Calibration of (B–V)$_0$ for MILES stars

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Abstract. The integrated spectral properties of a stellar system bring information from the mixture of stellar populations within the system. The (B–V) colour is one of the observational properties that can help determine the age and metallicity of stellar populations in a star cluster or even in galaxies. We have derived a series of empirical calibrations of the intrinsic colour, (B–V)$_0$, as a function of T$_{\mathrm{eff}}$, [Fe/H] and [α/Fe]. The stellar parameters of MILES stars have been redetermined homogeneously. The calibrations were obtained individually for distinct spectral types (O-B, A, F-G-K and M), which were then further subdivided into as many as five ranges in [Fe/H]. For the M types only, the stars were divided into dwarfs and giants. (B–V)$_0$ was measured directly using the MILES fully calibrated stellar spectra (typical error = 0.025 mag). Here, we present just the (B–V)$_0$ calibrations for F-G-K types that are split into five [Fe/H] ranges. We find that the error in (B–V)$_0$ varies from 0.014–0.022 mag. The next main goal is to compute (B–V)$_0$ self-consistently for semi-empirical simple stellar population models based on MILES.

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1.   Introduction

The ages and chemical abundances of a hypothetical simple stellar population (SSP) are imprinted in its integrated spectrum and photometric colours. Even in the case of more complex stellar systems such as a galaxy, those properties, or even their luminosity-weighted averages, can be extracted by a stellar population synthesis method. The intrinsic colour $(B–V)_0$ increases as the stellar system evolves, representing the classical evolution reddening. In fact, $(B–V)_0$ increases with mean age as well as with mean metallicity of the stellar component. There is also a dependence of $(B-V)_0$ on the star formation history, mainly through its timescale as that is directly related to mean stellar age.

The computation of the $(B–V)_0$ integrated colour of semi-empirical SSP models is performed by expressing $(B–V)_0$ for each stage of stellar evolution being considered for an isochrone of a given age τ and chemical composition ([M/H], [Fe/H], [α/Fe]). The stellar $(B–V)_0$ depends on stellar photospheric parameters such as T_{eff}, [Fe/H] and [α/Fe] since $(B–V)_0$ is calibrated as a function of them. The precision of the colour of the SSP model is dominated by the calibration errors introduced for the brightest stage in the isochrone. This computation of the colour in the SSP semi-empirical modelling with the MILES library can be considered self-consistent because the $(B–V)_0$ calibrations which are employed are derived by adopting MILES's own spectra. The procedure aims to minimise the errors in the derivation of $(B–V)_0$ for a large variety of semi-empirical SSP models. Thus, such modelling of $(B–V)_0$ for SSPs will be useful for deriving age, star formation history and metallicity of galaxies, when included in a full evolutionary stellar population synthesis.

2.   Multi-parametric calibration of $(B–V)_0$

The $(B–V)_0$ colours of MILES stars were measured directly on the MILES spectra by applying the Johnson & Morgan (1953) filter transmissions (the Revised Yerkes Atlas System of Spectral Classification, MK) and coupled with a spectrophotometric calibration of Vega such that $B_{Vega}=V_{Vega}=0.03$ mag (Castelli & Kurucz 1994). The average systematic error in $(B–V)_0$ is about 0.025 mag when comparing different samples that have stars in common, and for which the estimated offsets from those other samples are smaller than this value (Sánchez-Blázquez et al. 2006).

After analysing plots of $(B–V)_0$ versus T_{eff} for MILES stars, and taking into account the global metallicities [M/H] of BaSTI isochrones by Pietrinferni et al. (2004, 2006) (respectively scaled-solar and α-enhanced), we divided the MILES stars into T_{eff} and [Fe/H] intervals. The temperature ranges nearly resemble spectral types, as follows: $11000 \leq T_{eff} < 36000$ K (O-B types), $7000 \leq T_{eff} < 11000$ K (A type), $4750 \leq T_{eff} < 7000$ K (F-G-K types), $3000 \leq T_{eff} < 4750$ K (M type). Only the M types were split into dwarfs ($\log g \geq 3.0$) and giants ($\log g < 3.0$). The F-G-K types have five ranges of [Fe/H] that represent metal-poor stars ([Fe/H] $< −1.0$ dex), intermediate

metal-poor ones (–1.0 ≤ [Fe/H] < –0.2 dex), solar-metallicity ones (–0.2 ≤ [Fe/H] < +0.2 dex), intermediate metal-rich ones (+0.2 ≤ [Fe/H] < +0.6 dex), and metal-rich ones ([Fe/H] ≥ +0.6 dex). The O-B stars were not split into ranges of [Fe/H]; the A stars and the M giants both had two ranges of [Fe/H] ([Fe/H] < –0.2 dex and [Fe/H] ≥ –0.2 dex), while the M dwarfs with different [Fe/H] were dealt with together.

We have applied polynomial fits to calibrate (B–V)$_0$ as a function of T_{eff}, [Fe/H] and [α/Fe], following a similar procedure by Alonso et al. (1996). Eq. 1 shows a multi-parametric polynomial function with two quadratic terms for each parameter, where θ_{eff} = 5040 K/$T_{eff}(K)$. In order to derive the final dependence of (B–V)$_0$ on the terms of Eq. 1, we added each term one by one according to on the analysis of fit residuals as a function of each additional parameter. The base polynomial fit is $a + b.\theta_{eff} + c.\theta_{eff}^2$, and the inclusion of other terms was carried out according to the sequence [Fe/H], [Fe/H]^2, [α/Fe] and [α/Fe]^2. Consequently, each term is only included if the fit is improved (according to the resulting *rms* and χ^2) and the error of the correspondent fitting parameter is smaller than its value. Alonso et al. (1996) derived for a sample of F-G-K dwarfs a *rms* of 0.039 mag for a similar multi-parametric fit by including the cross term θ_{eff}.[Fe/H], but without adding any dependence on [α/Fe] and without dividing the stars into ranges of [Fe/H].

$$(B - V)_0 = a + b.\theta_{eff} + c.\theta_{eff}^2 + d.[Fe/H] + e.[Fe/H]^2 + f.[\alpha/Fe] + g.[\alpha/Fe]^2 \quad (1)$$

The stellar photospheric parameters T_{eff}, [Fe/H], log g, V_{micro} and [α/Fe] were thus determined homogeneously by a full spectrum analysis of the MILES spectra (flux normalised at λ 3544.1–7406.9 Å); details will be described soon in a separate paper. We have simply adopted spectra from the original MILES library (Sánchez-Blázquez et al. 2006). Next we will consider an additional sample of 205 stars whose spectra were observed with the 2.5-m Isaac Newton Telescope (Observatorio del Roque de Los Muchachos, La Palma, Spain) in 2011 and employing the same instrumental setup as MILES.

3. Results for F-G-K types

The best multi-parametric polynomial fits derived for the F, G and K types (4750 ≤ T_{eff} < 7000 K) and their five metallicity ranges are shown in Fig. 1. We obtained good agreement between our calibration of (B–V)$_0$ from a sample of MILES F-G-K dwarfs and that derived by Alonso et al. (1996); both adopted the same multi-parametric function with six terms and stellar parameters ranges. By adopting the parametric dependence given by Eq. 1, and based on the MILES library, the derived *rms* for the fit is 0.021 mag for the metal-poor range (reduced χ^2 = 0.9815), 0.015 mag for the intermediate metal-poor range (reduced χ^2 = 0.9928), 0.014 mag for the solar-metallicity range (reduced χ^2 = 0.9943), 0.019 mag for the intermediate metal-rich
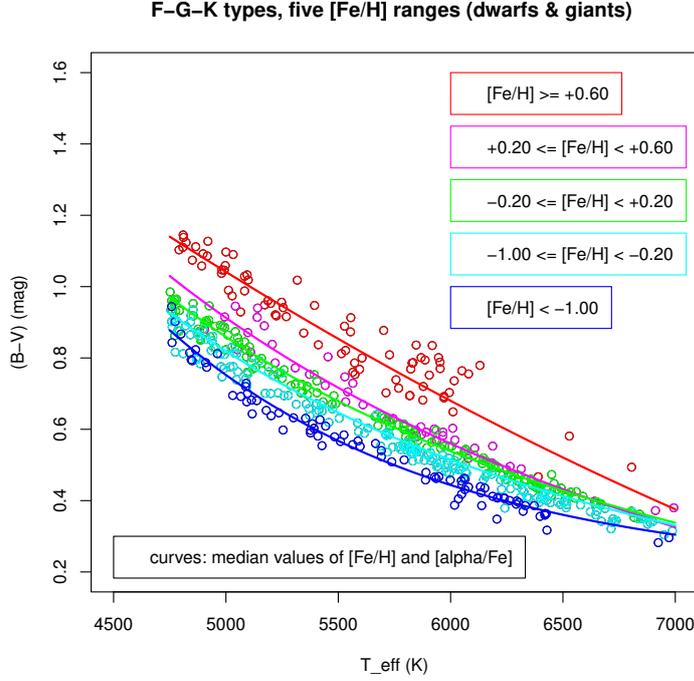
F–G–K types, five [Fe/H] ranges (dwarfs & giants)

Figure 1: $(B-V)_0$ as a function of T_{eff} for F-G-K types for five [Fe/H] ranges. The coloured curves represent the fits as given by Eq. 1, assuming median values for [Fe/H] and $[\alpha/Fe]$ for each subsample.

range (reduced $\chi^2 = 0.9856$), and 0.022 mag for the metal-rich range (reduced $\chi^2 = 0.9807$).

We found a dependence of $(B-V)_0$ on the abundance ratio $[\alpha/Fe]$ for intermediate metal-poor, solar-metallicity and intermediate metal-rich stars. For instance, the resulting *rms* of the calibration for the solar metallicity stars, having already included a single linear term for [Fe/H], decreases from 0.017 mag down to 0.014 mag after adding both terms $[\alpha/Fe]$ and $[\alpha/Fe]^2$. In that case the relative errors of the $[\alpha/Fe]$ fitting terms were, respectively, about 12.5% and 20%

Our calibrations of $(B-V)_0$ for F-G-K types are quite reliable and yield an acceptable precision for that parameter for computing a wide set of SSP models. We will present in a further work the $(B-V)_0$ calibrations for other spectral types as well as the set of T_{eff} calibrations as a function of $(B-V)_0$, [Fe/H] and $[\alpha/Fe]$.

Acknowledgements

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Round table section.