

An empirical temperature calibration for the Δa photometric system^{*,**}

I. The B-type stars

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ABSTRACT

We establish an empirical effective temperature calibration of main sequence, luminosity class V to III B-type stars for the Δa photometric system which was originally developed to detect magnetic chemically peculiar objects of the upper main sequence (early B-type to early F-type) at 5200 Å. However, this system provides the index $(g_1 - y)$ which shows an excellent correlation with $(B - V)$ as well as $(b - y)$ and can be used as an indicator of the effective temperature. This is supplemented by a very accurate color-magnitude diagram, y or V versus $(g_1 - y)$, which can be used, for example, to determine the reddening, distance and age of an open cluster. This makes the Δa photometric system an excellent tool to investigate the Hertzsprung-Russell-Diagram (HRD) in more detail. Using the reddening-free parameters and already established calibrations within the Strömgren $uvby\beta$, Geneva 7-color and Johnson UBV systems, a polynomial fit of third degree for the averaged effective temperatures to the individual $(g_1 - y)_0$ values was derived. For this purpose, data from the literature as well as new observations were taken resulting in 225 suitable bright normal B-type objects. The statistical mean of the error for this sample is 238 K which is sufficient to investigate the HRD of distant galactic open clusters as well as extragalactic aggregates in the future.

Key words. stars: chemically peculiar – stars: early-type – techniques: photometric

1. Introduction

One of the most important observational diagnostic tools of astrophysics is the Hertzsprung-Russell-Diagram (HRD) allowing the study of the correlation between the effective temperature and the absolute magnitude (or luminosity) of astronomical objects. Virtually all stellar astrophysical models are tested according to the HRD.

The absolute magnitudes of stellar objects can be derived directly via parallax measurements, appropriate photometric indices (e.g. Strömgren β) or on a statistical basis in open and globular clusters. The errors of such combined estimates are already rather small (<0.1 mag).

The photometric calibration of effective temperatures is still a very tricky business with several pit falls. The applied calibrations depend on the investigated spectral range and the physics introduced in the models. Smalley & Kupka (1997) give an excellent overview of how convection, for example,

can lead to significant deviations for A-type and cooler stars. The statistical calibration of effective temperatures via photometric indices has been done since the introduction of photometric systems (Johnson 1958; Strömgren 1966, and references therein). The applied calibrations have become more precise and sophisticated as the theoretical stellar atmospheres and the input physics became more realistic. Furthermore, the amount of available photometric and spectroscopic data is increasing.

Almost thirty years ago, Maitzen (1976) introduced the narrow-band, three filter Δa photometric system in order to investigate the flux depression at 5200 Å which is very likely enhanced by the effects of magnetic radiative transport phenomena within magnetic chemically peculiar stars of the upper main sequence (Kupka et al. 2003). Since then, more than two dozen papers have presented photoelectric and CCD results for galactic field stars, open clusters as well as the Large Magellanic Cloud in the relevant spectral range from early B to early F-type (Maitzen 1993; Paunzen et al. 2003; Paunzen et al. 2005a,b). The Δa system is based on the three narrow band filters g_1 , g_2 and y from which two indices are calculated $(g_1 - y)$ and $a = g_2 - (g_1 + y)/2$. An a versus $(g_1 - y)$ diagram can easily detect magnetic chemically peculiar stars (Sect. 2.1) whereas the $(g_1 - y)$ index shows an excellent correlation with $(B - V)$

* Based on observations at the Leopold-Figl Observatory for Astrophysics, University of Vienna.

** Table 2 of 225 objects is 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/444/941>

as well as $(b-y)$ and can be used as an indicator of the effective temperature. The main result of detecting peculiar stars is supplemented by a very accurate color-magnitude diagram, y or V versus $(g_1 - y)$, which can be used, for example, to determine the reddening, distance and age of an open cluster (Claret et al. 2003).

In the last few years, much theoretical effort was made to explain the results of the Δa photometric system in astrophysical terms. Kupka et al. (2003, 2004) established a synthetic photometric Δa system and confirm the observed dependency of the a index as a function of various colour indices sensitive to the effective temperature and surface gravity variations within the Strömgen $uvby\beta$ and Johnson UBV photometric systems using fluxes from ATLAS9 model atmospheres as well as most recent atomic line data together with opacity distribution function for individual chemical compositions. Furthermore, Claret et al. (2003) calculated isochrones, taking into account mass loss during the main sequence evolution, for the Δa photometric system on the basis of modern equations of state including partial ionization through Saha's approximation, the pressure of gas and radiation as well as the equations for degenerate electrons.

We now propose to establish an empirical effective temperature calibration for main sequence (luminosity class V to III) stars in terms of $(g_1 - y)_0$. This is most important in studying very distant galactic open clusters and extragalactic systems for which, in general, no photometric data within a standard system are available. The absolute magnitudes and thus luminosities can be easily estimated via y and the appropriate isochrones. In this first of two papers we deal with B-type stars because: 1) there are reddening-free parameters available allowing us to check the dereddening procedure for $(g_1 - y)$ and 2) the stellar interiors for these objects are very similar over the whole spectral range. The second paper will deal with A-type to early F-type objects for which the calibration has to be more sophisticated due to the increase of line blanketing and luminosity effects.

For the empirical temperature calibration, we use a homogeneous sample of bright ($V < 7$ mag), apparently normal type objects from the literature. But we also present new observations for 99 B-type objects that are included in our analysis. In total, 225 stars were used to derive effective temperatures within the Strömgen $uvby\beta$, Geneva 7-color and Johnson UBV systems which were then applied to establish a calibration in terms of $(g_1 - y)_0$. The final calibration is valid for effective temperatures between 33 000 and 10 000 K and yields a statistical mean error of 238 K for the whole spectral range.

2. Sample of program stars

We have selected “normal” B-type objects fulfilling the following criteria:

- classification as B-type, luminosity class V to III;
- no significantly deviating Δa values, i.e. ± 10 mmag;
- not listed in the catalogue of Ap and Am stars by Renson et al. (1991);

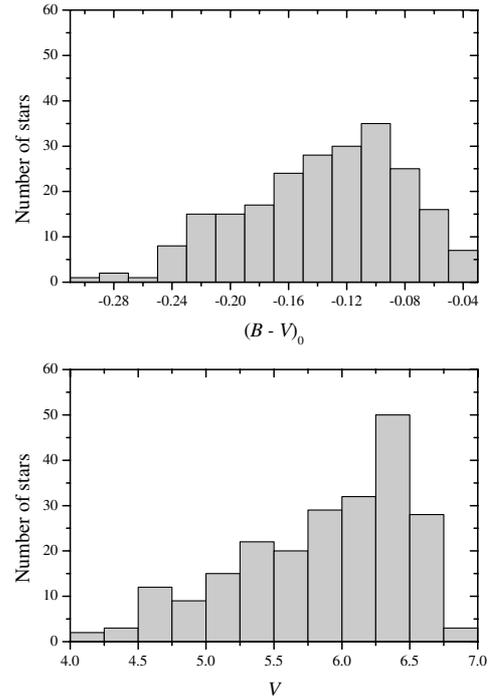


Fig. 1. The distribution of Johnson V and $(B - V)_0$, see Sect. 3, for our sample of 225 main sequence B-type objects.

- available data within the Johnson, Strömgen, Geneva and Δa photometric system.

Binary systems of all kinds and high $v \sin i$ stars were a priori not excluded. The Johnson, Geneva and Strömgen colors were taken from the General Catalogue of Photometric Data (GCPD, Mermilliod et al. 1997). The Δa photometry is from Vogt et al. (1998) with additional measurements as described in Sect. 2.1. The $(g_1 - y)$ data published by Vogt et al. (1998; see Table 4 therein) are not available in electronic form but were kindly provided by the authors.

The following stars have inconsistent photometric measurements and were therefore excluded: HR 345, HR 1375, HR 1617, HR 2870, HR 3470, HR 8854 and HR 8887. From the available data, we are not able to decide if measurement errors, a wrong identification or a binary nature causes these discrepancies.

The final list (Table 2) comprises 225 objects that satisfy our criteria. The complete list of program stars is only available in electronic form at the CDS or upon request from the first author. This table includes the identification of objects, the $(g_1 - y)_0$, $(B - V)_0$, X and $(u - b)$ values, V magnitudes, effective temperature with the corresponding errors (Fig. 4 and Sect. 4), $v \sin i$ values and spectral types, respectively.

The distribution of Johnson V and $(B - V)_0$ for our sample is shown in Fig. 1 (see Sect. 3 for the estimation of the reddening). The peak of the $(B - V)_0$ values is at about -0.10 mag (B8, Table 1) which reflects the coincidence that the chemically peculiar stars which were measured within the Δa photometric system also peak at this effective temperature (Schneider 1993) and the normal-type objects, used in this investigation, served as standard stars.

Table 1. Mean relation between the effective temperature and $(B-V)_0$, $(u-b)$, X as well as $(g_1 - y)_0$ for B-type, luminosity class V to III objects.

Spec.	T_{eff}	$(B-V)_0$	$(u-b)$	X	$(g_1 - y)_0$
B0	32 000	-0.292	0.020	0.060	-0.102
B1	26 000	-0.257	0.151	0.210	-0.090
B2	23 000	-0.236	0.239	0.310	-0.082
B3	18 000	-0.189	0.448	0.557	-0.065
B5	16 000	-0.164	0.570	0.705	-0.056
B6	14 500	-0.142	0.688	0.850	-0.049
B7	13 500	-0.125	0.785	0.970	-0.043
B8	12 500	-0.105	0.901	1.113	-0.036
B9	10 800	-0.064	1.155	1.411	-0.021
(A0)	9800	-0.031	1.338	1.603	-0.011

2.1. Additional observations

We observed a sub-sample of the bright B-type objects listed in Cowley (1972) in the Δa photometric system. She determined MK spectral types for all stars classified as B8 in the Bright Star Catalogue north of -20° in order to investigate the appearance of CP objects. The results of the Δa photometry are discussed in Sect. 2.2.

These photoelectric measurements in the Δa photometric system were carried out by one of us (A. Schnell) at the 60 cm telescope of the Leopold-Figl-Observatory on Mitter-Schöpf (880 m above sea level, 40 km southwest of Vienna). The telescope was equipped with a single channel photometer and a thermoelectrically cooled EMI 9844A photomultiplier using a diaphragm of $35''$ (only exceptionally $47''$). The integration times per filter ranged from 15 to 25 s. The g_1 and g_2 filters are identical to those described in Maitzen & Floquet (1981) while the third one is a conventional Strömberg y filter (Crawford 1978). The observations were obtained over 26 nights between October 1991 and August 1996.

The photometric measurements were reduced in the usual way, correcting for airmass and extinction. The program stars were observed continuously over the years (up to 35 times) which allows us to correct for different zero points and instrumental effects. The errors of the means for a and $(g_1 - y)$ are in the range between 1 and 7 mmag, with a “mean error” of 3 mmag only. This proves the high quality of the individual measurements and supports the reduction process.

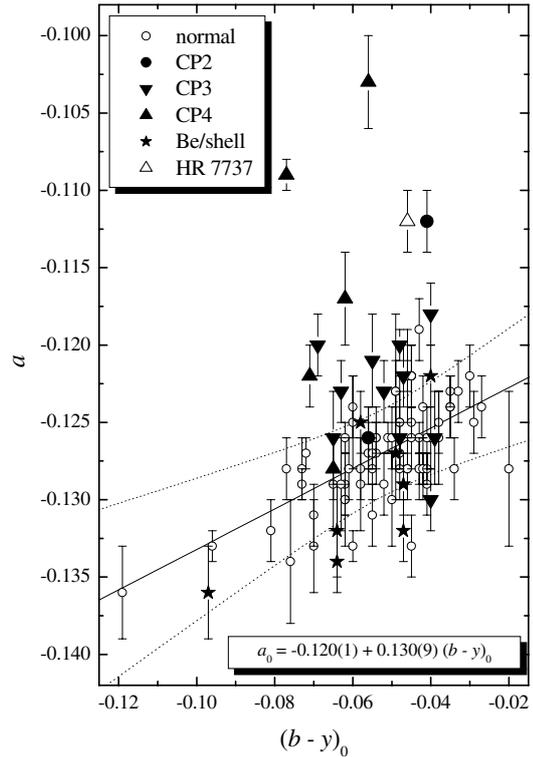
Three stars (HR 1363, HR 1617 and HR 8821) are in common with the paper by Vogt et al. (1998). The measurements of $(g_1 - y)$ and a agree within 2 mmag for these objects.

2.2. Δa photometry

The Δa intermediate band photometric system samples the depth of the 5200 \AA flux depression by comparing the flux at the center ($\lambda_C = 5210 \text{ \AA}$, $FWHM = 120 \text{ \AA}$, g_2), with the adjacent regions (5020 \AA , 120 \AA , g_1 and 5500 \AA , 230 \AA , y). The respective index was introduced as:

$$a = g_2 - (g_1 + y)/2. \quad (1)$$

It is optimized to detect magnetic chemically peculiar (CP2 and CP4) stars, but is also capable of detecting a certain percentage

**Fig. 2.** Observed a versus $(b - y)_0$ diagram for our sample of B-type objects. The solid line is the normality line whereas the dotted lines are the confidence intervals corresponding to 99.9%.

of non-magnetic CP1 and CP3 objects (Paunzen et al. 2005a). The nomenclature of the different CP groups is according to Preston (1974). The group of classical Be/shell and metal-weak stars (Paunzen et al. 2002) can be investigated. Since a is dependant on the temperature, the intrinsic peculiarity index had to be defined as

$$\Delta a = a - a_0[(b - y); (B - V); (g_1 - y)] \quad (2)$$

i.e. the difference between the individual a -values and those of non-peculiar stars for the same color. The locus of the a_0 -values has been called the normality line.

Figure 2 shows the results of our observations. We indicate the different CP groups and known Be/shell stars with individual symbols. The normality line was calculated using $(b - y)_0$ of all “normal” type objects, i.e. those not included in the catalogue of peculiar objects by Renson et al. (1991):

$$a_0 = -0.120(1) + 0.130(9) \cdot (b - y)_0. \quad (3)$$

Known binary system were a priori not excluded. The 3σ limit around the normality line is between 3 and 6 mmag.

As expected (Paunzen et al. 2005a), the magnetic CP stars show the most significant positive Δa values. In general, CP3 stars tend to lie above the normality line whereas Be/shell stars are below it. There are two exceptions, HR 6664 and HR 7721 which might be in their shell phases for which positive Δa values are expected (Maitzen & Pavlovski 1987). We note that the two apparently magnetic CP stars HR 481 (B8 IIIp Si) and HR 7401 (B8 IV He-weak) show no significant positive Δa values and should therefore be considered

as misclassified. Only one apparently normal type object, HR 7737 (B9 IV-V, $\Delta\alpha = +14$ mmmag), deviates significantly from the normality line. This star is a known spectroscopic binary system with unresolved components of 7.3 and 7.5 mag (combined magnitude: 6.79 mag; Germain et al. 1999). This seems to influence the photometric values in the sense that it mimics a peculiar object.

3. The estimation of the reddening

The reddening for B-type stars within the solar neighborhood is, in general, estimated using photometric calibrations in the Strömgren $uvby\beta$ (Crawford 1978) and the Q parameter within the Johnson UBV system (Johnson 1958). These methods are only based on photometric indices and do not take into account any distance estimates via parallax measurements.

The reddening in the Strömgren $uvby\beta$ photometric system is based on the comparison of the reddened $(b - y)$ and c_1 with the unreddened $(u - b)$ and β indices (Crawford 1978). The procedure of the Q method is straightforward and has been described in detail by Johnson (1958). Here are the basic correlations from this reference:

$$Q = (U - B) - 0.72 \cdot (B - V) - 0.05 \cdot (B - V)^2 \quad (4)$$

$$E(B - V) = (B - V) - 0.332 \cdot Q. \quad (5)$$

Throughout this paper, we use the following relation: $A_V = 3.1E(B - V) = 4.3E(b - y)$. Figure 3 shows the comparison of the derived A_V values for both methods. The agreement is very good indicating that photometric measurements within the Johnson and Strömgren systems are consistent. Otherwise, a severe deviation from the linear correlation would occur. The distribution of the adopted values (mean of both methods) shows that most of the program stars have an absorption which is below 0.1 mag.

However, we also derived the interstellar reddening using the model proposed by Chen et al. (1998) who combined galactic reddening maps, which are derived from open clusters as well as from galactic field stars with published empirical reddening laws from the literature. As input parameters, the galactic coordinates and the distance from the Sun (i.e. derived from Hipparcos parallax measurements) are needed. The error of the latter severely influences the error of the derived reddening. For program stars with distance errors smaller than 15%, a very good agreement with the results of the photometric calibrations has been found.

4. The calibration of the effective temperature

To reach our final goal, an empirical effective temperature calibration of $(g_1 - y)_0$ for B-type stars, we calibrated this astrophysical parameter for our sample using the published calibrations in the Geneva, Strömgren and Johnson photometric systems. Those calibrations are derived independently of each other which allows us to detect possible inconsistencies due to, for example, spectroscopic binary nature. We will now discuss the applied calibrations in more detail.

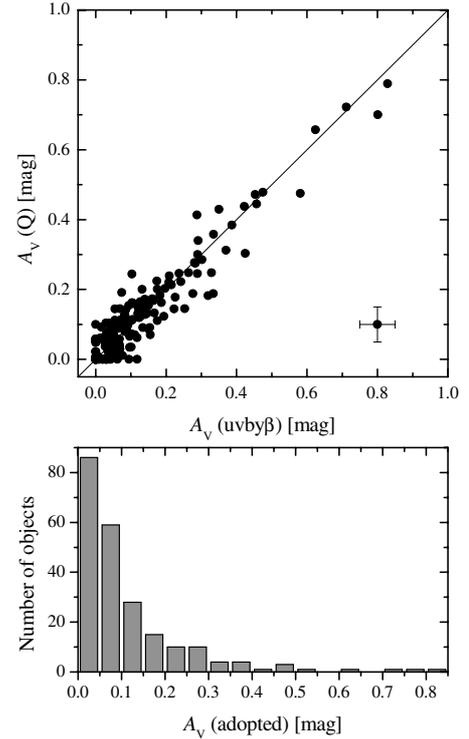


Fig. 3. The correlation of the absorption A_V estimated from the Strömgren $uvby\beta$ and the Q method (upper panel). The statistical error for both methods is indicated with the symbol in the lower left corner. The distribution of the adopted A_V values is shown in the lower panel.

Geneva system: detailed calibrations were published by Cramer (1984, 1999) and Künzli et al. (1997). They are all based on the reddening-free parameters X and Y which are valid for spectral types hotter than approximately A0. The results are therefore independent of the estimation of A_V for our program stars.

Strömgren system: the most recent and widely used reference is Napiwotzki et al. (1993). For stars hotter than 11 000 K, the unreddened $[u - b]$ and for cooler B-type objects, the a_0 index are used to calibrate the effective temperature. The latter is not reddening free.

Johnson system: we calculated the Q values for luminosity class III and V objects according to the Tables listed by Schmidt-Kaler (1982). The $(B - V)_0$ values for those luminosity classes were transformed into effective temperatures using the results by Code et al. (1976, Table 7). As final correlation we derived a polynomial fit for dependence of the effective temperature on Q as

$$\log T_{\text{eff}} = 3.983(5) - 0.31(3) \cdot Q + 0.33(3) \cdot Q^2 \quad (6)$$

which is valid for all B-type, luminosity class III to V objects. This relation has to be treated as an averaged statistical result. If one uses the individual measurements from Code et al. (1976) for the ten stars that are in the relevant effective temperature and luminosity regime (Sect. 2), the following relation is derived:

$$\log T_{\text{eff}} = 3.994(29) - 0.25(15) \cdot Q + 0.38(15) \cdot Q^2. \quad (7)$$

A comparison of these two relations give $\Delta T_{\text{eff}} = +141(147)$ K.

The individual effective temperature values within each photometric system were first checked for their intrinsic consistency and then averaged. These final values together with the standard deviations of the means are listed in the electronically available table. No outliers in any photometric system were detected.

5. The calibration procedure for the Δa photometric system

The starting point is one set of $(g_1 - y)$ measurements, for example, of an open cluster. The zero points of data sets from different instruments and filter systems may vary. An overview of all currently used Δa filters is listed in Paunzen et al. (2005a, Table 2). They have also investigated the effects on the absolute photometric values, which are in the range of the observational errors for the photoelectric as well as CCD technique (a few mmags only).

The reddening coefficient k of the relation $E(g_1 - y) = k \cdot E(B - V)$ was estimated which can then be transformed to other photometric systems. We derived the correlation coefficients for $(B - V)$ versus $(g_1 - y)$ and then applied these coefficients to $(B - V)_0$ using the estimated reddening for each individual star as well as $(g_1 - y)$ to derive $(g_1 - y)_0$ and thus $E(g_1 - y)$. Our final value, $k = 0.39(2)$ is in excellent agreement with the values derived from open cluster data (see Maitzen 1993, and references therein).

We then dereddened the individual indices and established the linear correlations between those parameters. We define a “standard $(g_1 - y)$ system” which is set to $(B - V)_0 = (b - y)_0 = (g_1 - y)_0 = 0$ as follows:

$$(B - V)_0 = -1.413(7) + 2.82(1) \cdot (g_1 - y)_0 \quad (8)$$

$$(b - y)_0 = -0.664(5) + 1.333(9) \cdot (g_1 - y)_0. \quad (9)$$

This system will also be kept for the second paper.

Figure 4 shows the relation between the effective temperature and the different temperature sensitive indices for the four investigated photometric systems. The temperatures range from approximately 33 000 to 10 000 K which covers the main sequence B-type stars. However, there are only four stars with temperatures hotter than 25 000 K (B1.5 V). We checked the temperature relations with and without those four data points and found no significant differences. Our final calibrations are:

$$\log T_{\text{eff}} = +4.520(3) - 0.754(15) \cdot (u - b) + 0.413(2) \cdot (u - b)^2 - 0.108(11) \cdot (u - b)^3 \quad (10)$$

$$= +4.546(3) - 0.698(13) \cdot X + 0.367(17) \cdot X^2 - 0.092(6) \cdot X^3 \quad (11)$$

$$= +3.956(5) - 1.04(7) \cdot (B - V)_0 + 2.89(24) \cdot (B - V)_0^2 \quad (12)$$

$$= +3.909(7) - 6.47(48) \cdot (g_1 - y)_0 - 47(9) \cdot (g_1 - y)_0^2 - 425(60) \cdot (g_1 - y)_0^3 \quad (13)$$

with the mean of the errors for the whole sample of $\Delta T_{\text{eff}}[(u - b), X, (B - V)_0, (g_1 - y)_0] = [157, 146, 333, 238 \text{ K}]$. These are statistical errors and should be treated as such. The mean relations between the effective temperature and $(B - V)_0$, $(u - b)$,

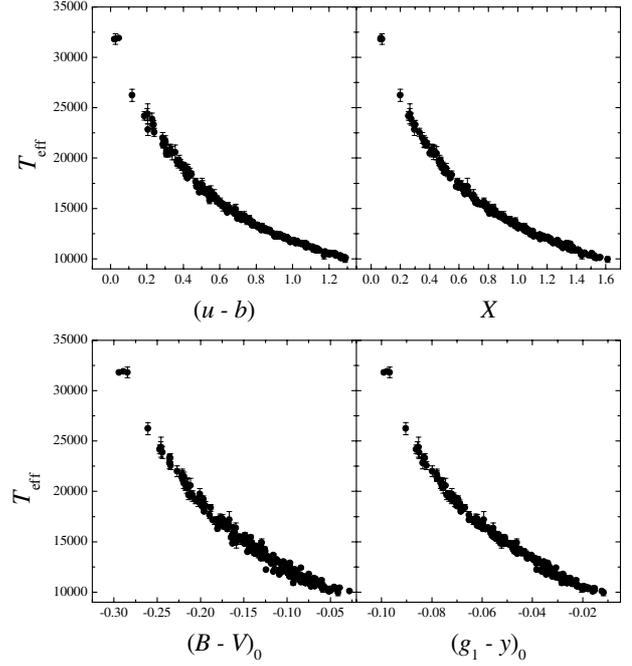


Fig. 4. Mean relation between the effective temperature and $(u - b)$, X , $(B - V)_0$ as well as $(g_1 - y)_0$ for B-type, luminosity class V to III objects.

X as well as $(g_1 - y)_0$ depending on spectral types are listed in Table 1. The agreement with standard values for those indices from the literature (Code et al. 1976; Crawford 1978; Cramer 1999) is excellent.

It is known that high rotational velocities can alter the photometric indices significantly (Collins et al. 1991). The break-up velocity ranges from about 540 to 400 km s^{-1} for B0 to B9 stars (Townsend et al. 2004). However, the inclination i is the crucial point for the comparison of these models with observations. The prototype A0 star Vega has a very low $v \sin i$ of 22 km s^{-1} but an equatorial velocity of 160 km s^{-1} (Hill et al. 2004). We searched in the papers by Glebocki & Stawikowski (2000) and Abt et al. (2002) for available $v \sin i$ values for our program stars, and averaged individual measurements from the different sources. In total, there are measurements for 175 stars of our sample available with the highest value of 390 km s^{-1} for HR 3502. Figure 5 shows the diagrams of $\Delta T_{\text{eff}} = T_{\text{eff}}(\text{orig}) - T_{\text{eff}}(\text{calib})$ versus $v \sin i$ for the different indices. There is no obvious correlation between these two parameters in any of the diagrams. The effect of the rotational velocity is therefore less significant than the precision of the method itself. Thus, the well-known alteration of stellar colors caused by high rotational velocities (Collins et al. 1991) cannot be distinguished from the overall statistical errors resulting from the calibration process.

The overall procedure of deriving the effective temperatures for main sequence B-type objects in the Δa photometric system should be:

- estimate the reddening, for example via isochrones for open cluster members;
- $E(g_1 - y) = 0.39 \cdot E(B - V)$;
- apply the reddening correction for all individual indices;

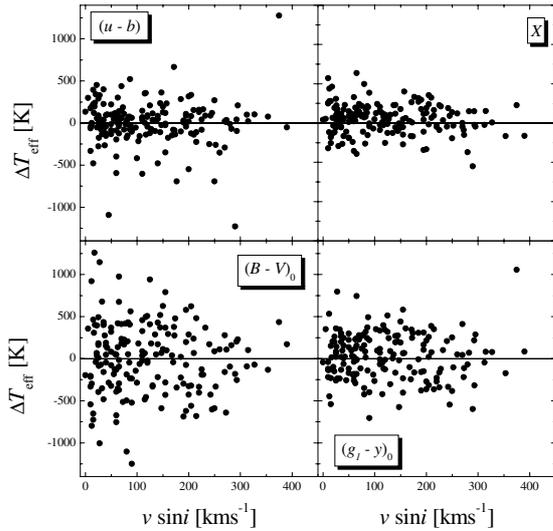


Fig. 5. No systematic correlation of ΔT_{eff} and the $v \sin i$ values were found for $(u - b)$, X , $(B - V)_0$ as well as $(g_1 - y)_0$.

- transform the $(g_1 - y)_0$ via the standard relations;
- check the intrinsic consistency of all available measurements according to the spectral type – effective temperature – photometric indices correlation;
- apply the effective temperature calibration.

The estimated effective temperature from the $\Delta\alpha$ system can in addition be compared with calibrated values from other photometric indices.

6. Conclusion and outlook

An empirical effective temperature calibration for the $\Delta\alpha$ photometric system for main sequence (luminosity class V to III) B-type stars was established. This system originally was developed to search for magnetic chemically peculiar objects of the upper main sequence. However, it also provides the temperature sensitive $(g_1 - y)$ index as well as y which can be used to determine the temperature and absolute magnitude (or luminosity) of a star. For this purpose, data from the literature as well as new observations were taken resulting in 225 suitably bright normal type objects. Known binary stars and high $v \sin i$ stars were a priori not excluded. All program stars were first dereddened and then calibrated using already established methods in the Strömgren $uvby\beta$, Geneva 7-color and Johnson UBV photometric systems. These calibrations are based on $(u - b)$, X and $(B - V)_0$, respectively.

The intrinsic consistency for the individual stars was checked and as final step, the averaged effective temperatures were calibrated in terms of $(g_1 - y)_0$ yielding a polynomial fit of third degree. The statistical mean of the error for the sample of 225 stars is 238 K which is very satisfactory and sufficient to investigate the HRD of distant galactic open clusters as well as extragalactic aggregates.

The second part of this series will investigate an empirical effective temperature calibration of A-type to early F-type objects for which the calibration has to be more sophisticated due

to the increase of line blanketing and luminosity effects without the availability of an independent reddening free parameter for the Johnson UBV and Geneva 7-color system.

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