Astron. Astrophys. 332, 643–650 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Be stars in open clusters

III. A *uvby*β calibration for the astrophysical parameters of Be stars

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Received 16 July 1997 / Accepted 17 December 1997

Abstract. We present linear relations between the equivalent widths of the Balmer lines of Be stars and the anomalies in the *uvby* photometric indices produced by continuum circumstellar emission. A similar relation exists when the emission in the Hβ line is measured through the photometric β index.

These relations have been used to elaborate an empirical calibration of the *uvby*β photometric system to determine the intrinsic colours and indices, the relevant astrophysical parameters and the absolute magnitude of the underlying B star, valid for Be stars of spectral types earlier than B5. The calibration is based on the study of 27 Be stars in 3 open clusters. The proposed calibration procedure allows the determination of the interstellar reddening with an accuracy of 0.033 mag. (rms) and the absolute magnitude with an accuracy of 0.7 mag.

Our calibration independently confirms the previously known result that Be stars of spectral types in the range B0-B5 are overluminous by a mean of 0.3 mag. with respect to their absorption-line counterparts of the same spectral type.

Key words: stars: fundamental parameters – techniques: photometric – stars: emission-line, Be – open clusters and associations: general

1. Introduction

The *uvby* and Hβ photometric systems, defined by Strömgren (1966) and Crawford & Mander (1966), were designed to measure fundamental spectral signatures in early- and intermediate-type stars. Their combined use is one of the most suitable photometric methods to determine temperatures, luminosity classes, absolute magnitudes and other stellar parameters of astrophysical interest.

In the case of Be stars, however, the usual techniques of *uvby*β calibration are not suitable. In their observed photometric indices, besides the contribution of photospheric emission and interstellar extinction, there is an additional emission contribution from a circumstellar envelope.

The main purpose of this work is to present a method to determine such intrinsic parameters from *uvby*β photometry. It has been shown by several authors (Dachs et al. 1986, 1988; Kaiser 1989) that the continuum emission of the circumstellar envelope is closely correlated with the equivalent width of the Balmer lines. Thus, by measuring the Balmer emission-line strengths, the underlying star contribution to the photometric indices can be decoupled from the circumstellar disk contribution, and then the usual *uvby*β calibrations can be applied. A preliminary exposition of this method is given by Fabregat & Reglero (1990), hereafter referred to as FR90.

In order to accurately determine the relationship between the circumstellar continuum emission and the emission in the Balmer lines, we have developed an observational programme of simultaneous *uvby*β photometry and Balmer line spectroscopy of Be stars in open clusters. The advantage of studying stars in clusters is that their intrinsic colours and distances can be inferred from the cluster parameters, and thus the anomalies in their photometric indices caused by the continuum emission from the envelope can be directly measured. The *uvby*β photometry is presented in Fabregat et al. (1996), hereafter referred to as Paper I. The Balmer line spectroscopy is presented in Torrejón et al. (1997), hereinafter Paper II.

2. Relationship between photometric anomalies and Balmer line equivalent widths

In Paper I we showed that Be stars occupy anomalous positions in the photometric diagrams, which can be explained in terms of the circumstellar continuum radiation contribution to the photometric indices. In the $M_V - (b-y)_0$ plane Be stars appear redder than the non emission B stars, due to the additional reddening caused by the hydrogen free-bound and free-free recombination in the circumstellar envelope. In the $M_V - c_0$ plane the earlier Be stars present lower c_0 values than absorption-line B stars, which is caused by emission in the Balmer discontinuity, while the later Be stars deviate towards higher c_0 values, indicating absorption in the Balmer discontinuity of circumstellar origin.

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Following FR90, we will denote $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$ the contribution of the circumstellar emission to the $(b-y)$ colour and c_1 index. The values of these circumstellar excesses can be directly measured for Be stars in open clusters. We consider the circumstellar excess value as the difference between the observed photometric index and the photometric index corresponding to the absorption-line B stars of the same absolute magnitude. The loci of the absorption-line B stars in the photometric M_V – $(b-y)_0$ and M_V – c_0 diagrams has been considered to be well represented by the cluster isochrones. In Fig. 1 we show graphically how the $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$ values are measured. The main source of error in the determination of the circumstellar excesses, in addition to the errors of the photometric measurements and the cluster reddening, is the assumption of the isochrone as being representative of the normal star positions. To estimate this error, we have computed the standard deviation of the differences between the positions of the absorption-line B stars and the isochrone, measured as explained in Fig. 1. The obtained values are 0.025 and 0.033 mag. for $(b-y)$ and c_1 respectively. We assume these values as the errors of our $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$ determinations.

It should be noted that with this approach we assume that there are not significant variations of the absolute magnitude of circumstellar origin. To check this assumption, in Fig. 2 we have plotted the excess in M_V for the Be stars in our sample against the Hα equivalent width. The M_V excess has been computed as the difference between the absolute magnitude derived from the observations and using the cluster reddening and distance modulus, and the mean M_V for the spectral type of each star. We have assumed the spectral types determined by Slettebak (1985). As it can be seen, no trend of absolute magnitude variation with the amount of circumstellar emission is apparent. On the other hand, Zorec & Briot (1991) have studied in depth the overluminosity effects produced by the presence of the circumstellar emission. They concluded that the mean M_V variation amounts between –0.5 and –0.1 mag., for spectral types between B0 and B5. As it can be seen in Fig. 1, this variation would introduce very small errors in the determination of $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$, well within the errors estimated in the above paragraph.

With the above precepts we have measured the $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$ values for all Be stars in the clusters h and χ Persei, NGC 663, Pleiades, NGC 2422 and α Persei for which *uvbyβ* photometry is given in Paper I. We have excluded stars 107 and 110 in NGC 663, because their peculiar position in the photometric diagrams makes the determination of the excesses very uncertain. We have also considered the cluster isochrones computed in Paper I.

The amount of circumstellar continuum emission is closely correlated with the equivalent widths of the Balmer emission lines (Dachs et al. 1986, 1988; Kaiser 1989). Thus, the circumstellar excesses in the photometric indices should be also correlated with the equivalent widths. We have determined these relations by comparing our values of $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$ with the Hα and Hβ equivalent widths presented in Paper II. In Paper I we have shown that Be stars earlier and later than B5 present different behavior in the photometric diagrams, showing $E^{\rm cs}(c_1)$ of opposite sign. In consequence, we have considered separately early and late Be stars.

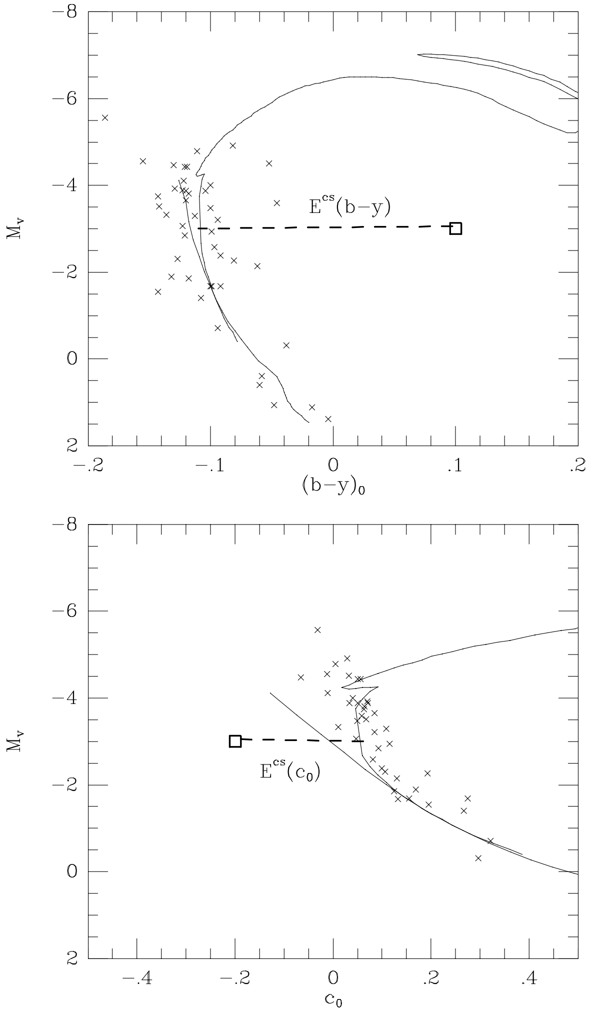

Fig. 1. Graphical interpretation of the $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$ photometric excesses for a given young open cluster. Lines represent the ZAMS and cluster isochrone, crosses the absorption-line stars and the open square a given Be star for which the photometric excesses are being measured. The cluster represented is h & χ Persei, and the photometric data are from Paper I.

For the late Be stars no clear relations are present between the photometric excesses and the equivalent widths. This may be caused by the small number of stars considered, only eight. Therefore we will restrict our study to Be stars earlier than B5, which implies that we will consider only stars in the clusters h and χ Persei and NGC 663. From this sample we obtain the following relations:

	σ	r	
$E^{\rm cs}(b-y) = -0.0014 W_{\rm e}({\rm H}\alpha) + 0.014$	0.043	0.61	(1)
$E^{\rm cs}(c_1) = 0.0019 W_{\rm e}({\rm H}\alpha) - 0.031$	0.038	0.77	(2)
$E^{\rm cs}(b-y) = -0.0086 W_{\rm e}({\rm H}\beta) + 0.042$	0.045	0.54	(3)

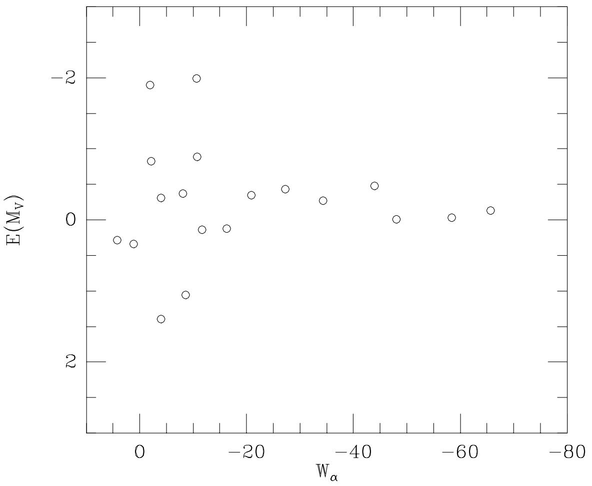

Fig. 2. Excess in the absolute visual magnitude versus the emission line strength.

$$E^{\rm cs}(c_1) = 0.0200 W_{\rm e}({\rm H}\beta) - 0.057 \qquad 0.030 \quad 0.91 \qquad (4)$$

where the equivalent widths, expressed in Å, are considered negative for emission lines. σ represents the standard deviation of the relation and r the correlation coefficient. These relations have been obtained with equivalent widths not corrected for photospheric absorption, as presented in Paper II. We have also computed the above relations for emission equivalent widths. To correct for photospheric absorption we have performed the following iterative procedure:

- We have used the above relations to compute the circumstellar excesses for each star, and corrected the photometric indices for circumstellar effects.
- With the corrected indices we have computed the $T_{\rm eff}$ and $\log g$ for each star, using the formulae given by Balona (1994) to interpolate in the grid of theoretical *uvby* indices computed by Lester et al. (1986).
- With these values we have computed the equivalent widths of the photospheric absorption lines by means of the Kurucz (1979) atmosphere models. The obtained values have been subtracted from the uncorrected equivalent widths. Doing this, we are adding to the measured emission line above the continuum the amount of emission filling-in the photospheric absorption line.
- We have computed new correlations, and repeated all the procedure until the result converges.

The final relations for corrected equivalent widths are the following:

$$\begin{array}{rlllr} & & \sigma & r & \\ E^{\rm cs}(b-y) = & -0.0015 W_{\rm e}({\rm H}\alpha) + 0.009 & 0.043 & 0.63 & (5) \\ E^{\rm cs}(c_1) = & 0.0019 W_{\rm e}({\rm H}\alpha) - 0.025 & 0.038 & 0.76 & (6) \\ E^{\rm cs}(b-y) = & -0.0085 W_{\rm e}({\rm H}\beta) + 0.019 & 0.045 & 0.53 & (7) \\ E^{\rm cs}(c_1) = & 0.0199 W_{\rm e}({\rm H}\beta) - 0.025 & 0.029 & 0.92 & (8) \end{array}$$

The slopes of the corrected relations remain practically unchanged with respect to the uncorrected ones. The only significant differences are in the zero points, which in the corrected equations are compatible with zero within the errors, as expected because in this last case we are comparing two effects produced by the presence of a circumstellar envelope. These relations are presented in Fig. 3. Eqs. (1) and (5) closely correspond to Eq. (39) in Dachs et al. (1988), which represents the relationship between the circmstellar excess in the $(B-V)$ colour and the Hα equivalent width, found by these authors.

From the σ and r coefficients of the above relations and from Fig. 3, the correlation between the photometric excesses and the equivalent widths is apparent. The correlation seems to be better for the Hβ equivalent width. This would mean that the region of the circumstellar disc in which the continuum emission contaminating the *uvby* indices arises is closer to the region in which the Hβ emission line is formed. This is expected from the fact that the wavelength of the Hβ line is closer to the *uvby* bandpasses.

If the Hβ equivalent width is closely correlated with the circumstellar continuum emission, the photometric β index has to be correlated as well. The β index is, by construction, linearly related to the Hβ equivalent width (Golay, 1974). Furthermore, Fabregat & Torrejón (1997) have shown that this linear relation is valid even for emission-line stars. Then we have also studied the correlation between the β index and the excesses in the photometric indices. As in the case of the spectroscopic equivalent widths, the value to be correlated with $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$ is not the β index, but the excess in the β index due to the circumstellar emission, which we will denote $\Delta\beta$. $\Delta\beta$ is defined as the difference between the observed β index and the β index of the underlying B star. The latter is not known *a priori*, and we have to estimate its value by means of an iterative procedure. As this discussion applies to a rather narrow range of spectral types, O9 to B5, we have considered a mean value for the β index in this spectral range, namely β = 2.63. We obtain a first approximation to the β excess as $\Delta\beta = \beta - 2.63$, where β is the observed value. Then we correlate these values with the photometric excesses, and obtain a first approximation to $E^{\rm cs}(b-y)$ and $E^{\rm cs}(c_1)$. With the latter value we obtain c_0 corrected from circumstellar effects, and from it we determine the β value of the underlying star -which we will denote β_* in order to avoid confusion with the observed β value -by means of the following relation

$$\beta_* = 2.620 + 0.2517 c_0 - 0.1400 c_0^2 + 0.1704 c_0^3 \qquad (9)$$

(Balona & Shobbrook, 1984). The β_* values obtained with this equation can safely replace the observed β indices in the range of the early B-type main sequence and giant stars (Balona 1994). With the β_* values obtained in this way we re-determine $\Delta\beta = \beta - \beta_*$, and repeat the procedure until convergence.

As the relations we are now studying are only between photometric indices, we have searched the literature for *uvby*β photometry of Be stars in open clusters, in order to derive the relations from as large a sample as possible. We have used, as well as our photometry for h and χ Persei and NGC 663 (Paper I),

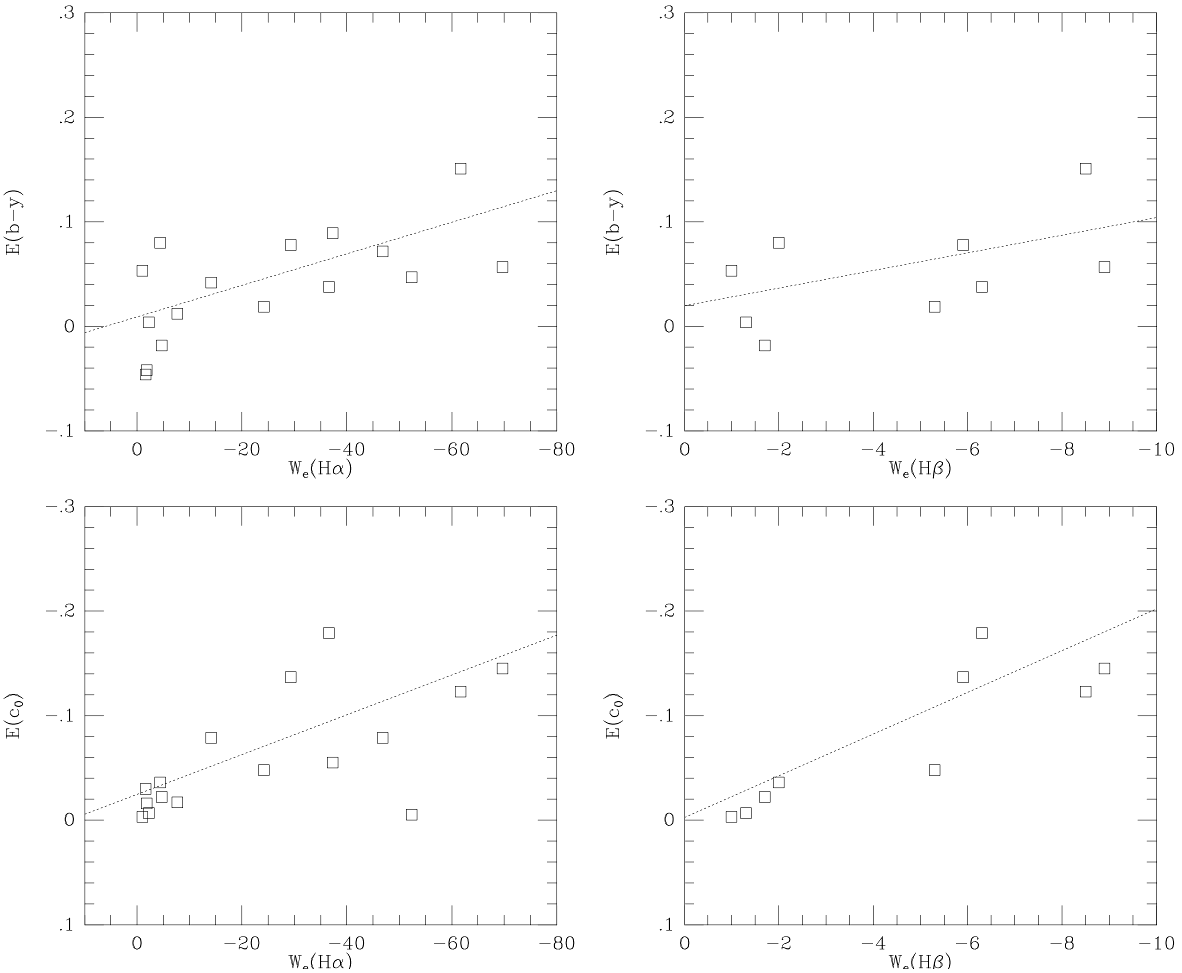

Fig. 3. Relationship between the photometric circumstellar excesses and the emission line equivalent widths corrected for photospheric absorption.

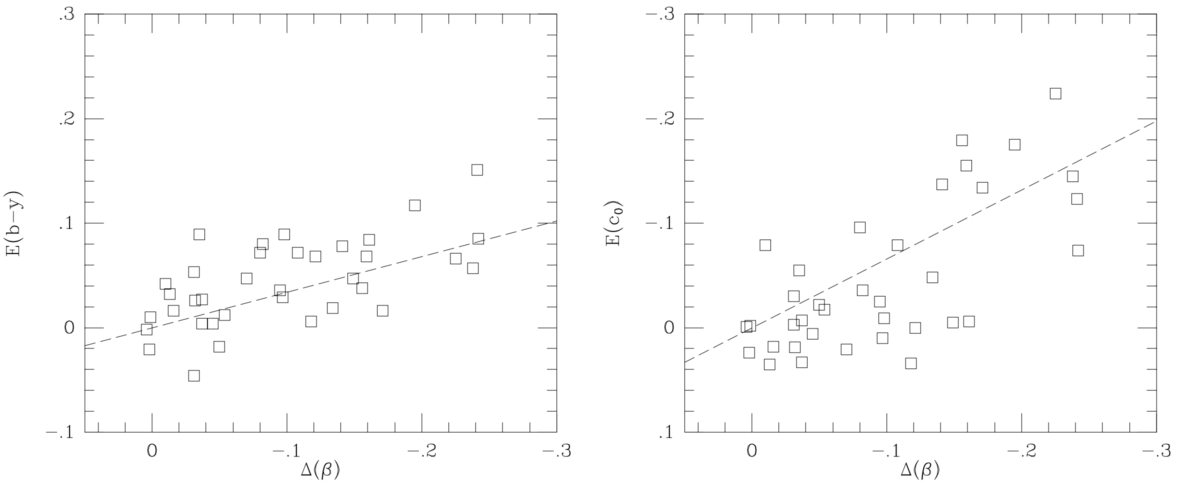

Fig. 4. Relationship between the *uvby* circumstellar excesses and the excess in the β index.

data for Be stars in the clusters NGC 3766 (Shobbrook 1985, 1987) and NGC 4755 (Perry et al. 1976).

In the relation obtained after the iterative procedure the zero points are again compatible with zero. Then, with the final $\Delta\beta$ values we have computed the correlations assuming no zero point. The results are the following:

$$\begin{array}{rlr} & \sigma & \\ E^{\mathrm{cs}}(b-y) = -0.339\Delta\beta & 0.033 & (10) \\ E^{\mathrm{cs}}(c_1) = 0.661\Delta\beta & 0.051 & (11) \\ E^{\mathrm{cs}}(m_1) = 0.125\Delta\beta & 0.024 & (12) \end{array}$$

The two first relations are presented in Fig. 4. For the sake of completeness, we have also computed the relation for the m_1 index.

Balona & Shobbrook (1984) proposed an alternative to Eq. (9) to determine β_* for stars of luminosity class IV-III. We have reproduced all the above procedure and the discussion in Sect. 4 using different equations for stars of luminosity class V or IV-III. The results obtained are basically the same that those presented here (Torrejón 1997). We have preferred to construct our calibration using only Eq. (9), because in this way we do not need a previous knowledge of the star's luminosity class.

3. The *uvby*β calibration

In the previous section we have derived relations between the emission in the Hβ line, measured through the β index, and the excesses in the photometric *uvby* indices of circumstellar origin. The existence of such relations opens the possibility to use the Hβ photometry to correct the *uvby* indices for circumstellar emission, and then derive the interstellar reddening and the intrinsic indices of the underlying star. These intrinsic indices can be used to estimate the astrophysical parameters of the underlying star by means of the usual *uvby* calibrations.

3.1. Interstellar reddening and intrinsic colours

The procedure to obtain the intrinsic *uvby* indices of a B star, correcting for the effect of the interstellar reddening, has been given by Crawford (1978). In the case of a Be star, we have to correct for both interstellar reddening and circumstellar continuum emission. In this section we propose a procedure to determine the circumstellar excesses, the interstellar reddening and the intrinsic colours of the underlying star. The basic idea is to use the β index as additional information to characterize the circumstellar emission, and then use the Crawford (1978) method to measure the interstellar reddening. As both effects are coupled, there is not an easy way to decouple the effects of circumstellar and interstellar reddening. We propose an iterative procedure to determine both of them, which consist in the following steps:

- Make a first aproximation of $\Delta\beta = \beta - 2.63$. Substitute this value in Eqs. (10) and (11) to obtain $E^{\mathrm{cs}}(b-y)$ and $E^{\mathrm{cs}}(c_1)$. Whit this values obtain $(b-y)$ and c_1 corrected for circumstellar excess.
- Whit the above $(b-y)$ and c_1 obtain the interstellar reddening and the intrinsic colours and indices, by means of the Crawford (1978) procedure.
- Use the intrinsic c_0 index to estimate the value of β_* by means of Eq. (9).
- Make a new determination of $\Delta\beta = \beta - \beta_*$. Repeat all the procedure until convergence.

3.2. Luminosity calibration

The β index is the main luminosity indicator for OB stars in the *uvby*β photometric system. In the case of Be stars, however, the β index is contaminated by the circumstellar emission, and is not useful to estimate the luminosity. Moreover, in the calibration method we are proposing, the β index has been used to characterize the circumstellar emission and correct the other indices for circumstellar effects. There is not any other independent index which can be related with the stellar luminosity, and therefore there is not any way to directly determine the luminosity within our approach.

It has to be considered, however, that the present calibration is to be applied to a rather narrow range of luminosity classes. When studying absorption-line OB stars, there is a wide range of variation of the β index for a given c_0, originated by the differences in the Hβ line strenght between supergiants and main sequence stars. Our calibration deals with Be stars, which are, by definition, restricted to luminosity classes III to V. As we stated in Sect. 2, within this range of luminosities the value of β can be inferred from c_0 by means of Eq. (9). Then we propose to estimate the absolute magnitude of Be stars from the c_0 index alone, by means of the following procedure:

- Derive the β_* value from c_0 by means of Eq. (9).
- Substitute the values of c_0 and β_* in the Balona & Shobbrook (1984) calibration of absolute magnitude.

4. Discussion

To estimate the accuracy of the above procedures we have computed the intrinsic indices, interstellar reddening and absolute magnitude for all the cluster Be stars with available *uvby*β photometry used in Sect. 2, by means of the method described in Sect. 3. We have compared the obtained reddening values with the mean reddening of each cluster, and the obtained M_V with the value directly derived from the photometry and the cluster reddening and distance. We have used the same values for the clusters' reddening and distance modulus as in Paper I. References for these values are also given in Paper I. The results are shown in Table 1. In Table 2 we compare the mean values for each cluster obtained with our procedure and the values from the literature given in Paper I. Columns 4 and 5 are the mean values of the reddening and distance modulus obtained with the procedure presented in Sect. 3 for all the Be stars in each cluster with available *uvby*β photometry. Columns 6 and 7 are the same for reddening and distance modulus values obtained with the FR90 calibration. Note that the DM values have been computed from the absolute magnitudes in the usual way, without taking into account the 0.3 mag. correction suggested below in Eq. (14).

In column 4 of Table 1 we present the differences between our $E(b-y)$ values and the mean reddening for each cluster. The mean value of the differences is zero. In Table 2 we present the mean values we obtain for each cluster. They are the same as the values found in the literature and determined from observations of the non-emission B stars. We can conclude that there is not any systematic difference in our calibration. The accuracy of our values can be estimated as 0.033 mag., from the deviation of the differences in Table 1. This value is less than twice the mean deviation for the $E(b-y)$ determination of normal absorption-line stars, namely 0.018 mag. (Perry & Johnston 1982; Franco 1989).

The differences in the determination of the absolute magnitude are shown in columns 5 and 6 of Table 1. Column 5 presents the absolute magnitudes obtained from the *uvbyβ* photometry with our calibration, which we denote $M_V(\beta_*)$. Column 6 gives the differences between our determinations and the values obtained from the photometry and the cluster reddening distance modulus, computed in the following way:

$$\Delta M_V = M_V(\beta_*) - (V_0 - DM) \tag{13}$$

In this case there is an apparent systematic difference, our determinations being 0.5 mag. fainter that the values derived from the distance modulus. The main contribution to this difference came from stars in NGC 3766. In Table 2 it can be seen that our distance modulus determination is lower by more than one magnitude than the value in the literature. This is caused by the difficulty of Eq. (9) to reproduce the unusual main sequence rising verticaly at $c_0 = 0.2$, as already stated by Shobbrook (1987). As our luminosity calibration is based on the assumption of Eq. (9), when this equation is not a good representation of the absorption-line stars locus in the $\beta - c_0$ plane, our calibration is unsuitable. This is the case of NGC 3766. Hence, within our approach we cannot obtain reliable luminosity estimations for stars in this cluster, and consequently we will not consider it in the following discussion. It is difficult to know whether this is a peculiarity of NGC 3766 or if it is common to all clusters of the same age. More *uvbyβ* photometry of clusters of similar age would be needed to decide on this issue.

If we do not consider stars in NGC 3766, the mean difference of the absolute magnitudes is 0.32 ± 0.65. There is still a nonzero mean difference. However, this value of 0.3 mag. is the expected difference in M_V between an absorption-line B star and a Be star of the same spectral type in the range B0–B5, as determined by Zorec & Briot (1991) and already mentioned in Sect. 2. Our procedure estimates the absolute magnitude of the underlying B star without considering the circumstellar contribution. The values derived from the uncorrected photometry and the cluster mean reddening and distance include the circumstellar contribution. Our values are systematicaly lower by 0.3 mag., confirming independently the Zorec & Briot finding that there is an overluminosity of around this magnitude produced by the circumstellar envelope emission. Then we can conclude

Table 1. Comparison between the $E(b-y)$ and M_V values obtained with our calibration and the values derived from the clusters' reddening and distance.

Star	β_*	$E(b-y)$	$\Delta E(b-y)$	$M_V(\beta_*)$	$\Delta(M_V)$
h & χ Per					
49	2.619	0.362	-0.048	-3.02	0.77
309	2.604	0.396	-0.014	-3.65	-0.15
717	2.625	0.366	-0.044	-2.80	0.84
847	2.634	0.421	0.011	-2.50	1.30
1161	2.632	0.454	0.044	-2.55	0.18
1261	2.624	0.463	0.053	-2.84	0.49
1268	2.622	0.444	0.034	-2.89	0.64
1702	2.631	0.372	-0.038	-2.60	0.61
1926	2.608	0.460	0.050	-3.44	-0.45
2138	2.622	0.454	0.044	-2.90	0.73
2165	2.610	0.439	0.029	-3.36	-0.43
2284	2.625	0.377	-0.033	-2.80	0.42
2262	2.636	0.427	0.017	-2.44	-0.12
2371	2.625	0.392	-0.018	-2.80	0.90
2563	2.616	0.422	0.012	-3.12	-0.75
2566	2.645	0.423	0.013	-2.15	0.25
2649	2.648	0.358	-0.052	-2.07	0.50
2804	2.615	0.453	0.043	-3.19	-0.72
NGC 663					
2	2.636	0.611	0.020	-2.42	0.07
6	2.629	0.657	0.067	-2.65	0.04
10	2.622	0.624	0.034	-2.90	-0.05
21	2.643	0.566	-0.024	-2.21	1.95
93	2.657	0.559	-0.031	-1.83	0.94
NGC 3766					
1	2.661	0.116	-0.034	-1.74	1.71
15	2.672	0.117	-0.033	-1.50	1.99
26	2.665	0.140	-0.010	-1.66	1.21
27	2.654	0.132	-0.018	-1.92	1.67
63	2.659	0.139	-0.011	-1.79	1.01
81	2.672	0.133	-0.017	-1.50	0.48
239	2.653	0.141	-0.009	-1.93	0.67
NGC 4755					
H	2.634	0.295	0.014	-2.49	0.54
I-17	2.636	0.274	-0.007	-2.41	-0.62
III-06	2.639	0.269	-0.012	-2.33	0.40
IV-17	2.603	0.273	-0.008	-3.67	-0.79
$mean$			0.001		0.48
σ			0.033		0.75

Table 2. Comparison between the mean clusters' reddening and distance values found in the literature and the mean values obtained with the present calibration and the FR90 calibration. DM values in columns 5 and 7 do not include the 0.3 mag. correction suggested in Eq. (14).

Cluster	Literature		This work		FR90	
	$E(b-y)$	DM	$E(b-y)$	DM	$E(b-y)$	DM
h & χ Per	0.41	11.4	0.42	10.9	0.41	10.4
	2	4	4	5	4	5
NGC 663	0.58	12.0	0.59	11.6	0.58	10.7
	5	2	4	7	3	3
NGC 3766	0.15	11.5	0.15	10.3		
	1	4	5	5		
NGC 4755	0.28	11.4	0.28	11.5		
	1	1	1	6		

Table 3. Comparison between the $E(b-y)$ and M_V values obtained with the FR90 calibration and the values derived from the clusters' reddening and distance.

Star	β_*	$E(b-y)$	$\Delta E(b-y)$	$M_V(\beta_*)$	$\Delta(M_V)$
			h & χ Per		
309	2.639	0.391	-0.019	-2.63	0.86
717	2.626	0.379	-0.031	-2.77	0.87
1261	2.694	0.441	0.031	-1.33	2.00
1268	2.626	0.459	0.049	-2.83	0.71
1702	2.636	0.381	-0.029	-2.42	0.79
2138	2.594	0.482	0.072	-3.74	-0.10
2165	2.632	0.442	0.032	-2.72	0.20
2284	2.728	0.338	-0.072	-0.83	2.40
2371	2.630	0.404	-0.006	-2.68	1.01
			NGC 663		
2	2.747	0.578	-0.012	-0.56	1.93
6	2.773	0.611	0.021	-0.36	2.33
10	2.686	0.613	0.023	-1.62	1.22
21	2.630	0.588	-0.002	-2.51	1.66
93	2.746	0.533	-0.057	-0.38	2.39
$mean$			0.000		1.30
σ			0.040		0.82

that there are not systematic effects in our luminosity calibration. The mean error associated to our M_V determination can be assumed as 0.7 mag., again lower than twice the mean error of the Balona & Shobbrook (1984) M_V calibration for absorption-line B stars, namely 0.43 mag.

The fact that the present calibration gives the M_V value for the underlying star has to be taken into account when using this value for the distance determination. In this last case, the mean 0.3 mag. overluminosity of the Be star has to be considered. The value of the distance modulus has to be computed in the same way:

$$DM = V_0 - (M_V(\beta_*) - 0.3) \tag{14}$$

Finally, for comparison we have computed the $E(b-y)$ and M_V values for stars with simultaneous *uvbyβ* photometry and Hα spectroscopy using the preliminary calibration given in FR90. The obtained values are shown in Tables 2 and 3. For the interstellar reddening the FR90 calibration gives the same results than the present work, with similar accuracy. The M_V calibration, however, is significantly worse, presenting a very high systematic error. Even in the case of the interstellar reddening, the present calibration has the advantage that it is fully photometric, whereas the FR90 calibration needs the use of simultaneous *uvby* photometry and Hα spectroscopy. Therefore, we consider that the present work completely supersedes the FR90 calibration.

5. Conclusions

We have used a sample of Be stars in open clusters with simultaneous *uvbyβ* photometry and Balmer line spectroscopy to derive linear relations between the equivalent widths of the Balmer lines and the anomalies in the *uvby* photometric indices produced by continuum circumstellar emission. Similar relations exist when the emission in the Hβ line is measured through the photometric β index.

These relations have been used to elaborate an empirical calibration of the *uvbyβ* photometric system to estimate the relevant astrophysical parameters of the underlying B star, valid for spectral types earlier than B5. The proposed calibration allows the determination of the intrinsic colours, interstellar reddening and absolute magnitude with estimated errors lower than twice the errors of the usual *uvbyβ* calibrations for absorption-line B stars.

We have also independently confirmed the previous finding that Be stars have absolute magnitudes brigther by 0.3 mag. in average than the B stars of the same spectral type.

Acknowledgements. We wish to express our gratitude to the referee Dr. E.H. Olsen for his careful reading of the manuscript and valuable comments which improved the final presentation of the paper.

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