547$ nm, we obtain:

$$\delta T \simeq -T^2/4893\, \delta(b-y) \quad (10)$$

Let us now assume, following Magain (1983), that the "mean veil line" is an Fe I line of 3 eV excitation potential. Then,

$$\delta T \simeq -(T^2/4893) 1.086 k\, 10^{[\mathrm{Fe/H}]+4.12(\theta-1)} \quad (11)$$

However, as we have already pointed out, this model may require a slight change in the zero-point of either the temperature scale or the $b-y$ calibration. We assume that this last one has to be modified (a change in the temperature zero-point would give nearly identical results, but the perfect agreement with Bell and Oke (1986) and with VB for the Population II stars suggests that our zero-point is free from significant error). According to our model, the theoretical colours must equal the observed ones in the case of stars with no metals ([Fe/H] $\ll 0$). We thus determine the zero-point correction from our sample of 11 metal-poor stars in the following way. We plot $\delta(b-y) = -4893 T^{-2}\, \delta T$ as a function of $10^{[\mathrm{Fe/H}]+4.12(\theta-1)}$ for these 11 stars and fit a straight line by least squares through these points. The zero-point correction is the intercept of that line with the $\delta(b-y)$ axis, i.e. the value of $\delta(b-y)$ corresponding to [Fe/H] $= -\infty$. We obtain:

$$\delta(b-y)_0 = -0.018(\pm 0.004) \quad (12a)$$

for the RK calibration and

$$\delta(b-y)_0 = -0.002(\pm 0.005) \quad (12b)$$

for the VB calibration. Equation (11) can thus be modified in the following way:

$$\delta T = \frac{T^2}{4893}\left[-\delta(b-y)_0 - 1.086 k\, 10^{[\mathrm{Fe/H}]+4.12(\theta-1)}\right] \quad (13)$$

The only unknown parameter, k, may be determined from a fit to the stars of SH. Excluding three discrepant stars (HR 1008, HR 4054 and HR 4102), we obtain by least squares:

$$k = 0.19(\pm 0.02) \quad (14a)$$

for the RK calibration and

$$k = 0.08(\pm 0.02) \quad (14b)$$

for the VB calibration. The quoted uncertainty is the standard deviation of the mean value (the standard deviation of the individual determinations amounting to some 0.10). These values compare well with the determination of Magain (1983) at the effective wavelength of the b band ($k \simeq 0.1$, see Fig. 2 of that paper). The fair agreement between these independent (and very different) determinations gives a strong support to the simple model considered. In Figs. 4 and 5, we have plotted the "empirical" temperature errors ($\delta T = T_t - T_e$) versus the values computed from Eqs. (13) and (14). It is clear that the scatter ($\sigma \simeq 65$ K) can be entirely explained by the observational uncertainties. Note that the differences between the calibrations of RK and VB and, in particular, the superiority of the last one, may be explained in part by the lack of molecular opacities in in Kurucz models, this lack being compensated in our model by an artificial increase of the line veil.

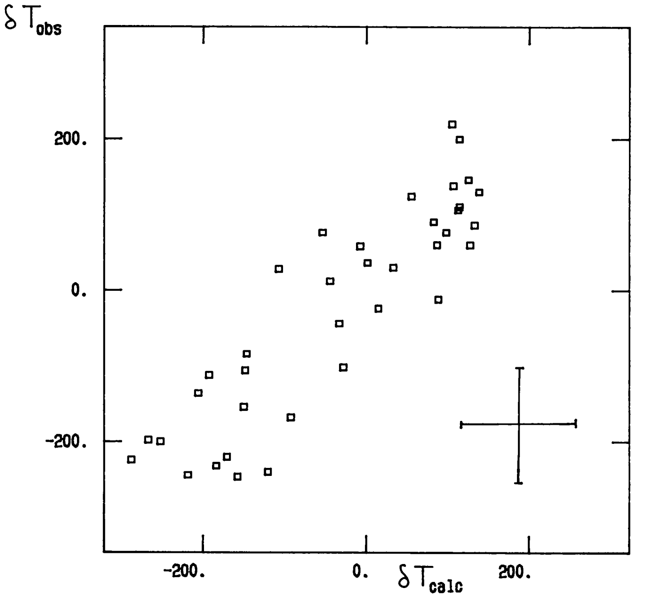

Fig. 4. The "empirical" temperature errors δT_{obs} for the Relyea and Kurucz (1978) calibration versus the temperature errors given by Eqs. (13) and (14a). A typical error bar is also indicated

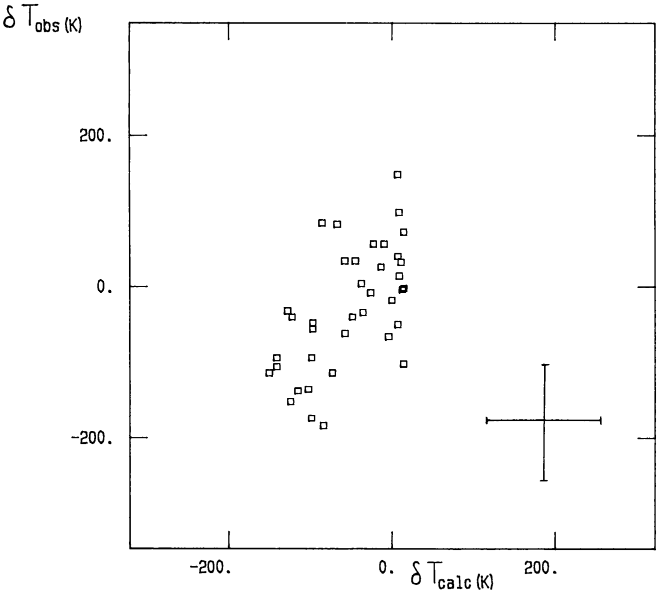

Fig. 5. Same as Fig. 4 for the VandenBerg and Bell (1986) calibration

5. Discussion

The success of Eq. (13) to reproduce the observed temperature (or colour) discrepancies, with a parameter k compatible with the completely different determination of Magain (1983) – which, we recall, was based on the solar flux – strongly argues in favour of the "missing opacity" as the cause of the problem. Although we cannot rule out the explanation in terms of convective effects, we have given evidence that this is not the most natural explanation of the discrepancy. Since no quantitative model based on the convective hypothesis has been able to explain the discrepancy, and since simple veil models are completely successful in that respect, we may safely conclude that the veil of weak lines (or any other opacity source varying in the same way with temperature and metallicity) is the right explanation of that effect. This also means that the safer way to improve the situation is through the tedious inclusion of thousands (or millions) of weak lines in the model opacities.

Before such models are available, we will have to rely on empirical corrections, such as the one presented here. As a matter of fact, we have found that the formulae:

$$T_e = 8330 - 7040(b-y)\{1 - 0.099\,10^{[\mathrm{Fe/H}]}\} \tag{15}$$

$$T_e = 7950 - 4230(B-V)\{1 - 0.204\,10^{[\mathrm{Fe/H}]}\} \tag{16}$$

give reasonable fits to the empirical temperatures $T_e = 0.5(T_J + T_K)$ for the stars of SH and of Table 1, the scatter amounting to some 60 K for $(b-y)$ and 110 K for $(B-V)$. Note that the zero-points of Eqs. (15) and (16) are somewhat uncertain due to the uncertainty in the zero-point of the empirical temperatures. Any other choice would nevertheless leave the slope essentially unchanged.

The solar colours deduced from Eqs. (15) and (16) are $(b-y)_\odot = 0.402$ and $(B-V)_\odot = 0.644$, in agreement with SH and with Magain (1983).

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