The B[e] Phenomenon: Forty Years of Studies
ASP Conference Series, Vol. 508
A. Miroshnichenko, S. Zharikov, D. Korčáková, and M. Wolf, eds.

Characterizing Classical Be Stars via Intermediate-band Photometry

N. Kaltcheva[1] and V. Golev[2]

[1]*Department of Physics and Astronomy, University of Wisconsin Oshkosh, 800 Algoma Blvd., Oshkosh, WI 54901, USA;* kaltchev@uwosh.edu

[2]*Department of Astronomy, Faculty of Physics, St Kliment Ohridski University of Sofia, 5 James Bourchier Blvd., BG-1164 Sofia, Bulgaria;* valgol@phys.uni-sofia.bg

Abstract. Photometry-based determination of physical parameters of classical Be stars is useful to clarify their evolutionary status and their presence in star-forming complexes and open clusters. We use a sample of nearly 600 stars with complete *uvbyβ* data to evaluate various methods for providing estimates of absolute magnitude and color excess for O- and B-type emission-line objects.

1. Introduction

Reliable physical parameters of classical Be stars are critical in the study of the stellar content of the Milky Way star-forming fields. These stars are a significant part of the young stellar population of the Galactic shells and supershells, and photometry-based distances are often the only way to associate them with specific star-forming features. The luminosity-based estimates of the total energy deposit delivered by the massive stars into the surrounding interstellar media (see, e.g., Kaltcheva & Golev 2014) depend on the derived physical parameters of the Be-star fraction as well. These short-lived, intrinsically bright objects are also useful tracers of the Galactic spiral structure.

The intermediate-band *uvbyβ* photometry (Strömgren 1966; Crawford & Mander 1966) should in general be able to provide independent estimates of reddening, distance, and age. This photometry is most suitable for studies of the Galactic star-forming fields since these investigations rely heavily on distances to individual stars. Well-evaluated calibrations of color excess and absolute magnitude exist for non-emission B-type stars and provide results in agreement with the *Hipparcos* parallaxes (Kaltcheva & Golev 2011). However, this is only partly true in the case of emission-line objects.

In general, all *uvbyβ* photometric quantities for Be stars are expected to be affected by a certain amount of circumstellar emission. Extensive previous work has been done by several authors to correct for this effect. If Hα data are available, the circumstellar color excess that accounts for the contribution of circumstellar emission in the $(b - y)$ color can be calculated. Fabregat & Reglero (1990) developed a procedure based on *uvbyβ* quantities and Hα equivalent width measurements that yields the photometric indices for the underlying stars of Be-type objects. These indices - corrected for the circumstellar emission - can then be used to calculate color excess and absolute magnitude via the calibrations for non-emission stars. In addition, Fabregat et al. (1996) and

Fabregat & Torrejon (1998) proposed empirical corrections based only on the *uvbyβ* quantities. Another way to reduce the effect of the emission on the derived absolute magnitudes is to replace the observed β index with a β index calculated via c_0. This replacement was in general recommended by Balona (1994) and Balona & Shobbrook (1984) for stars from the upper part of the main sequence as providing more accurate M_V values. Since the upper MS is most likely to be influenced by emission, using a calculated β index should prevent an overestimation of the intrinsic stellar brightness because of a β index influenced by emission.

All these procedures can be tested via Be stars with independently obtained distances based on their membership in open clusters, or based on *Hipparcos* parallaxes and also on the first data release of the astrometry data from the *Gaia* space mission (Gaia Collaboration 2016). Their verification is, however, difficult since various data sets refer to different emission states of a given star. In general, larger samples should improve the statistics of the comparisons. At present, a relatively large sample of *uvbyβ* data for Be stars can be collated. In this contribution we explore a procedure for obtaining the color excess $E(b-y)$ and the absolute magnitude M_V based on "corrected for emission" *uvbyβ* photometry.

2. Results and Discussion

The total color excess $E(b-y)$ of a Be star is a sum of the circumstellar and interstellar components (for a detailed discussion see Fabregat & Reglero 1990). In order to investigate the effect of emission on the photometric quantities, these authors collated a sample of nearly 70 stars for which Hα equivalent width measurements are available in addition to the *uvbyβ* data. We combined the Hα data from Fabregat & Reglero (1990) with the photometry from the new catalog of Paunzen (2015) which contains unweighted mean *uvbyβ* indices. Following Fabregat & Reglero (1990), quantities V^*, $(b-y)^*$, c_1^*, m_1^*, and β^* corrected for emission via the Hα equivalent widhts were calculated. This also yielded the circumstellar $E^{cs}(b{-}y)$ and interstellar $E^{is}(b{-}y)$ components of the total color excess $E(b-y) = E^{cs}(b-y) + E^{is}(b-y)$. In addition, we calculated $E(b-y)$ via the calibration by Crawford (1978) for (non-emission) B-type stars, which is based on the observed (and thus affected by emission) $b-y$ and c_1 quantities.

Figure 1 presents various comparisons of these color-excess components. On the first plot we compare the total color excess obtained as a sum of the circumstellar and interstellar components $E^{cs}(b-y)+E^{is}(b-y)$ to the $E(b-y)$ obtained via the calibration for normal stars (Crawford 1978). We found an excellent agreement between the two estimates. As can be seen on the second plot, the method involving Hα underestimate the total excess by less than 0.01 mag on average in comparison to an estimate solely based on *uvbyβ*. The third and fourth plots compare the interstellar component $E^{is}(b{-}y)$ to the color excess $E(b{-}y)$. The total color excess $E(b{-}y)$ is overestimated significantly if only *uvbyβ* data are considered. On the last plot, filled squares are used for $E^{cs}(b-y)$ obtained via Hα, and plus-symbols for the circumstellar color-excess calculated as $E(b-y)$-$E^{is}(b-y)$. The good agreement between the two methods is again evident here, suggesting that the circumstellar component can be as large as 0.1 magnitude for the stars of this sample.

These comparisons demonstrate that not taking into account the circumstellar component of the color excess can lead to an overestimation of A_V of up to $0.4-0.5$ mag (for an adopted value of the total-to-selective extinction ratio 3.2). In addition, a cor-

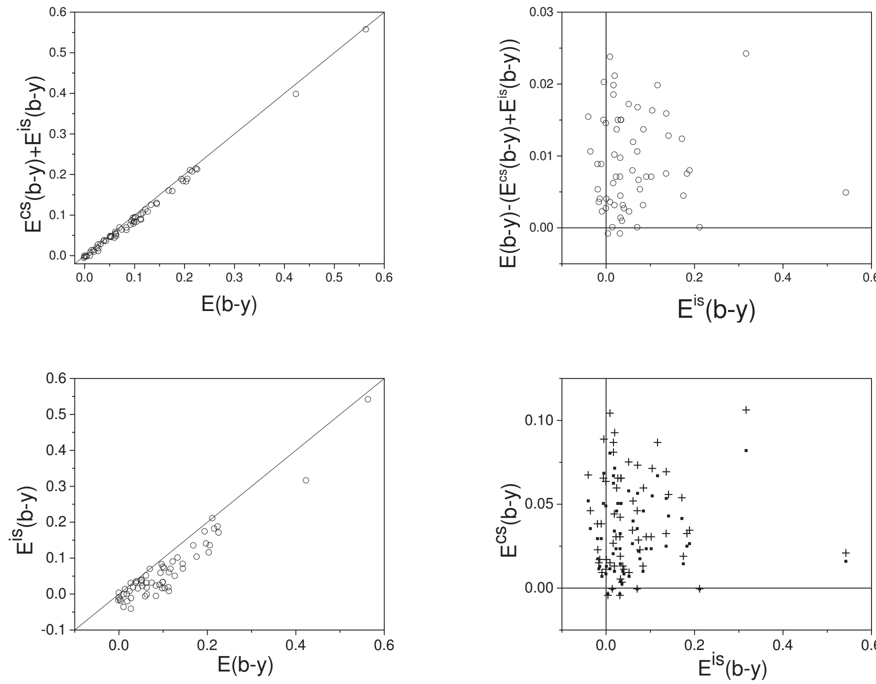

Figure 1. Comparisons of color-excess components for a sample of Be-star with available $uvby\beta$Hα data. *Upperleft*: total color excess obtained via $uvby\beta$Hα data as a sum of the circumstellar $E^{cs}(b-y)$ and interstellar $E^{is}(b-y)$ components vs. $E(b-y)$ based on $uvby\beta$ data only. *Upperright*: difference between these two estimates as a function of the interstellar component. *Bottomleft*: $E^{is}(b-y)$ vs. the total excess $E(b-y)$. *Bottomright*: $E^{cs}(b-y)$ vs. $E^{is}(b-y)$. Filled squares are used for $E^{cs}(b-y)$ obtained via Hα and plus symbols are for $E^{cs}(b-y) = E(b-y) - E^{is}(b-y)$.

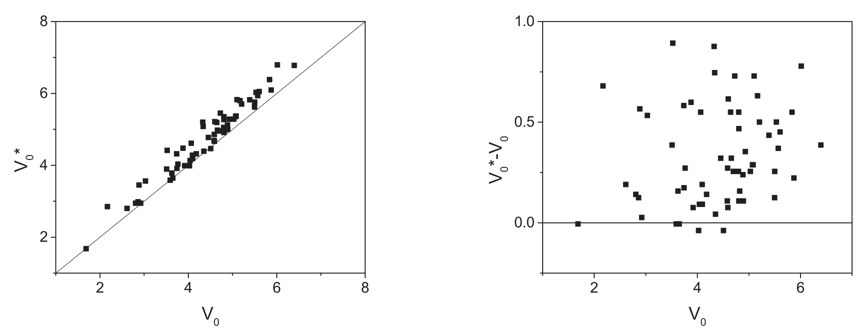

Figure 2. Comparison of the V magnitudes corrected for extinction for the stars on Fig. 1. V_0 is based on *uvby* data only, while V_0^* also utilizes Hα.

rection of the V magnitude for circumstellar emission is needed, which causes an additional decrease in the value of the V magnitude. Thus, a significant discrepancy is expected between the V_0 values, which is indeed the case for this test sample. The V_0

values corrected for reddening obtained via the two methods are shown in Fig. 2. Not taking the emission into account results in a significantly smaller (up to 1 magnitude) value of V_0 for emission-line objects. In addition, not considering the circumstellar extinction affects the reddening correction of c_0 and thus the M_V calculation. All this in general yields erroneous distance moduli.

Since in many cases Hα data are not available, we explored a procedure to intrinsically correct (for circumstellar emission) the $V, b-y, c_1$, and β quantities based only on *uvby*β data. For the test sample we compared these quantities to those corrected for emission via the Hα equivalent widhts and deduced empirical relationships that yield $V, b-y, c_1$, and β corrected for circumstellar emission. The (still preliminary) relationships between the corrected $V_{cor}, (b-y)_{cor}, c_{1cor}$ and observed $V, b-y, c_1$ quantities are as follows:

$$V_{cor} = V + 0.132$$

$$(b-y)_{cor} = 0.9512(b-y) - 0.0299$$

$$c_{1cor} = 0.1073 + 0.873c_1 + 0.027c_1^2$$

We note that a correction in c_1 is needed only for $c_1 < 0.5$. Since the Hβ index is expected to be most strongly influenced by emission, this correction involves several steps and is based on β calculated from c_{1cor}. These photometric quantities, corrected for emission, should yield better estimates for the color excess, absolute magnitude, and distance modulus for classical Be stars. A comparison of the photometric parallaxes calculated from photometry corrected in this way with the *Hipparcos* parallaxes shows a reasonable agreement for the test sample.

Next, we applied this method to a larger sample of Be stars with complete *uvby*β data. We used the catalog by Paunzen (2015) as a source of accurate and homogeneous data. The spectral types we extracted from the SIMBAD database. We found 636 stars classified as emission-line objects, from which 590 are of luminosity classes III, IV, and V and can be considered classical Be stars. Figure 3 presents the $[c_1]/[m_1]$ and $\beta/[c_1]$ diagrams for this sample. The quantities $[c_1]$ and $[m_1]$ are almost reddening-free, and both diagrams in Fig. 3 are classification diagrams in terms of spectral type and luminosity class. In both diagrams the emission-line objects are plotted together with all stars of spectral types O-B9 with complete *uvby*β data in the Paunzen (2015) catalog, which are not presently recognized as emission-line objects. It can be noticed that the classical Be stars cannot be distinguished from the normal B-type stars based on the $[c_1]/[m_1]$ diagram. On the $\beta/[c_1]$ diagram, however, they are located on average above the sequence of the normal B-type stars, which is due to the effect of the emission on the β index. For this sample of classical Be stars we calculated A_V, M_V, and distances via the photometry corrected for emission.

A significant part of these stars have *Hipparcos* and *Gaia* parallaxes. Our preliminary tests show that the "corrected for emission" *uvby*β photometry provides better agreement with both of these sets than the "original" *uvby*β. In addition, about 90 of these stars are listed as members of clusters. The comparison of the photometric distances with the cluster distances also indicates that the corrected photometry provides better estimates.

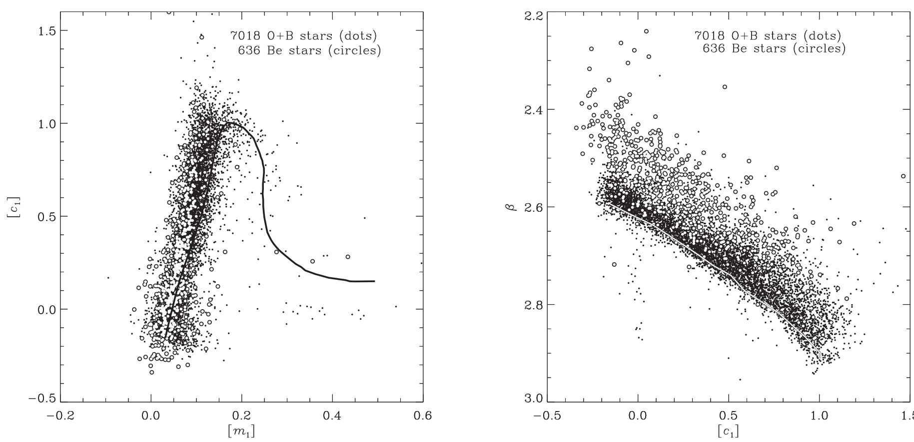

Figure 3. The $[c_1]/[m_1]$ and $\beta/[c_1]$ diagrams for the emission-line objects with complete *uvbyβ* photometry. The emission-line objects are plotted together with all stars from O to B9 types. The reference line for the zero-age-main-sequence is shown in both diagrams. The *uvbyβ* data were taken from the catalog of Paunzen (2015).

3. Summary

We explore a procedure for obtaining $E(b-y)$ and M_V based on "corrected for emission" *uvbyβ* photometry. Based on the work of Fabregat & Reglero (1990) and *uvbyβ* data extracted from the catalog of Paunzen (2015) we derive empirical corrections in $V, b-y, c_1$, and β that should reduce the influence of the circumstellar emission in these quantities to an extent to safely apply the calibrations for non-emission B III, IV, and V stars. However, more tests based on the recent data release of the *Gaia* astrometry is needed to fully evaluate this method. The preliminary procedure was applied to a sample of nearly 600 classical Be stars with accurate and homogeneous *uvbyβ* photometry to calculated A_V, M_V, and photometry-based distances.

Acknowledgments. This study made use of the NASA Astrophysics Data System, SIMBAD database and WEBDA open cluster database operated at the Institute for Astronomy of the University of Vienna. This work is supported by the NSF grant AST–1516932. V. G. would like to acknowledge St. Kliment Ohridski University of Sofia Science Foundation grant No. 81/2016.

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