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Late A-type stars: new Strömgren photometric calibrations of absolute magnitudes from Hipparcos*

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Abstract. Hipparcos trigonometric parallaxes have been used to derive a photometric absolute magnitude calibration of main-sequence late A-type stars in terms of Strömgren photometric indices – accounting for temperature, evolution and metallicity effects – and projected equatorial rotational velocities. The derived calibrations are valid for main-sequence normal A3-A9 and metallic Am stars, showing residuals of 0.22 and 0.20 magnitudes, respectively. One of the fitting methods used (BCES) allows the derivation of the observational ZAMS in this spectral range, showing an excellent accordance with theoretical evolutionary models. The evolutionary state of the Am stars is also discussed.

Key words: stars: chemically peculiar – stars: distances – stars: early-type – stars: fundamental parameters – stars: Hertzsprung–Russel (HR) and C-M diagrams

1. Introduction

Before the publication of the HIPPARCOS results (ESA, 1997), the few accurate trigonometric parallaxes known for main-sequence A-type stars were not sufficient for a direct derivation of a photometric absolute magnitude calibration in this spectral range. As an example, the Crawford (1979) absolute magnitude calibration, the most widely used, was derived using open cluster data, fitting the zero point of the calibration to that obtained for F-type stars. Now and for the first time, the recent release of the Hipparcos data enables us to undertake this study using both the highly accurate trigonometric parallaxes (mean precision of 0.97 mas for $H_{\rm p} < 9^{\rm m}$) and larger samples, out of which stars with complementary astrophysical data from the ground (photometry, rotational velocities,...) can be selected for the study.

In this context, we have undertaken the reexamination of the M_V photometric calibration for main-sequence late A-type stars (A3-A9). Special attention has been paid to chemically peculiar Am stars, taking into account that their frequency can reach a value up to 50 % for some types in this spectral range (Schneider, 1993). We have focused on Strömgren photometry, since it is widely accepted that this photometric system is a powerful tool for characterizing physical parameters in both normal and Am stars, such as the temperature, evolutionary state and metallicity.

As reported by Wolff (1983), rotational velocities and the appearance of the spectrum in A-type stars are closely correlated, i.e., normal stars rotate much more quickly ($v \sin i$ up to 250 km s^{-1}) than peculiar ones. Considering this correlation and the systematic effects of stellar rotation on the photometric derivation of atmospheric parameters and absolute magnitudes (Zorec, 1992; Crawford, 1979; Figueras & Blasi, 1998) it has been necessary, as already shown by Guthrie (1987), to take into account rotational effects in our calibration of absolute magnitudes.

The paper is organized as follows: Sect. 2 describes the construction of the working samples; Sect. 3 is devoted to the reexamination – in the light of the new Hipparcos data – of the Strömgren photometric calibrations of luminosity used so far for normal and Am stars; Sect. 4 deals with a new derivation of the absolute magnitude calibration using two different techniques: least squares and the iterative BCES fits (Akritas & Bershady, 1996), the latter allowing the determination of the observational ZAMS. Finally, in Sect. 5 the position of the Am stars in the theoretical HR diagram is presented.

2. The sample

We selected from the Hipparcos Catalogue (ESA, 1997) a sample of 188 main-sequence normal A-type stars in the range A3-A9, with spectral types taken from the Hipparcos Input Catalogue (Turon et al., 1992a). The information contained in these sources and in the compilation by Renson et al. (1991) was checked in order to retain only those stars that were not variables and had no peculiarities in the spectra. All selected stars have complete Strömgren photometric data, extracted from the compilation of Hauck & Mermilliod (1998) and our own observations (Figueras et al., 1991; Jordi et al., 1996), and according to the classification scheme proposed by Figueras et al. (1991), the selected stars belong to the late Strömgren region. Furthermore, as the normal stars are the most rapidly rotating in this spectral range, and as one of the objectives of this work is to take

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into account the influence of this effect on the absolute magnitudes, all the stars that were selected have a measured projected equatorial rotational velocity ($v \sin i$), derived from Abt & Morrell (1995) (78 % of the sample) and Uesugi & Fukuda (1982) (22 %). The Uesugi & Fukuda (1982) measurements are very old and are affected by systematic errors; nevertheless, we have preferred not to impose additional restrictions on our sample according to the source of $v \sin i$. With the 78 % of the sample having data from both sources we found a mean difference $< v \sin i_{A\&M} - v \sin i_{U\&F} >= -11 \pm 28\,\mathrm{km\,s^{-1}}$. Due to the large dispersion and the small influence of this difference in our final absolute magnitude calibration ($< 0.01^{\mathrm{m}}$), no systematic correction was applied.

Our compilation of Am stars contains 197 stars selected from the Hipparcos Catalogue (ESA, 1997) and spectroscopically classified as highly probable metallic line stars by Renson et al. (1991). All have complete $uvby\mathrm{H}_\beta$ photometry from Hauck & Mermilliod (1998), and were checked in order to remove known variables, δ–Del, spectroscopic binaries and stars with variable radial velocity (VRV) according to the above mentioned references. After checking the information on variability and duplicity included in the Hipparcos Catalogue (ESA, 1997), the stars belonging to double systems with angular separation lower than 10″ and $\Delta m < 4^{\mathrm{m}}$ – thus implying combined Strömgren magnitudes and colours – were rejected. As the Am stars are slow rotators, we did not limit ourselves to stars with measured projected equatorial rotational velocities ($v \sin i$). According to Abt & Morrell (1995), Renson et al. (1991) and Hauck (1992), $v \sin i$'s are available for 48 % of the sample. The final sample of 197 Am stars shows a bimodal distribution of apparent magnitudes, probably induced by both selection effects in the Hipparcos Survey (Turon et al., 1992b) and by the fact that fainter stars without $v \sin i$ have been retained.

3. Test of the existing calibrations using Hipparcos data

In this section we will re-examine, in the light of the new Hipparcos data, some of the most widely used absolute magnitude calibrations in the Strömgren system. To reduce the noise, we worked only with stars having a relative parallax error smaller than 0.2, that is, 127 Am and 179 normal A-type stars. The Crawford (1979) unreddening procedure and its standard relations among colour indices were used to derive the intrinsic δc_0 and δm_0 parameters accounting for evolution and metallicity in this photometric region, respectively.

Crawford (1979) defined a $M_V(ZAMS, \beta)$ standard relation for the ZAMS and considered the degree of evolution using the δc_0 parameter:

$$M_V = M_V(ZAMS, \beta) - 9\,\delta c_0 \qquad (1)$$

Applying this calibration to our samples, the mean residuals obtained (i.e., Hipparcos minus Crawford), were -0.45^{m} and -0.04^{m} for the Am and normal A-type stars, respectively, with root mean square residuals of $\sigma_{\mathrm{res}} = 0.75^{\mathrm{m}}$ for the Am stars and $\sigma_{\mathrm{res}} = 0.35^{\mathrm{m}}$ for the normal A-type stars.

Guthrie (1987) proposed a new parameter $\delta c_0'$ to account for evolution which was designed to be free of metallicity and rotational effects:

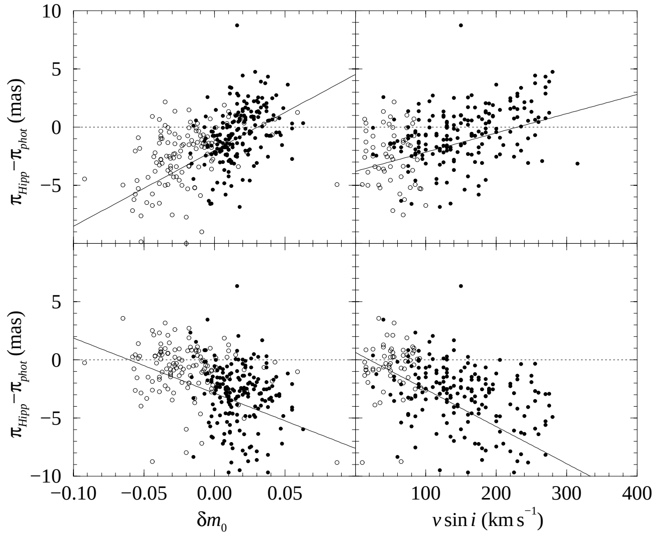

Fig. 1. Differences between the Hipparcos parallax and the parallax computed using Crawford (1979) (*upper panels*) and Guthrie (1987) (*lower panels*) calibrations as a function of δm_0 and $v \sin i$ (normal A-type stars: dots, Am stars: open circles).

$$\delta c_0' = \delta c_0 - 1.2\,\delta m_0 - 1.1\,10^{-6}(v \sin i)^2$$

Using the Crawford (1979) relation for the ZAMS, the author presented a new absolute magnitude calibration:

$$M_V = M_V(ZAMS, \beta) - 9.1\,\delta c_0' - 0.1 \qquad (2)$$

In this case, the resulting mean residuals (i.e., Hipparcos minus Guthrie), were -0.15^{m} and -0.39^{m} for the Am and normal A-type stars respectively, with a root mean square residuals of $\sigma_{\mathrm{res}} = 0.60^{\mathrm{m}}$ for the Am stars and $\sigma_{\mathrm{res}} = 0.51^{\mathrm{m}}$ for the normal A-type stars.

Our results indicate that Crawford (1979) calibration, deduced twenty years ago, is able to reproduce quite well the absolute magnitudes of normal A-type stars although, as already noticed by Guthrie (1987), it is subject to important systematic trends and large dispersions for the Am stars. Besides, we observe that Guthrie's correction to this calibration is too large; although it succeeds in reducing the observed dispersion for Am stars, it introduces an important systematic trend in the M_V computation for normal A-type stars without a significant reduction of the scatter either for normal or for Am stars. These effects can be clearly seen in Fig. 1, which shows the difference between Hipparcos parallaxes and those derived from photometry as a function of metallicity and projected equatorial rotational velocity. We notice that, although metallicity and rotational corrections are needed for Crawford (1979) calibration, those proposed by Guthrie (1987) are too large.

4. New calibrations based on Hipparcos absolute magnitudes

Before deriving a new calibration in the A3-A9 range, it is necessary to decide if normal and Am stars must be treated separately

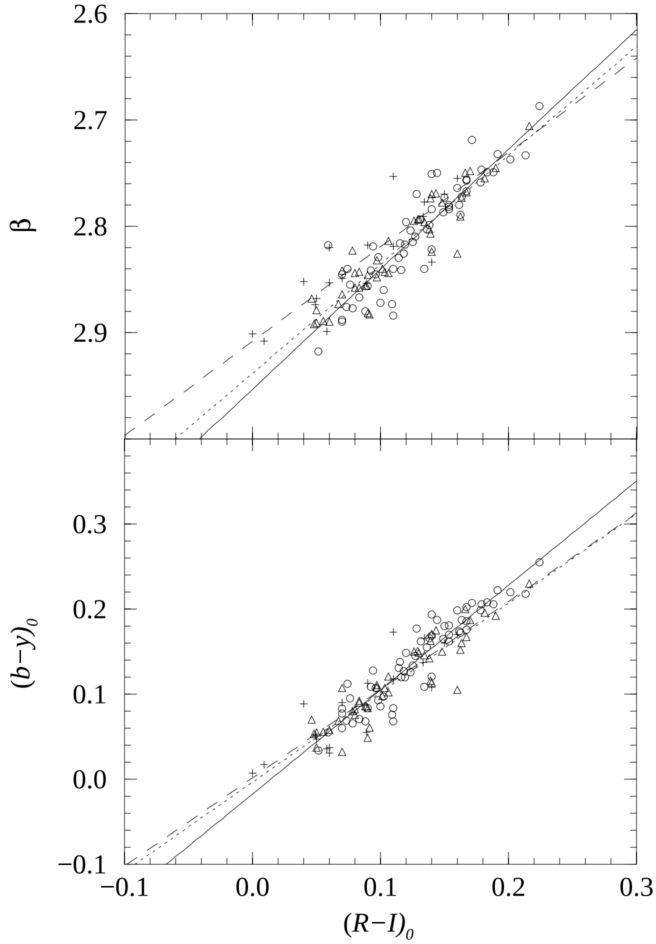

Fig. 2. Strömgren versus Cousins intrinsic colours accounting for effective temperature. The continuous line is the lineal regression obtained from Am stars with $-0.1 < \delta m_0 < -0.025$ (circles), dotted line from Am stars with $-0.025 < \delta m_0 < 0$ (triangles), and long dashed line from those having $0 < \delta m_0 < 0.09$ (pluses).

or, on the contrary, if there can be some advantages in treating them jointly. As already pointed out by several authors, the stars in this spectral range show a clear correlation between $v \sin i$ and δm_0, better defined when both types of stars are plotted together. This continuous trend, also seen in Fig. 1, and in some previous analysis performed by independently fitting normal and Am stars (Domingo, 1998), indicated that a large range of variation in the δm_0 and $v \sin i$ parameters helped us to define the M_V dependence on these parameters. Thus, we decided to produce new luminosity calibrations for late A-type stars by considering jointly normal A-type and Am stars.

In this spectral range, both $(b-y)_0$ and β are Strömgren colour indices accounting for effective temperature. Although β has the advantage of being reddening-free, it is important to check how these indices are affected by blanketing effects. In Fig. 2 we have plotted these indices against the intrinsic $(R-I)_0$ Cousins colour index, the latter being taken from the literature and from our own observations (see Appendix A:). As blocking decreases with increasing λ, $(R-I)_0$ has been commonly accepted as blanketing-free and as a good indicator of effective temperature for Am stars (Jaschek & Jaschek, 1987). Fig. 2 shows that some blanketing effects are present in the β index, and the regression lines at different δm_0 are even more separated than when $(b-y)_0$ is used. Bearing in mind these advantages and disadvantages, and also that the β index is not always available (see Hauck & Mermilliod, 1998), we decided to derive absolute magnitude calibrations using both colour indices, $(b-y)_0$ and β, as indicators of effective temperature.

In the next paragraphs we will analyze the possible biases that can affect our calibrations due to both the observational data used and the procedure followed to select our working sample:

– A possible error in the zero point of Hipparcos parallax. According to Brown et al. (1997) such error is probably less than 0.1 mas. It is a systematic error in the absolute magnitudes of $0.022^{\rm m}$ for a distance of 100 pc and $0.043^{\rm m}$ for 200 pc.
– The non-linear dependence of absolute magnitude on the parallax causes a bias in the M_V computed from parallaxes. Simulations performed by Luri & Arenou (1997) and Brown et al. (1997) using a lower bound in parallax of 0.01 mas showed that the absolute magnitudes computed from Hipparcos parallaxes were almost unbiased for relative errors in parallax less than 0.1.
– The Malmquist (1936) bias caused by the combination of the apparent magnitude limit of the sample and the intrinsic dispersion in the absolute magnitudes. Considering the low dispersion in the calibrations obtained in this paper (see below), and according to Luri et al. (1993), this effect should be less than a few hundredths of a magnitude. For the total sample of Am stars, the estimation of this bias is very difficult due to its bimodal distribution of apparent magnitudes.
– The Lutz & Kelker (1973) bias, as a consequence of the observational errors in the parallax combined with the fact that the number of stars per unit interval of parallax depends on the parallax. Individual corrections for this bias were computed and applied to our stars according to Lutz (1979).

After analyzing all these biases, we decided as a compromise to derive our calibration using only the stars at distances less than 100 pc (59 Am and 143 normal A-type stars). Therefore, the first and second biases were negligible, the distance limit almost superseded that for the apparent magnitude, and thus the Malmquist bias also vanished almost completely. Furthermore, the bimodal distribution in apparent magnitude present in the sample of Am stars also disappeared. Besides, the individual Lutz & Kelker corrections applied – with a mean of $-0.037^{\rm m}$ in the sense $\langle M_V(true) - M_V(observed)\rangle$ – were more realistic, since they depended on the apparent magnitude distribution, which could be simulated.

With this distance limit, the reddening corrections ($E(b-y)$) showed a normal distribution around zero with $\mid E(b-y) \mid$ always smaller than 0.025. As reported by Crawford (1979), this distribution of $E(b-y)$ around zero is induced by the observational errors and the intrinsic colour calibrations used; therefore, to avoid the introduction of additional noise in the calibration, we assumed that the stars used to derive our

Table 1. Coefficients of the calibrations obtained through a weighted least squares fit to Eq. (4). The first column shows the relations used to compute the ZAMS and the δc_0 and δm_0 parameters (for explanation, see text): Cr for Crawford (1979) and MR for Mathew & Rajamohan (1992). σ' and r are the standard deviation (weighted) and the multiple correlation coefficient, respectively. The last columns show the root mean square of the residuals for only Am stars (σ_{Am}), only normal A-type stars (σ_A) and the total sample (σ_{Am+A}).

method (WLS)	a	c	d	e	σ'	r	σ_{Am}	σ_A	σ_{Am+A}
Cr (β)	-0.33 ± 0.03	-8.0 ± 0.2	$+5.9 \pm 1.0$	$+4.1 \pm 0.9$	0.19	0.94	0.26	0.23	0.24
Cr $(b-y)_0$	-0.26 ± 0.03	-9.6 ± 0.4	$+7.0 \pm 1.1$	$+4.9 \pm 1.0$	0.21	0.91	0.21	0.26	0.25
MR (β)	-0.24 ± 0.03	-8.1 ± 0.2	$+6.8 \pm 0.9$	$+4.5 \pm 0.8$	0.18	0.95	0.24	0.22	0.23
MR $(b-y)_0$	-0.17 ± 0.03	-9.6 ± 0.4	$+6.3 \pm 1.1$	$+5.7 \pm 1.0$	0.21	0.90	0.20	0.26	0.24

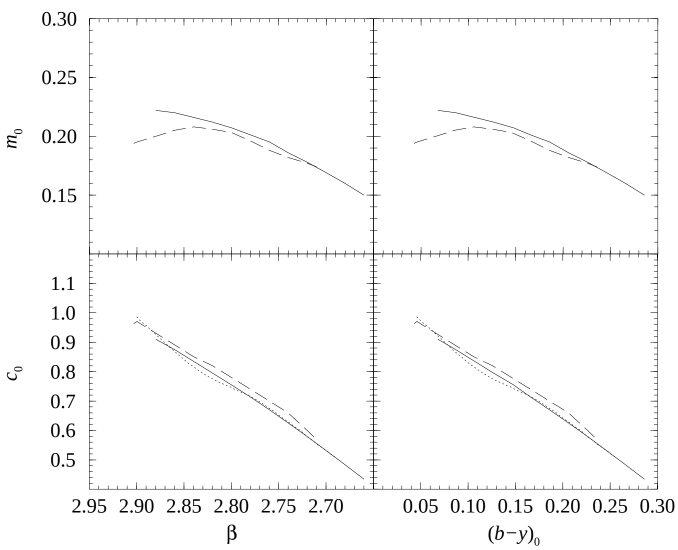

Fig. 3. Hyades standard relations for the m_0 index (*upper panels*) and ZAMS relations for the c_0 index (*lower panels*) from different sources. Long dashed line: Crawford (1979), continuous line: Mathew & Rajamohan (1992), dotted line: Schaller et al. (1992).

calibration were unreddened ($\delta c_0 = \delta c_1$, $\delta m_0 = \delta m_1$ and $(b-y)_0 = (b-y)$).

As in Guthrie's work, our calibrations depend on the photometric parameters δc_0 and δm_0, on $v \sin i$ and, in the least squares fit, also on an already published $M_V(ZAMS)$ relation. The calibrations most widely used to derive these photometric parameters are those of Crawford (1979). Mathew & Rajamohan (1992) published new ZAMS relations (Appendix B:) which were constructed accounting for rotational effects. These relations are compared in Fig. 3. The Hyades relations $m_0 - \beta$ and $m_0 - (b-y)_0$ of both authors differ significantly for the hottest stars (smallest $(b-y)_0$ and largest β values). The observed difference in the $c_0 - \beta$ or $c_0 - (b-y)_0$ planes plays an important role in the final position of the ZAMS relation ($M_V - \beta$, $M_V - (b-y)_0$) derived with the BCES method (see Sect. 4.2). Fig. 3 also shows the theoretical ZAMS of the Schaller et al. (1992) evolutionary models, translated to the observational plane through the Masana's (1998) code based on the Napiwotzki et al. (1993) interpolation procedure and the Moon & Dworetsky (1985) grids for solar abundance. The $(b-y)_0$ index was derived using the $\beta - (b-y)_0$ relation of Crawford (1979).

4.1. *Least squares fit*

The first method we used to derive a new calibration was the classical weighted least squares fit. The stars were weighted with $w_i = 1/\sigma^2_{M_V}$, σ_{M_V} calculated according to:

$$\sigma_{M_V} = 2.172 \frac{\sigma_\pi}{\pi} \tag{3}$$

where π and σ_π are the parallax and its standard error from Hipparcos data, respectively. We fit the relation:

$$M_V - M_V(ZAMS) = a + c\,\delta c_0 + d\,\delta m_0 + \\ +\ e\,10^{-6}(v \sin i)^2 \tag{4}$$

where a, c, d and e are the coefficients to fit and $M_V(ZAMS)$ the absolute magnitude the star would have on the ZAMS, computed through their β or $(b-y)_0$ using the Crawford (1979) or Mathew & Rajamohan (1992) relations. For the 15 Am stars without observed $v \sin i$, a mean value of $54\,\mathrm{km\,s^{-1}}$ was assigned (the mean $v \sin i$ value calculated for the rest of Am stars).

The relations obtained with this method are presented in Table 1. "Cr" and "MR" in the first column mean that we used the Crawford (1979) or Mathew & Rajamohan (1992) standard relations respectively to compute $M_V(ZAMS)$, δc_0 and δm_0. We have also included in this first column the colour index used to calculate $M_V(ZAMS)$ and the δc_0 and δm_0 parameters.

As an example, the correlation matrix obtained in the MR(β) weighted least squares fit (third row in Table 1) was:

$$\begin{pmatrix} 1.00 & -0.43 & -0.08 & -0.39 \\ & 1.00 & -0.28 & -0.16 \\ & & 1.00 & -0.50 \\ & & & 1.00 \end{pmatrix}$$

indicating that all the correlations between the "independent" variables of δm_0, δc_0 and $(v \sin i)^2$ are smaller than 0.5 and thus should not adversely affect the least squares solution. We can observe the presence of a correlation between δm_0 and $(v \sin i)^2$, already commented in a previous paragraph. Another correlation between δc_0 and δm_0, already pointed out by Crawford (1979) and Gray & Garrison (1989), is also present but less

Table 2. Coefficients of the calibrations obtained using the iterative BCES method (5). The first column shows the relation used to compute the δc_0 and δm_0 parameters (see the explanation in the main text). We also show the root mean square of the residuals for only Am stars (σ_{Am}), only normal A-type stars (σ_A) and the total sample (σ_{Am+A}).

method (BCES)	a	$b_{(\beta-2.7)}$	$b_{(b-y)_0}$	c	d	e	σ_{Am}	σ_A	σ_{Am+A}
Cr relations	2.88 ± 0.03	-4.6 ± 0.5	–	-7.9 ± 0.2	$+6.3 \pm 0.9$	$+4.2 \pm 1.1$	0.24	0.23	0.23
	1.86 ± 0.03	–	4.0 ± 0.4	-9.2 ± 0.3	$+5.0 \pm 0.8$	$+2.7 \pm 1.1$	0.20	0.24	0.23
MR relations	3.20 ± 0.03	-6.3 ± 0.5	–	-7.9 ± 0.2	$+6.4 \pm 0.8$	$+4.3 \pm 1.1$	0.24	0.22	0.23
	1.75 ± 0.03	–	5.9 ± 0.4	-9.1 ± 0.3	$+4.4 \pm 0.7$	$+3.0 \pm 1.1$	0.20	0.24	0.23
Cr-MR relations	3.16 ± 0.03	-5.5 ± 0.5	–	-7.9 ± 0.2	$+6.2 \pm 0.8$	$+4.4 \pm 1.1$	0.24	0.22	0.23
	1.88 ± 0.03	–	5.2 ± 0.4	-9.1 ± 0.3	$+4.9 \pm 0.8$	$+2.7 \pm 1.0$	0.20	0.24	0.23

important. To confirm that these correlations did not invalidate the calibrations obtained, we checked that no remaining trends were present in the final residuals plotted against each of the variables involved in the fitting procedure.

Nevertheless, the least squares method does not allow us to take into account the errors either in photometry or in rotational velocities, for which only the errors in the dependent variable (the absolute magnitude) were considered. Akritas & Bershady (1996) discussed extensively how the ordinary least squares (OLS) method can lead to biased slopes if measurement errors are present in the independent variables, which is our case. Furthermore, in the weighted least squares (WLS), a weight according to the variance of the measurement errors can also introduce biases if this variance depends on the observation (Akritas & Bershady, 1996). Taking all that into account, an alternative fitting procedure is described in the next section.

4.2. BCES fit

Akritas & Bershady (1996) proposed a new method for linear regression analysis named the BCES estimator (for Bivariate Correlated Errors and intrinsic Scatter). This estimator is an extension of the OLS which makes it possible to have correlated errors between both variables and to consider the case when the standard deviation of the errors depends on the observation. It also accommodates an entirely unknown intrinsic scatter. The method has only been developed for two variables, so in order to apply the BCES method to our case we developed an iterative procedure to fit the five parameters (a, b, c, d and e) present in the relation:

$$M_V \;=\; a + b\,\chi + c\,\delta c_0 + d\,\delta m_0 + e\,10^{-6}(v \sin i)^2 \qquad (5)$$

where χ denotes $(\beta - 2.7)$ or $(b-y)_0$, depending on the index used to account for temperature effects. The computation of the individual errors for all the variables involved in the relation to be fitted can be found in Appendix C:. In contrast with the WLS method described in the previous section, no a priori ZAMS relation in the $M_V - \beta$, $M_V - (b-y)_0$ planes is included in Eq. (5).

In the first step of the iterative procedure, a linear M_V fit to the colour index accounting for temperature was performed. A second fit allowed the finding of a linear relation between the residuals obtained in the first fit and the second parameter δc_0.

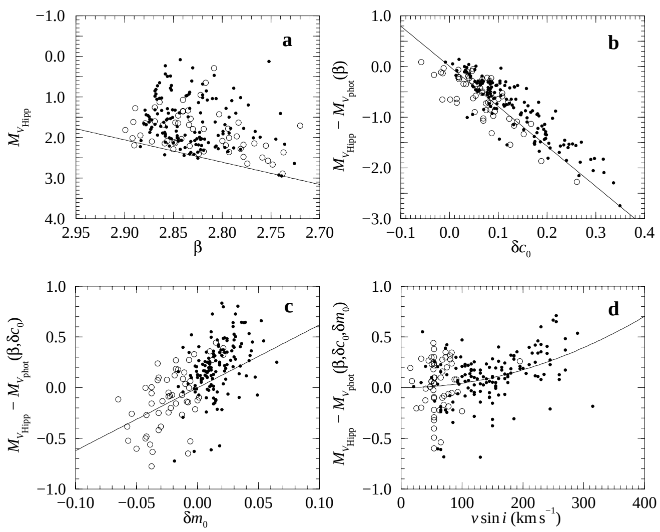

Fig. 4a–d. Effects of temperature **a**, evolution **b**, metallicity **c** and rotation **d** on the photometric absolute magnitude computed with Cr-MR relations. In all panels, the continuous curve represents the result obtained through the BCES method. (Normal A-type stars: dots; Am stars: open circles).

From the new residuals, the same procedure was followed to derive the dependence on δm_0 and finally on $v \sin i$. An iterative procedure was then performed until the convergence of all the coefficients was achieved. We checked that the final coefficients obtained were independent of the order followed to fit the parameters. Fig. 4 shows how the different effects are taken into account step by step in this BCES fit (the β index has been used as indicator of effective temperature). Panel **a** represents an HR diagram, while the others show the residuals between Hipparcos and photometric M_V, when the latter is calculated accounting only for the term with β (panel **b** $=$ evolutionary effects), the terms with β and δc_0 (panel **c** $=$ metallicity effects) and the terms with β, δc_0 and δm_0 (panel **d** $=$ rotational effects). The fit in panel **a** (Fig. 4) can be considered as the zero rotation ZAMS at Hyades metallicity found through the BCES method.

Table 2 shows the results of the BCES fit according to Eq. (5). As in Sect. 4.1, we used the relations from Crawford (1979) (Cr relations) and Mathew & Rajamohan (1992) (MR relations) to compute the δc_0 and δm_0 parameters. The row labeled as "Cr-MR relations" in the first column represents the

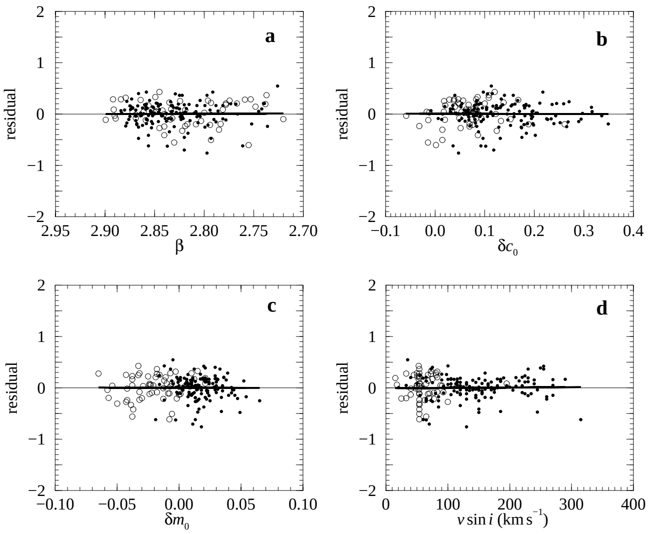

Fig. 5a–d. Residuals obtained using our calibration (Eq. (5) and Cr-MR relations) plotted against each of the fitted parameters. We also shown the regression line in each panel (thick lines). (Normal A-type stars: dots; Am stars: open circles).

results obtained using the Cr relation to compute δm_0 and the MR relation to compute δc_0. Again, to confirm that the correlation among variables do not invalidate the calibrations obtained, the final residuals have been plotted against each of the independent variables. As shown in Fig. 5, there are no remaining trends in the residuals.

In Fig. 6 we compare the ZAMS derived from the BCES method with the observational (Crawford, 1979 and Mathew & Rajamohan, 1992) and the theoretical ZAMS (Schaller et al., 1992) from the literature. The theoretical ZAMS was translated to the observational plane following the same procedure used in Fig. 3. As indicated above, the observed discrepancy in the $c_0 - \beta$ or $c_0 - (b-y)_0$ planes (Fig. 3) between Crawford (1979) and Mathew & Rajamohan (1992), becomes important in the derivation of the vertical position of the ZAMS relations ($M_V - \beta$, $M_V - (b-y)_0$). Fig. 6 also shows that the discrepancy observed in the Hyades relation $m_0 - \beta$ and $m_0 - (b-y)_0$ (Fig. 3) changed the slope of the computed ZAMS slightly. On the other hand, we checked that the ZAMS derived with the BCES method using only Crawford (1979) colour-colour relations was not a good lower envelope, since a relatively large number of stars (Am and normal A-type) were located below this ZAMS. This could be caused by an error in the zero point of the $c_0 - \beta$ and $c_0 - (b-y)_0$ relations. When we used only the MR relations to compute δc_0 and δm_0, some hot stars were also located below the computed ZAMS. So, we conclude that the ZAMS derived using Cr-MR relations (see Fig. 4a) is a good lower envelope of the stars with high precision Hipparcos parallax in this spectral range.

4.3. Discussion

Both BCES and WLS fits are equally good in the light of the obtained root mean square residuals. However, the BCES method

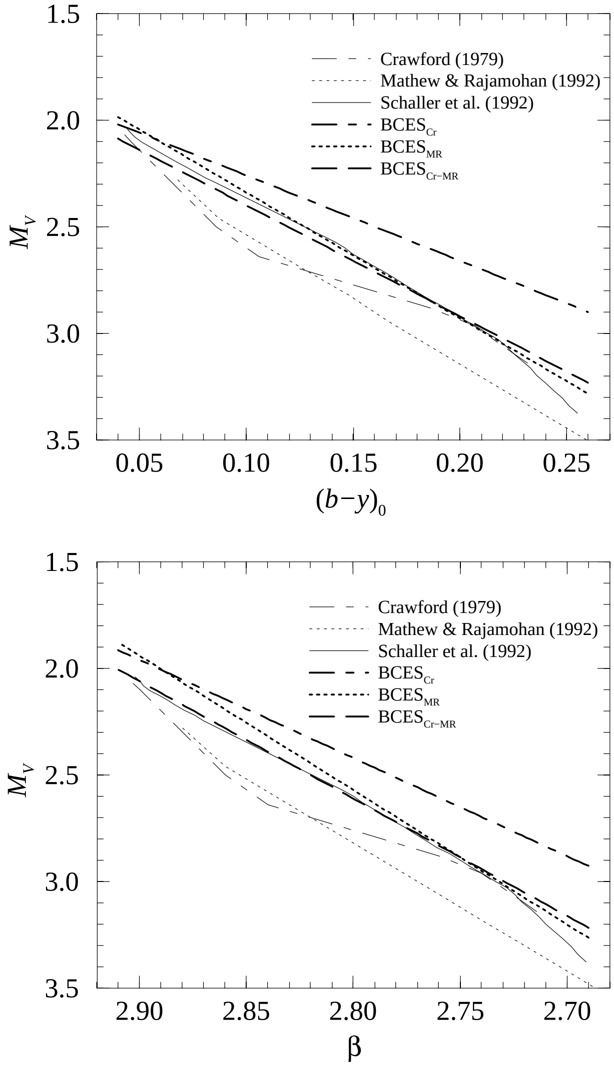

Fig. 6. Comparison between ZAMS relations from the literature (observational: Crawford, 1979 and Mathew & Rajamohan, 1992; theoretical: Schaller et al., 1992) and ZAMS relations computed with the BCES method using different colour-colour relations (Cr, MR and Cr-MR; see the explanation in the main text) to calculate the δc_0 and δm_0 parameters.

is more advantageous because it takes into account all the observational errors and removes the possible biases derived from them. Furthermore, the zero point derived in the least squares fit method (a coefficient, Table 1), revealed that a correction of about 0.2–0.3 magnitudes had to be added to the old observational ZAMS used in the least squares fit method.

In contrast, the ZAMS obtained from the BCES fit when the Cr relation is used to derive δm_0 and the MR relation is used to derive δc_0 is a good lower envelope for the stars of our sample. We note that the theoretical ZAMS (Schaller et al., 1992) is also in excellent agreement with this ZAMS. When we consider only the MR relations, the derived ZAMS is also a good lower envelope for the coolest stars of the sample but a little worse for the hottest stars (mainly for the ZAMS in the $M_V - \beta$ plane). Therefore, we recommend the calibrations obtained in Table 2, emphasizing the good ZAMS obtained when the combined Cr-MR relations are used. From this table, the final calibrations in this case are:

$$M_V = (3.16 \pm 0.03) - (5.5 \pm 0.5)\,(\beta - 2.7) - (7.9 \pm 0.2)\,\delta c_0 + (6.2 \pm 0.8)\,\delta m_0 + (4.4 \pm 1.1)\,10^{-6}(v \sin i)^2 \quad (6)$$

$$M_V = (1.88 \pm 0.03) + (5.2 \pm 0.4)\,(b - y)_0 - (9.1 \pm 0.3)\,\delta c_0 + (4.9 \pm 0.8)\,\delta m_0 + (2.7 \pm 1.0)\,10^{-6}(v \sin i)^2 \quad (7)$$

Table 2 shows the influence of the photometric relations used in the computation of δc_0 and δm_0, on the derivation of a good photometric absolute magnitude calibration. Future work will be necessary to solve the discrepancies between the Crawford (1979) and the Mathew and Rajamohan (1992) photometric relations.

5. Evolutionary state of Am stars

At the early 1980's, the evolutionary state of Am stars was studied by Gómez et al. (1981) using the Heck (1975) statistical parallax method. That study concluded that Am stars were above the main sequence, about a magnitude brighter than main-sequence normal A-type stars. More recently, Nicolet (1997) has used Hipparcos data to analyze the position of Am stars in the HR diagram concluding that even considering that binarity can raise the star position up to -0.75 magnitudes, most Am stars are raised by a higher value. In contrast, Gómez et al. (1998) using the LM method (Luri et al., 1996) and also Hipparcos data, concluded that Am stars present the same kinematical behaviour of non-peculiar main-sequence disk stars younger than about 1.5 Gyr.

In Fig. 7 we have plotted our stars in the $M_{\rm bol} - \log T_{\rm eff}$ plane. As in Sect. 4, only stars with Hipparcos distance less than 100 pc have been considered (59 Am stars and 143 normal A-type stars), and no reddening correction has been applied to them. In this way, almost all stars have relative distance errors lower than 10 %; that is, an error in absolute magnitude less than $0.22^{\rm m}$. The effective temperatures were computed with Strömgren photometry, interpolating in the Moon & Dworetsky (1985) grids for solar abundance with the Napiwotzki et al. (1993) algorithm. Absolute bolometric magnitudes were computed using parallaxes and apparent magnitudes from Hipparcos and bolometric corrections from Flower (1996). In the same figure, the theoretical ZAMS, evolutionary tracks and isochrones from the Schaller et al. (1992) models for solar abundance have been plotted. The position of the Am stars in the HR diagram is totally compatible with that of normal A-type stars, Am stars being along the whole width of the main sequence. We checked that the shift in $\log T_{\rm eff}$ produced when we used grids at $[Fe/H] = 0.5$ (Napiwotzki, 1998) instead of $[Fe/H] = 0.0$ does not change our conclusion. This shift was estimated ~ -0.005 dex for $\log g = 4.0$ dex. Furthermore, even taking into account the shift in the evolutionary models produced by diffusion effects (see Michaud & Proffitt, 1993; Richer et al., 1992), our results indicate that there are no significant differences between the evolutionary state of Am stars and main-sequence normal A-type stars.

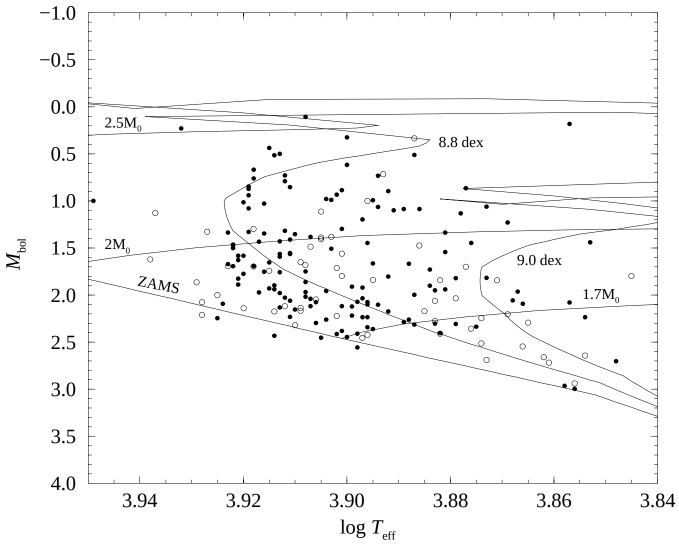

Fig. 7. Am stars (open circles) and normal A-type stars (dots) in the HR diagram. Bolometric magnitudes have been computed from Hipparcos parallaxes and Flower (1996) bolometric corrections; effective temperatures from Moon & Dworetsky (1985) grids. Theoretical ZAMS, tracks and isochrones are from Schaller et al. (1992).

6. Conclusions

Using highly accurate Hipparcos trigonometric parallaxes (ESA, 1997) the old photometric calibrations of absolute magnitudes for main-sequence late A-type stars have been revised, and a new calibration valid for normal A-type and Am stars is proposed. Special attention has been paid to minimize the possible biases caused by selection effects. The main conclusions of our work can be summarized as follows:

- The Crawford (1979) calibration, although reproducing quite well the absolute magnitudes of normal A-type stars, shows important systematic trends and large dispersions when it is applied to Am stars: differences up to ~ 5 mas between photometric and Hipparcos parallaxes are clearly above the Hipparcos accuracy.
- The corrections proposed by Guthrie (1987) for metallicity and rotation are too large. Systematic trends ~ 5 mas are present for normal A-type stars.
- Although metallicity and rotation are highly correlated in this spectral range, a dependence of M_V on $(v \sin i)^2$ is detected for stars with $v \sin i > 100\,{\rm km\,s^{-1}}$.
- The observational ZAMS proposed by Crawford (1979) and Mathew & Rajamohan (1992) are 0.2–0.3$^{\rm m}$ below the ZAMS derived in the present paper. Our derived observational ZAMS is in excellent agreement with the theoretical ZAMS (Schaller et al., 1992).
- When we analyzed the evolutionary state of Am stars in an HR diagram, we observed that they are scattered along the

Table B1. ZRZAMS relations for A-type stars (Mathew & Rajamohan, 1992).

β	$(b-y)_0$	m_0	c_0	M_V
2.66	0.286	0.150	0.435	3.66
2.68	0.266	0.160	0.484	3.54
2.70	0.246	0.169	0.532	3.42
2.72	0.226	0.178	0.580	3.30
2.74	0.206	0.186	0.626	3.18
2.76	0.186	0.195	0.670	3.06
2.78	0.166	0.201	0.713	2.94
2.80	0.148	0.207	0.755	2.82
2.82	0.127	0.212	0.795	2.70
2.84	0.107	0.216	0.835	2.58
2.86	0.087	0.220	0.874	2.46
2.88	0.068	0.222	0.910	2.28

whole width of the main sequence, like normal A-type stars. Consequently, there are no significant differences between the evolutionary state of both types of stars, in agreement with Gómez et al. (1998).

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Appendix A: new VRI Cousins photometry

Some of the Am stars of our sample without VRI photometry from the literature were observed on the 17th June, 1996 with the 1.52 m telescope of the Observatorio Astronómico Nacional (O.A.N.) at Calar Alto (Almería, Spain), and on the 25th and 26th of the same month using the 1 m Jakobus Kapteyn telescope at the Observatorio del Roque de los Muchachos (O.R.M., Canary Islands, Spain). Combining the results of all three nights, we have new VRI Cousins photometry for 63 Am stars. The reduction procedure followed is explained in Rosselló et al. (1985), and Landolt (1983a; 1983b) standard stars were used.

Table A1 (available only in electronic form) gives VRI Cousins measurements for these 63 Am stars. We provide the V magnitude, the $(V-R)$ and $(V-I)$ colour indices, their associated standard errors and the number of observations performed for each star.

Appendix B: computation of δm_0 and δc_0 from Mathew & Rajamohan (1992)

Table B1 shows the Mathew & Rajamohan (1992) standard photometric relations for the zero rotation ZAMS for A-type stars, from which δm_0 and δc_0 can be computed following the procedure described in Crawford (1979).

Appendix C: errors assigned to the parameters involved in the BCES fit

Standard deviations of absolute magnitude M_V have been computed by propagating the individual σ_π given in the Hipparcos catalogue and adopting a mean value of $\sigma_V = 0.02^{\,\mathrm{m}}$.

Individual observational errors in $(b-y)$, c_1 and m_1 are only available for 64 % of our sample, and errors on the β index only for 54 %. The mean of these errors has been assigned to the remaining stars. Keeping in mind the definition of δc_1 and δm_1 parameters, we estimate their individual standard errors as follows:

$$\begin{aligned}\sigma^2_{\delta c_1} &= \sigma^2_{c_{obs}} + \sigma^2_{c_{ZAMS}} + \sigma^2_{\chi\longrightarrow c_{ZAMS}}\\ \sigma^2_{\delta m_1} &= \sigma^2_{m_{obs}} + \sigma^2_{m_{Std}} + \sigma^2_{\chi\longrightarrow m_{Std}}\end{aligned}$$

where χ denotes β or $(b-y)$. $\sigma_{c_{obs}}$ and $\sigma_{m_{obs}}$ are the observational errors on c_1 and m_1 colour indices, $\sigma_{c_{ZAMS}}$ and $\sigma_{m_{Std}}$ the intrinsic scatter of the $c_1(\chi)_{ZAMS}$ and $m_1(\chi)_{Hyades}$ relations, and $\sigma_{\chi\longrightarrow c_{ZAMS}}$ and $\sigma_{\chi\longrightarrow m_{Std}}$ the errors propagated from the observational errors on χ on the above relations. We have adopted $\sigma_{\chi\longrightarrow c_{ZAMS}} = 2\,\sigma_\chi$ and $\sigma_{\chi\longrightarrow m_{Std}} = \frac{3}{10}\sigma_\chi$, deduced through the slope of their respective relations.

Systematic errors can appear in our compilation of equatorial rotational velocities, as they have been extracted from different sources. Therefore, as a compromise we have applied a mean standard error of $\sigma_{v\sin i} = 20\,\mathrm{km\,s^{-1}}$ for all the stars.

References

Abt H.A., Morrell N.I., 1995, ApJS 99, 135
Akritas M.G., Bershady M.A., 1996, ApJ 470, 706
Brown A.G.A., Arenou F., van Leeuwen F., Lindegren L., Luri X., 1997, Hipparcos Venice'97, ESA SP-402, p. 63
Crawford D.L., 1979, AJ 84, 1858
Domingo A., 1998, Master Thesis, Universitat de Barcelona
ESA, 1997, The Hipparcos and Tycho Catalogues. ESA SP-1200
Figueras F., Blasi F., 1998, A&A 329, 957
Figueras F., Torra J., Jordi C., 1991, A&AS 87, 319
Flower P.J., 1996, ApJ 469, 355
Gómez A.E., Grenier S., Jaschek M., Jaschek C., Heck A., 1981, A&A 93, 155
Gómez A.E., Luri X., Sabas V., et al., 1998, Astron. Obs. Skalnaté Pleso 27, 171
Gray R.O., Garrison R.F., 1989, AJS 70, 623
Guthrie B.N.G., 1987, MNRAS 226, 361
Hauck B., 1992, Bull. Inf. CDS 40, 19
Hauck B., Mermilliod M., 1998, A&AS 129, 431
Heck A., 1975, Ph.D. Thesis, Liège
Jaschek C., Jaschek M., 1987, The Classification of Stars. Cambridge University Press, p. 217
Jordi C., Figueras F., Torra J., Asiain R., 1996, A&AS 115, 401
Kurucz R.L., 1979, ApJS 40, 1
Landolt A.U., 1983a, AJ 88, 439
Landolt A.U., 1983b, AJ 88, 853
Luri X., Arenou F., 1997, Hipparcos Venice'97, ESA SP-402, p. 449
Luri X., Mennessier M.O., Torra J., Figueras F., 1993, A&A 267, 305
Luri X., Mennessier M.O., Torra J., Figueras F., 1996, A&AS 117, 405

Lutz T.E., 1979, MNRAS 189, 273
Lutz T.E., Kelker D.H., 1973, PASP 85, 573
Malmquist K.G., 1936, Meddel. Stockholm Obs. 26
Masana E., 1998, private communication
Mathew A., Rajamohan R., 1992, JA&A 13, 61
Michaud G., Proffitt C.R., 1993, Particle Transport Processes. In: Weiss W.W., Baglin A. (eds.) Inside the Stars. ASP Conference Series, vol. 40, 246
Moon T.T., Dworetsky M.M., 1985, MNRAS 217, 305
Napiwotzki R., 1998, private communication
Napiwotzki R., Schönberner D., Wenske V., 1993, A&A 268, 653
Nicolet B., 1997, Hipparcos Venice'97, ESA SP-402, p. 245
Renson P., Gerbaldi M., Catalano F.A., 1991, A&AS 89, 429
Richer J., Michaud G., Proffitt C.R., 1992, ApJS 82, 329
Rosselló G., Calafat R., Figueras F., et al., 1985 A&AS 59, 399
Schaller G., Schaerer D., Meynet G., Maeder A., 1992, A&AS 96, 269
Schneider H., 1993, CP Stars at High Galactic Latitude: Photometry near the Galactic Poles. In: Dworetsky M.M., Castelli F., Faraggiana R. (eds.) Peculiar Versus Normal Phenomena in A-Type and Related Stars. ASP Conference Series, vol. 44, 592
Turon C., Crézé M., Egret D., et al., 1992a, The Hipparcos Input Catalogue. ESA SP-1136
Turon C., Gómez A., Crifo F., et al., 1992b, A&A 258, 74
Uesugi A., Fukuda I., 1982, Revised Catalogue of Stellar Rotational Velocities. Kyoto Univ., Japan
Wolff S.C., 1983, The A-Type Stars: Problems and Perspectives. Monograph Series on Nonthermal Phenomena in Stellar Atmospheres, NASA SP-463
Zorec J., 1992, L'effet de la rotation sur la magnitude absolue des étoiles. In: Benest D., Froeschlé C. (eds.) Hipparcos. Une nouvelle donne pour l'Astronomie, Goutelas, p. 407