PHOTOMETRIC CALIBRATIONS OF THE EFFECTIVE TEMPERATURE

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Abstract. We have reconsidered the calibration of various color indices in terms of the effective temperature. In addition, a new calibration of the Geneva system in terms of $T_{\text{eff}}$, $\log g$ and $[\text{M/H}]$ is presented.

Key words: methods: data analysis – techniques: photometric – stars: fundamental parameters (effective temperature)

1. INTRODUCTION

The first paper giving a relation between the effective temperature and a color index was published by Popper (1959). Since then, many calibrations of color indices of various photometric systems in terms of $T_{\text{eff}}$, $\log g$ and $[\text{M/H}]$ have been made. Among the most used systems, we can mention the calibration of Claria et al. (1994) for the DDO system, of Smalley & Dworetsky (1995) for the Strömgren system, Kobi & North (1990, hereafter KN90) and North & Nicolet (1990, hereafter NN90) for the Geneva system.

Since many calibrations of color indices are based on different sets of $T_{\text{eff}}$ values, it seemed interesting for us to use the same set of $T_{\text{eff}}$ values to calibrate several color indices.

2. CALIBRATION OF COLOR INDICES IN TERMS OF $T_{\text{eff}}$ FOR THE MAIN-SEQUENCE STARS

Since many color indices, which will be used in the subsequent calibration, can be affected by a luminosity effect, we have restricted
this part to the main-sequence stars only. The $T_{\text{eff}}$ values, which we use in the present study, are mainly determined by a direct or semi-direct method. We took our data from Code et al. (1976), Blackwell & Shallis (1977), Saxner & Hammerbäck (1985), Leggett et al. (1986), Blackwell et al. (1990), Malagnini et al. (1990), Blackwell et al. (1991) and Blackwell & Lynas-Gray (1994). To complete this sample, $T_{\text{eff}}$ for a few stars were taken from Hauck (1985).

Color indices for this study were taken from an updated version of the General Catalogue of Photometric Data (Hauck et al. 1990). This database will shortly be available on AstroWeb.

For each considered color index, we use a fitting with linear segments rather than a polynomial fitting. The indices we have calibrated in terms of $T_{\text{eff}}$ are $B2 - V1$ and $B2 - G$ in the Geneva system, $B - V$ for the $UBV$ system, $b - y$ for the Strömgren system, $R - I$ for the Johnson, Kron and Cousins systems, and finally $V - S$ and $VPT = (X - V) + (Y - V)$ for the Vilnius system. The $VPT$ parameter was chosen on the basis of the correlation between it and $B - V$ of the $UBV$ system shown by Sviderskiené & Straizys (1970). The results are given in Table 1 where $n$ is the number of stars used to determine the relations.

<table>
<thead>
<tr>
<th>$\theta_{\text{eff}}$ vs various indices for main-sequence stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{eff}} = +2.245(B2 - V1) +0.902$</td>
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<tr>
<td>$\pm 0.058$</td>
</tr>
<tr>
<td>$\theta_{\text{eff}} = +0.629(B2 - V1) +0.635$</td>
</tr>
<tr>
<td>$\pm 0.006$</td>
</tr>
<tr>
<td>$\theta_{\text{eff}} = +1.597(B2 - G) +1.586$</td>
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<tr>
<td>$\pm 0.036$</td>
</tr>
<tr>
<td>$\theta_{\text{eff}} = +0.455(B2 - G) +0.832$</td>
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<tr>
<td>$\pm 0.004$</td>
</tr>
<tr>
<td>$\theta_{\text{eff}} = +1.444(B - V) +0.561$</td>
</tr>
<tr>
<td>$\pm 0.044$</td>
</tr>
<tr>
<td>$\theta_{\text{eff}} = +0.816(B - V) +0.543$</td>
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<td>$\pm 0.005$</td>
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Table 1 (continued)

<table>
<thead>
<tr>
<th>$\theta_{\text{eff}}$</th>
<th>$(b - y)$</th>
<th>$(R - I)_J$</th>
<th>$(R - I)_K$</th>
<th>$(V - S)$</th>
<th>$VPT$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+2.961(b - y)$</td>
<td>$+0.544$</td>
<td>$+0.559$</td>
<td>$+0.679$</td>
<td>$+0.096$</td>
<td>$+0.658$</td>
</tr>
<tr>
<td>$\pm 0.023$</td>
<td>$\pm 0.008$</td>
<td>$\pm 0.009$</td>
<td>$\pm 0.216$</td>
<td>$\pm 0.086$</td>
<td>$\pm 0.057$</td>
</tr>
<tr>
<td>$+0.822(b - y)$</td>
<td>$+0.544$</td>
<td>$+0.550$</td>
<td>$+0.624$</td>
<td>$+0.477$</td>
<td>$+0.128$</td>
</tr>
<tr>
<td>$\pm 0.003$</td>
<td>$\pm 0.009$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.033$</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>$1.483(R - I)_J$</td>
<td>$+0.559$</td>
<td>$+0.550$</td>
<td>$+0.624$</td>
<td>$+0.477$</td>
<td>$+0.128$</td>
</tr>
<tr>
<td>$\pm 0.060$</td>
<td>$\pm 0.009$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.012$</td>
<td>$\pm 0.005$</td>
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<tr>
<td>$1.545(R - I)_K$</td>
<td>$+0.559$</td>
<td>$+0.550$</td>
<td>$+0.624$</td>
<td>$+0.477$</td>
<td>$+0.128$</td>
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<tr>
<td>$\pm 0.216$</td>
<td>$\pm 0.043$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.012$</td>
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<td>$+0.550$</td>
<td>$+0.624$</td>
<td>$+0.477$</td>
<td>$+0.128$</td>
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<td>$\pm 0.216$</td>
<td>$\pm 0.043$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.012$</td>
<td>$\pm 0.003$</td>
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<tr>
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<td>$+0.550$</td>
<td>$+0.624$</td>
<td>$+0.477$</td>
<td>$+0.128$</td>
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<tr>
<td>$\pm 0.012$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.003$</td>
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<tr>
<td>$+3.216(V - S)$</td>
<td>$+0.096$</td>
<td>$+0.427$</td>
<td>$+0.017$</td>
<td>$+0.128$</td>
<td>$+0.658$</td>
</tr>
<tr>
<td>$\pm 0.621$</td>
<td>$\pm 0.066$</td>
<td>$\pm 0.007$</td>
<td>$\pm 0.017$</td>
<td>$\pm 0.007$</td>
<td>$\pm 0.007$</td>
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<tr>
<td>$+0.789(V - S)$</td>
<td>$+0.427$</td>
<td>$+0.017$</td>
<td>$+0.128$</td>
<td>$+0.658$</td>
<td>$+0.658$</td>
</tr>
<tr>
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<td>$\pm 0.007$</td>
<td>$\pm 0.007$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.005$</td>
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<tr>
<td>$+0.585VPT$</td>
<td>$+0.128$</td>
<td>$+0.128$</td>
<td>$+0.658$</td>
<td>$+0.658$</td>
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</tr>
<tr>
<td>$\pm 0.057$</td>
<td>$\pm 0.026$</td>
<td>$\pm 0.026$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>$+0.245VPT$</td>
<td>$+0.390$</td>
<td>$+0.620$</td>
<td>$+0.658$</td>
<td>$+0.658$</td>
<td>$+0.658$</td>
</tr>
<tr>
<td>$\pm 0.005$</td>
<td>$\pm 0.008$</td>
<td>$\pm 0.008$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.005$</td>
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</tr>
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3. COLOR OF THE SUN

Many attempts have been made to determine the color indices of the Sun and reviews of problems related to this determination are also numerous! One of the latest is that of Gray (1992). The $B - V$ values for the Sun are spread between 0.62 and 0.68!
Taylor (1994) has pointed out the existence of a wavelength boundary: the $H\beta$ and $H\alpha$ lines yield a value near 0.63, while the spectroscopy at wavelengths shortward of $H\beta$ yields a value near 0.66. To quote Taylor, “The Balmer-line derivations are largely blan- keting insensitive, so for the present, it seems defensible to assume that the Balmer-line result is correct and that its short-wavelength counterparts are affected by some unknown property of solar blan- keting.” Taylor has obtained $(R-I)_\odot = 0.331$ in the Cousins system and $(B-V)_\odot = 0.633$.

Gray (1995) disagrees with this assumption. In a study based on line-depth measurements in the red, he finds for $(R-I)_\odot$ and $(B-V)_\odot$ 0.338 and 0.648, respectively. The $R-I$ value is identical to Taylor’s value but the $B-V$ value is exactly midway between Taylor’s two camps! We can remark that the previous result of Gray (1992) was slightly redder, i.e. $(B-V)_\odot = 0.656$.

Straizys & Valiauga (1994) have determined the color indices of the Sun in the Vilnius and $UBV$ systems by using numerical convolution of the solar irradiance function and the spectral response functions of both systems. The authors find a $(Y-V)_\odot$ of 0.54 and a $(B-V)_\odot$ of 0.63. Thanks to relations established by Meylan & Hauck (1981), the $(Y-V)_\odot$ value gives a $(B2-V1)_\odot$ of 0.358, while a $(B-V)_\odot$ of 0.63 leads to a $(B2-V1)_\odot$ of 0.377. Thus the solar values in the Vilnius system appear to be very blue! However, that does not invalidate Straizys and Valiauga’s conclusion that color indices of the Sun in the Vilnius photometric system are in accordance with a spectral type of G2 V.

The mean value of $B2-V1$ for the G2 V stars is 0.365 (Hauck 1993), in good agreement with the result from the Vilnius system. If we use the relation $\theta_{\text{eff}}$ vs $B2-V1$ given in Table 1 to derive a $(B2-V1)_\odot$ value, we obtain for the solar $T_{\text{eff}}$ of 5791 K, given by Gray (1995), a value of $(B2-V1)_\odot = 0.370$, also in a good agreement with the G2 V MK type. This value is also in a good agreement with that derived from the $(R-I)_\odot$ value of Taylor (1994). Gray mentions that the temperature of the Sun is close to that of HR 8314, 16 CygA, 26 Dra and π¹ UMa. The mean $B2-V1$ value of these four stars is 0.361 ± 0.024. On this basis, we can adopt $(B2-V1)_\odot = 0.370$.

To compare this value with a solar value derived in other sys- tems, we can use the relations given by Meylan & Hauck (1981). $B2-V1 = 0.370$ corresponds to $(R-I)_C = 0.325$, $B-V = 0.62$ and $Y-V = 0.548$. Since Meylan and Hauck give a relation for $R-I$ of Johnson, we have used a relation given by Bessel (1979) to transform
(R - I)_j into (R - I)_C. Thus the (B2 - V1)⊙ value we propose is in good agreement with the bluest obtained in some other systems.

4. CALIBRATION OF THE GENEVA SYSTEM FOR B TO G STARS IN TERMS OF T_{eff}, \log g and [M/H]

The first use of grids of models to derive T_{eff}, \log g and [M/H] was made a quarter of a century ago by Philip & Releya (1979) for the Strömgren system. Since that time many calibrations, based mainly on the Kurucz models, have been proposed. In a work in preparation, Künzli & North (hereafter KN95) use the new atmosphere models (Kurucz 1991, 1993) and a larger sample of standard stars, especially for metallicity, to revise the previous calibration made by NN90 for B-type stars and by KN90 for mid-A to mid-G stars in the Geneva system. In addition, Künzli and North have defined two new parameters, \( pT \) and \( pG \), which are sensitive to effective temperature and surface gravity, respectively. They are the Geneva equivalents of Strömgren’s \( a_9 \) and \( r \) parameters and allow to fill the gap which existed between the two calibrations for the early A-type stars.

4.1. B-type stars

For hot stars, Künzli and North use the reddening-free parameters \( X \) and \( Y \) defined by Cramer & Maeder (1979) which have the optimum efficiency for determining the temperature and gravity, respectively. The standard stars are roughly the same as those used in the paper NN90. The stars with a known \( T_{eff} \) are taken from Code et al. (1976), Lanz (1987) and Leggett et al. (1986) and those with a known \( \log g \) are eclipsing binaries or nearby stars with a reliable surface gravity, as well as members of the Orion association whose \( \log g \) is given by the internal structure models of Schaller et al. (1992).

The rms scatter of the difference between the interpolated and fundamental temperature is 386 K for \( T_{eff} \leq 21 000 \) K to 1388 K for \( T_{eff} > 21 000 \) K. There is a zero-point shift of 73 K, essentially due to hot stars which are weighted differently by using \( \theta_{eff} \) instead of \( T_{eff} \) to define the correction. The calibration of NN90 presented a zero-point shift of about 180 K. The rms scatter of the difference between the interpolated and fundamental \( \log g \) is only \( \sigma_{res} = 0.105 \) dex.
4.2. The intermediate stars

For this temperature range (8500–11 000 K), Künzli and North use $pT$ and $pG$, which are defined in a similar way as $a_0$ and $r$. They obtain:

$$
pT = B2 - V1 + 0.1X + 0.0635(Y - 0.2d) - 0.006
$$
$$
pG = Y - 0.2d + 1.1(B2 - V1 + 0.1X) + 0.31
$$

where $X$ and $Y$ are the reddening-free parameters of Cramer & Maeder (1979), $B2 - V1$ is the temperature parameter for intermediate and cool stars and $d$ is the reddening-free parameter measuring the Balmer jump. As $pT$ and $pG$ depend on interstellar reddening, because of the presence of $B2 - V1$, we have to correct these parameters by the formula:

$$
pT_0 = pT - E_{B2-V1}
$$
$$
pG_0 = pG - 1.1E_{B2-V1}
$$

For determination of $T_{\text{eff}}$, Künzli and North took the standard stars from the papers cited in the previous section (for B-type stars) and also some stars from Blackwell et al. (1991, 1994). The standard stars for log $g$ are the eclipsing binaries listed by Moon & Dworetzky (1985) and the stars of the Orion association, IC 2391 and the Pleiades.

The rms scatter of the difference between the interpolated and fundamental values is $\sigma_{\text{res}} = 197$ K for temperature and $\sigma_{\text{res}} = 0.135$ dex for log $g$.

4.3. Late A to mid-G stars

The $B2 - V1$ color index is used as a temperature indicator, the reddening-free $d$ parameter as a gravity indicator and $m_2$ as a metallicity indicator. As standards of temperature, Künzli and North use essentially the stars of Blackwell et al. (1991, 1994) which form a homogeneous sample. They use the stars of the Hyades and of IC 2391 as the surface gravity standards. For metallicity, they take the numerous F and G stars which have empirical surface gravities derived from Strömgren photometry and the precise and homogeneous
element abundances determined by Edvardsson et al. (1993). These metallicity standards are also used as a gravity reference even if they are not, strictly speaking, standards for this parameter. They allow to show a strong metallicity dependence of the correction in gravity for the cooler stars. Künzli and North also show that the correction in metallicity is not only dependent on the effective temperature but also on the metallicity itself.

The rms scatter of the difference between the interpolated and fundamental values are $\sigma_{res} = 0.16$ dex for log $g$ and $\sigma_{res} = 0.093$ dex for metallicity.

The drawback of this calibration is a discontinuity which appears in the Kurucz models in the $d$ vs $B2 - V1$ diagram. It distorts the iso-log $g$ lines for $T_{eff} = 8000$ K at high gravity and $T_{eff} = 6500$ K at low gravity. The origin of this discontinuity is not physical, as shown by North et al. (1994). Castelli (1995) managed to trace the bug in Kurucz's ATLAS9 code, and new models are now being computed. The discontinuity made the correction in gravity very difficult, and for this temperature range, the present correction in log $g$ applies only to unevolved stars. The new atmosphere models will be available within a few months, and then the calibration for cool stars will be revised.

5. COMPARISON BETWEEN THE EMPIRICAL AND THE KÜNZLI AND NORTH CALIBRATION

Using their calibration, Künzli and North have estimated temperatures of the 177 stars, used to define the completely empirical relation between $B2 - V1$ and $\theta_{eff}$ (see Section 2), and compared them with the fundamental values. For their calibration, the rms scatter of the difference between the interpolated and fundamental $\theta_{eff}$ is about $\sigma_{res} = 0.013$, while it is $\sigma_{res} = 0.014$ if we use the linear regression given in Section 2. This latter method gives a more accurate $T_{eff}$ value for $B2 - V1 \geq 0$ ($T_{eff} \leq 8000$), but for the smaller values of $B2 - V1$, $X$ and $pT$ are better, being more sensitive than $B2 - V1$ for hot and intermediate stars, respectively. These comments are summarized in Table 2.

6. DETERMINATION OF $T_{eff}$ FOR THE CP STARS

Hauck & North (1993) have considered the determination of $T_{eff}$ for various types of chemically peculiar stars. Since we propose here
the improved ways for determining the effective temperature, it was necessary to reconsider the results of this paper and to check the validity of our new calibrations.

First, we have considered the validity of the Künzli and North calibration for the hottest CP2 stars given in the paper of Hauck & North (1993). As mentioned by Stepien & Dominiczak (1989), the ultraviolet fluxes of these stars are weaker than those of normal stars with a similar visual energy distribution and therefore the effective temperature deduced from the visual part of the spectrum is overestimated. Hauck and North have proposed a linear relation to take this effect into account by correcting the $T_{\text{eff}}$ value obtained by NN90. Due to the new grids of models and a new treatment of these grids to calibrate the photometric parameters, this relation is, of course, no longer valid. The new relation, based on KN95, is

$$T_{\text{eff}} = -230 + 0.941 \, T_{\text{eff}}(K,N95)$$

with a coefficient correlation of 0.97.

For this kind of star, there is a blocking effect in the region of the $V1$ filter and, as a result, both $B2 - V1$ and $pT$ are too blue and cannot be used as temperature parameters. For instance, the effective temperature of HD 192678, deduced from $pT$ and $pG$, is 10 924 K; after correction by the formula given above, it is 10 077 K. These values are too high in comparison with the value of 9000 K given in the literature. Thus, for the coolest CP2 stars we have to use the relation between $T_{\text{eff}}$ and $B2 - G$ given in Hauck & North (1993).

For the CP1 (Am), CP3 (HgMn) and CP4 (He-weak) stars we can use the values obtained with the new calibration of Künzli and North. For the CP1 stars we can also use the relation between $\theta_{\text{eff}}$ and $B2 - V1$ given in Table 1.
Concerning the $\lambda$ Bootis stars, we have tried to use the Künzli and North calibration which gives good results for the hottest stars, but it is not the case for the coolest ones. The small metal deficiency leads to a bad choice of a grid, and thus we obtain too large values for $T_{\text{eff}}$ and $\log g$.

7. Conclusions

We have presented above two ways of determining the effective temperature from photometric data. These ways have different ranges of application. The relations given in Table 1 allow us to estimate rapidly $T_{\text{eff}}$ but only for unreddened main-sequence stars, while the method used by Künzli and North takes the luminosity effect into account and is valid both for dwarfs and giants. Furthermore, this method allows determination of $\log g$ and of $[\text{M}/\text{H}]$. In addition, for the stars hotter than 11 000 K this method does not depend on interstellar reddening.

The advantages of this new calibration (KN95) over the NN90 and KN90 are:
- the possibility to determine the physical parameters of intermediate stars,
- the possibility to estimate the physical parameters of metallic-line stars, due to disappearance of the ambiguity in the $m_2$ vs $B2 - V1$ diagram (see KN90),
- a more reliable estimate for the metallicity for cool stars, thanks to the numerous metallicity standards.

Concerning the chemically peculiar stars, the conclusions of Hauck & North (1993) must be slightly modified in the case of the CP1 stars. For $B2 - V1$, we can use the relation from Table 1 and, in addition, the KN95 calibration. For the CP2 stars, a correction must always be applied and for the CP3 and CP4 stars we can directly use the KN95 calibration. Unfortunately, the calibration of Künzli and North is not valid for the $\lambda$ Bootis stars.

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