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Colour–Magnitude analysis of five old open clusters*

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Abstract. The Galileo Telescope was used to carry out *BV* photometry of five faint open clusters, for which no Colour Magnitude Diagrams were available in the literature. The clusters Berkeley 24, Berkeley 35, Berkeley 78, PWM 1, and PWM 4 are found to be old open clusters. Berkeley 24, Berkeley 35, and PWM 4 show a red clump. We fitted Padova isochrones to derive reddening and distance. The clusters Berkeley 35 and Berkeley 78 show low $E(B-V) = 0.0$ and 0.01 compatible with their relatively high Galactic latitudes, whereas higher values of $E(B-V) = 0.4$, 0.94 and 0.62 are found for Berkeley 24, PMW1, PMW4. Their distances to the Sun are in the range $4.4 < d_{\odot} < 7.9$ kpc implying that they are at distances of 11.5 to 13.5 kpc from the Galactic center. The isochrone fitting show ages in the range 1.0 < Age (Gyr) < 6.3. Further discussion of the different methods used to derive age is given, in particular using the difference in magnitude between turn-off and giant clump, which gives lower ages. The contribution of the five old open clusters studied here, with basic parameters known, increases the overall sample to 108 objects. An important addition is the very old (6.3 Gyr) open cluster PWM 4.

Key words. Galaxy: disk – hertzsprung-Russell (HR) and C-M diagrams – open clusters and associations: general

1. Introduction

An important Galactic disk subsystem is that of old open clusters, which helps tracing disk structure and evolution. Dias et al. (2002, and references therein) catalogued 1537 open clusters. Assuming old open clusters are older than the Hyades with age of 787 Myr (according the WEBDA database at `http://obswww.unige.ch/webda`, Mermilliod 1996), Friel (1995) and Ortolani et al. (2005) updated and included new objects. The age histogram of 103 old open clusters shows an interesting peak at 5 Gyr. In studies of individual stars, prominent peaks are seen around 8, 4, and 2.5 Gyr (Fig. 2 of Rocha-Pinto et al. 2000). The open cluster histogram instead reflects the formation and destruction rates of these objects.

Five old open clusters, with no previous Colour-Magnitude Diagram (CMD) studies are presented. One of our team (E.B.) selected candidates to be old open clusters by extensive inspection of images of non-studied open clusters and improved coordinates based on inspection of Digitized Sky Survey images DSS and XDSS. The selection was based on stellar brightness distribution, degree of concentration (maybe related to a core), and rather smooth radial distribution of stars checked on DSS and XDSS.

We are dealing with faint clusters requiring large telescopes with good image quality. The objects studied are Berkeley 24 (OCl-539), Berkeley 35 (OCl-541) , Berkeley 78 (OCl-536), PWM 1 and PWM 4. Note that Dias et al. (2002) designate these clusters as Pfleiderer 1 and 4. The Berkeley (Be) clusters are from Setteducati & Weaver (1960) and the PWM ones are from Pfleiderer et al. (1977). The PWMs are faint, supposedly due to high reddening, since they are located at low Galactic latitudes.

No parameters are currently available for these clusters according to the WEBDA open cluster database (Mermilliod 1996).

Isochrones have been improving in recent years, such as the Padova sets of isochrones by Bertelli et al. (1994), Girardi et al. (1996), Girardi et al. (2000a), available at `http://pleiadi.pd.astro.it`. In the present study we derive cluster parameters, and we address the problem of the offset often observed between the observed giant branch clump and its location in the models.

In Sect. 2 the observations are described, while in Sect. 3 the Colour Magnitude Diagrams (CMD) are presented. In Sect. 4 we derive and discuss cluster parameters. Concluding remarks are given in Sect. 5.

* Observations collected at the Galileo National Telescope, La Palma, Spain.

Table 1. Log of observations.

Target	Date	Filter	Exp. (s)	Seeing ″
Be 24	3/2/00	*V*	30	1.2
		V	600	1.2
		B	30	1.5
		B	600	1.3
Be 35	4/2/00	*V*	30	0.9
		V	600	0.9
		B	30	1.0
		B	900	1.0
Be 78	4/2/00	*V*	30	1.1
		V	300	1.1
		V	30	1.1
		B	480	1.1
PWM 1	3/2/00	*V*	30	1.5
	4/2/00	*V*	480	1.2
		B	600	1.3
PWM 4	3/2/00	*V*	30	1.2
		V	480	1.4
		B	30	1.5
	4/2/00	*B*	236	1.0

2. Observations and reductions

The log of observations is presented in Table 1. The object identifications, Galactic and equatorial coordinates, and angular sizes are given in Table 2. Their Galactic latitudes range from close to the plane up to $\approx 10^\circ$. The observations were carried out from February 2–5, 2000, with the 3.55 m Galileo National Telescope at La Palma. The Galileo Optical Imager (OIG) installed at the Nasmyth focus was employed. OIG uses two EEV 42–80 CCDs with 2048×4096 pixels and pixel size 13.5 μm. The CCD was read in a binned mode of 2×2 pixels. The projected binned pixel size on the sky is $0.144''$, with a total field of view of $4.9' \times 4.9'$. The nights were photometric. Each night, typically 30 images of standard star fields from Landolt (1983, 1992) were observed. For details on reductions, calibration procedure, and equations see Ortolani et al. (2005).

In Figs. 1 to 5 we show the cluster images. The observing frame is a mosaic of two CCD chips, separated by a gap of $2.8''$. Be 24, Be 35, and Be 78 have angular sizes, estimated from XDSS and DSS images, as given in Table 2, comparable or larger than the frame. Be 24 is populous, Be 78 has a clear core; and a core may be also present in Be 24 and Be 35. PWM 1 and PWM 4 are fainter and with angular size within the frame. Offset fields at $5'$ south were also observed.

3. Colour–Magnitude Diagrams

Short and deep exposures are combined to produce the CMDs. The isochrone best fit primarily optimizes the colour match involving the upper MS and red giant branch (horizontal method). Alternatively, the fit takes the magnitude difference into account between the giant clump and turn-off (TO) of old open clusters, $\Delta V^{\rm TO}_{\rm clump}$ (vertical method), with the latter a potentially accurate age indicator, almost independent of

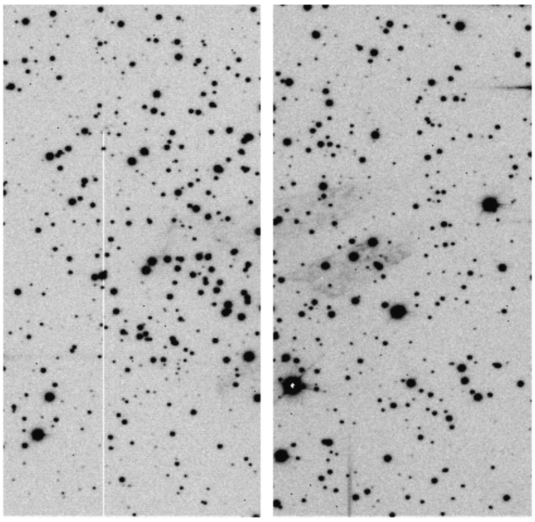

Fig. 1. *V* image (10 min) of Berkeley 24. The field size on each frame is $\approx 4.9' \times 2.45'$, with a gap of $2.8''$ between the two frames. Some reflections arise from bright field stars. North is down and east to the right.

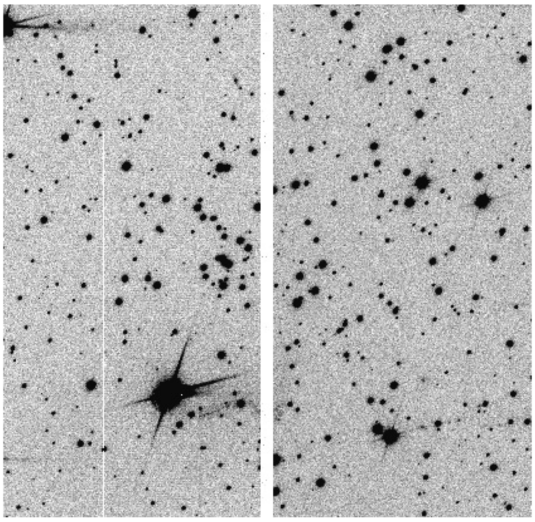

Fig. 2. *V* image (30 s) of Berkeley 35. Some reflections are present. Field size and orientation are as in Fig. 1.

metallicity. Table 2 gives the $\Delta V^{\rm TO}_{\rm clump}$ measured for 3 of the sample clusters. This quantity was measured directly from the observed CMDs and not through fits of isochrones. Based on the Padova isochrones, we derived the age from the best colour match *t*(colour). A measure on the observed diagram of the vertical quantity $t(\Delta V^{\rm TO}_{\rm clump})$ was carried out, independently of the isochrones. Both values are given in Table 4. Surprisingly, the two age values differ by a factor 2.

In order to investigate this problem, we used the Morphological Age Indicator (MAI) method (Janes & Phelps 1994) to derive age *t*(MAI), which establishes a relation between $\Delta V^{\rm TO}_{\rm clump}$ and observed ages. We also considered the $\Delta V^{\rm TO}_{\rm clump}$ method as calibrated by Carraro & Chiosi (1994, hereafter CC94), and derived the age values *t*(CC94). The latter calibration gives values younger than the horizontal method and MAI, but older than our $\Delta V^{\rm TO}_{\rm clump}$ age values (Table 4).

Table 2. Coordinates, angular size, apparent distance modulus, reddening, and $\Delta V^{\rm TO}_{\rm clump}$. The uncertainty on the reddening due to fits is around ±0.03, whereas allowing for metallicities lower by 0.3 dex it might amount to as much as $\Delta E(B-V) \approx +0.11$.

Object	α(2000)	δ(2000)	l (∘)	b (∘)	Size (arcmin)	$(m-M)$	$E(B-V)$	$\Delta V^{\rm TO}_{\rm clump}$
Be 24	06 37 47	−00 52 19	212.15	−3.43	7	14.6	0.4	1.4
Be 35	07 09 56	02 44 01	212.60	5.36	6	13.2	0.0	0.1
Be 78	07 23 38	05 22 15	211.78	9.59	6	13.4	0.01	–
PWM 1	01 08 07	65 38 50	124.65	2.83	3	17.2	0.94	–
PWM 4	23 50 55	62 19 15	115.96	0.27	4	16.4	0.62	2.3

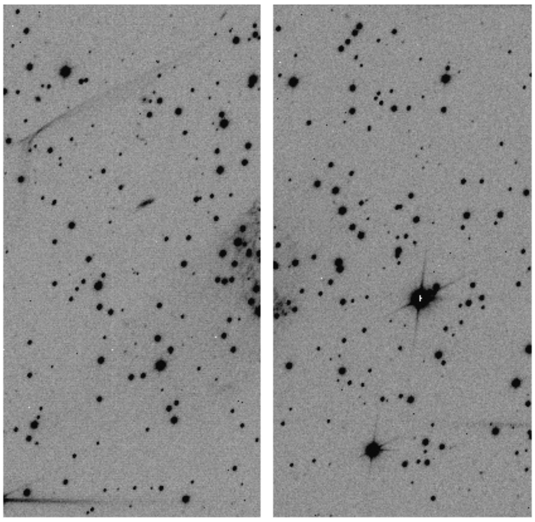

Fig. 3. *V* image (5 min) of Berkeley 78. Field size and orientation as in Fig. 1.

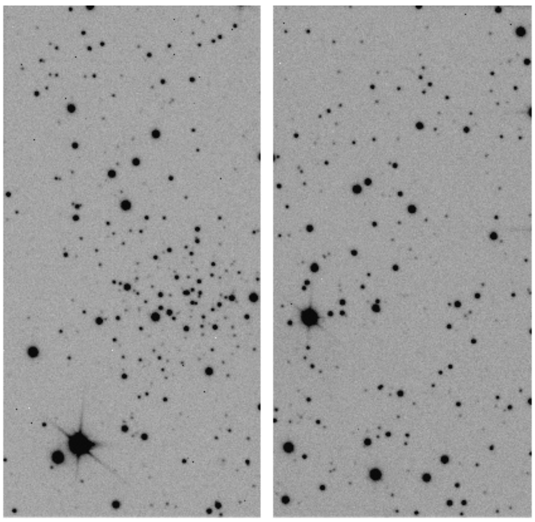

Fig. 4. *V* image of PWM 1 (8 min). Field size and orientation as in Fig. 1.

We note that the MAI method is actually an average of two measurements, the $\Delta V^{\rm TO}_{\rm clump}$ and the colour difference between the turnoff and a point one magnitude above the turnoff. The latter is similar to our t(colour). Therefore t(MAI) is close to t(colour).

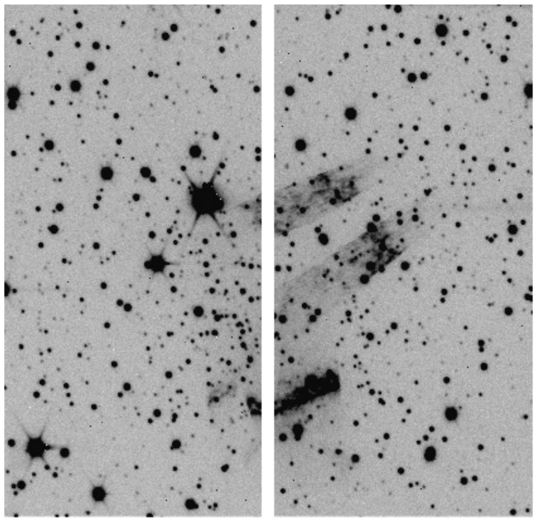

Fig. 5. *V* image of PWM 4 (8 min). Reflections arise from bright field stars. Field size and orientation as in Fig. 1.

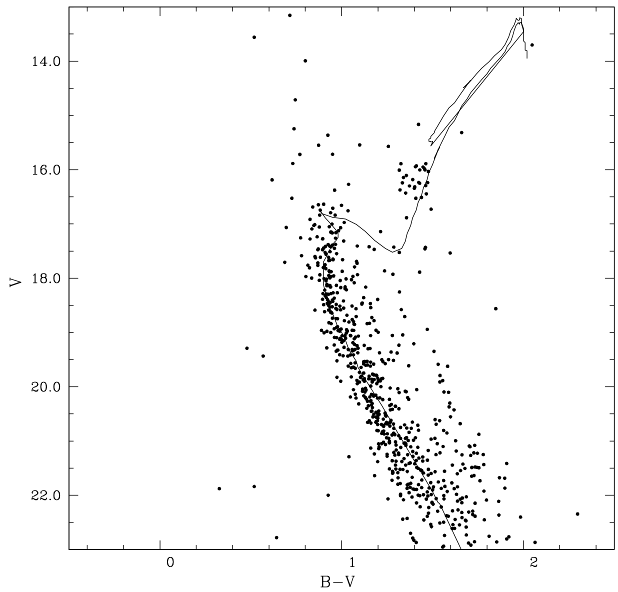

Fig. 6. *V*, $B-V$ diagram of Be 24 for the whole field. An isochrone of 2.5 Gyr is overplotted.

The *V* vs. $B-V$ CMD of Be 24 for the whole field is shown in Fig. 6. The cluster Main Sequence (MS) and the giant clump are clearly seen. A best fit of 2.5 Gyr isochrone is overplotted. Tentative fits with 3.0 and 2.0 Gyr showed that the internal error

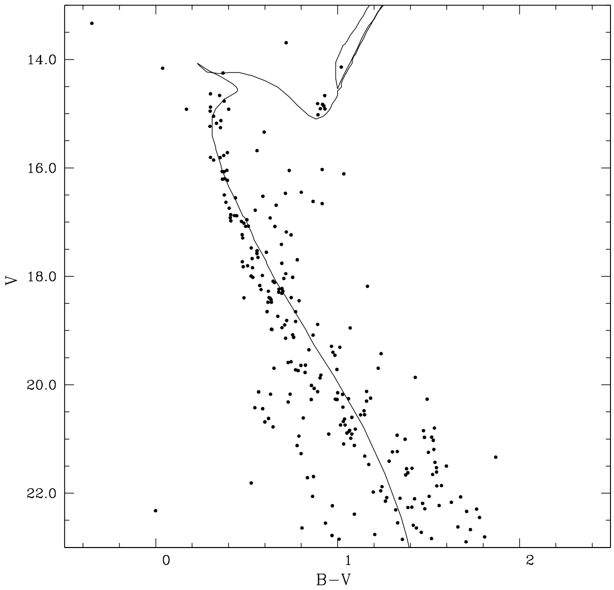

Fig. 7. V, $B-V$ diagram of Be 35 for an extraction of $r < 100''$ with a 1.1 Gyr isochrone overplotted.

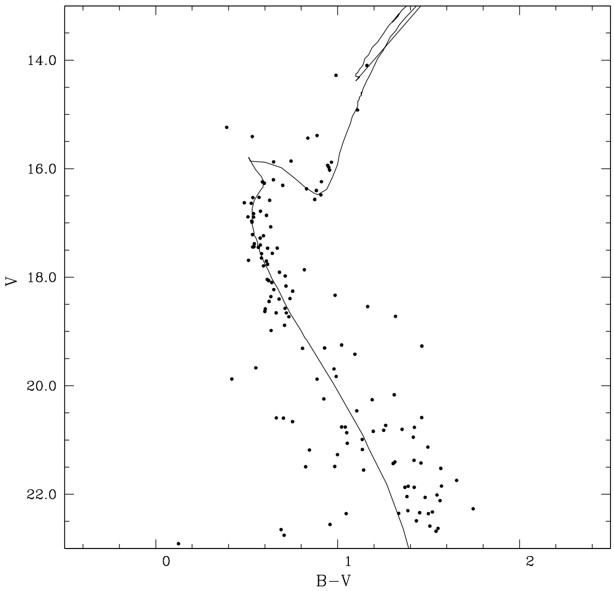

Fig. 8. V, $B-V$ diagram of Be 78 for an extraction of $r < 94''$ with a 2.8 Gyr isochrone overplotted.

on the age is ±0.5 Gyr. Using instead the $\Delta V_{\rm clump}^{\rm TO}$ method, an age of 1.4 Gyr is derived.

The CMD of Be 35 (Fig. 7) for an extraction of $r <$ 700 pixels ($r < 100''$) shows a clear cluster MS and a giant clump. A best fit is obtained for 1.1 Gyr. A younger age of 0.5 Gyr is obtained with the $\Delta V_{\rm clump}^{\rm TO}$ measure.

For Be 78 (Fig. 8), an extraction of $r < 650$ pixels, or $r < 94''$, shows an interesting old cluster diagram. A subgiant branch appears, typical of older clusters. An age of 2.8 Gyr is deduced from a best fit isochrone. The lower MS appears to be depleted below $V < 19$, as expected from the cluster dynamical evolution.

PWM 1, in an extraction of $r < 550$ pixels ($r < 79''$), is well fitted with an isochrone of 1 ± 0.3 Gyr, as shown in Fig. 9. The

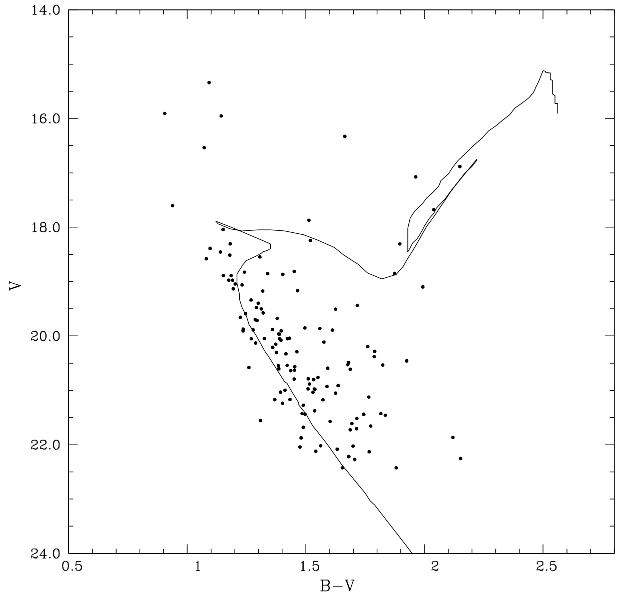

Fig. 9. V, $B-V$ diagram of PWM 1 for an extraction of $r < 79''$ with a best fit obtained for a 1.0 Gyr isochrone.

Table 3. $\Delta V_{\rm clump}^{\rm TO}$ and corresponding age.

$\Delta V_{\rm clump}^{\rm TO}$	0.2	0.7	2.0	2.6	3.3
t(Gyr)	0.5	1.0	2	3	10

spatial location of stars in the MS was checked, and it appears that a core is present.

Two upper MS clumps are located at $V = 18.38$ and $B - V = 1.14$, and $V = 19.0$ and $B - V = 1.19$. All stars of these two clumps are located in the cluster area. The brightest clump is most likely composed of blue stragglers. The lower clump could be the MS TO for the age of 1 Gyr, or alternatively, the cluster could be older (1.5 Gyr), and these stars could be blue stragglers as well, or binaries.

Finally, PWM 4's CMD (Fig. 10b) is an extraction of $r < 500$ pixels ($r < 72''$), and the best fit isochrone is obtained for an age of 6.3 Gyr. The cluster is faint and strongly contaminated by disk stars. The whole field (Fig. 10a) shows that in the lower part of the field MS there is a TO, probably related to the cluster. In fact, despite contamination, Fig. 10b shows an adequate fit to an old open cluster. The $\Delta V_{\rm clump}^{\rm TO}$ method gives, on the other hand, a much younger age of 3.0 Gyr. For this cluster, both the MAI and CC94 are more compatible with the older value.

4. Cluster parameters and discussion

Distances and reddening values are based on the isochrone best fit method. The values derived are dependent on the adopted age values, and would be modified in particular if the ages from the $\Delta V_{\rm clump}^{\rm TO}$ method were adopted. Reddening and apparent distance modulus are given in Table 2. A total-to-selective absorption $R = A_{\rm V}/E(B-V) = 3.1$ is assumed in order to derive $A_{\rm V}$. The distances are derived and given in Table 4.

Table 4. Distance from the Sun, Galactocentric coordinates and distance, and age determinations.

Object	$d_\odot$ (kpc)	X (kpc)	Y (kpc)	Z (kpc)	R_{GC} (kpc)	t(colour) (Gyr)	$t(\Delta V^{TO}_{clump})$ (Gyr)	t(MAI) (Gyr)	t(CC94) (Gyr)
Be 24	4.7	−11.4	−2.5	−0.3	11.6	2.5	1.4	2.2	1.6
Be 35	4.4	−11.7	−2.4	0.4	11.9	1.1	0.5	0.8	–
Be 78	4.8	−12.0	−2.5	0.8	12.3	2.8			
PWM 1	7.2	−12.1	5.9	0.4	13.5	1			
PWM 4	7.9	−11.5	7.1	0.0	13.5	6.3	3	7.0	5.6

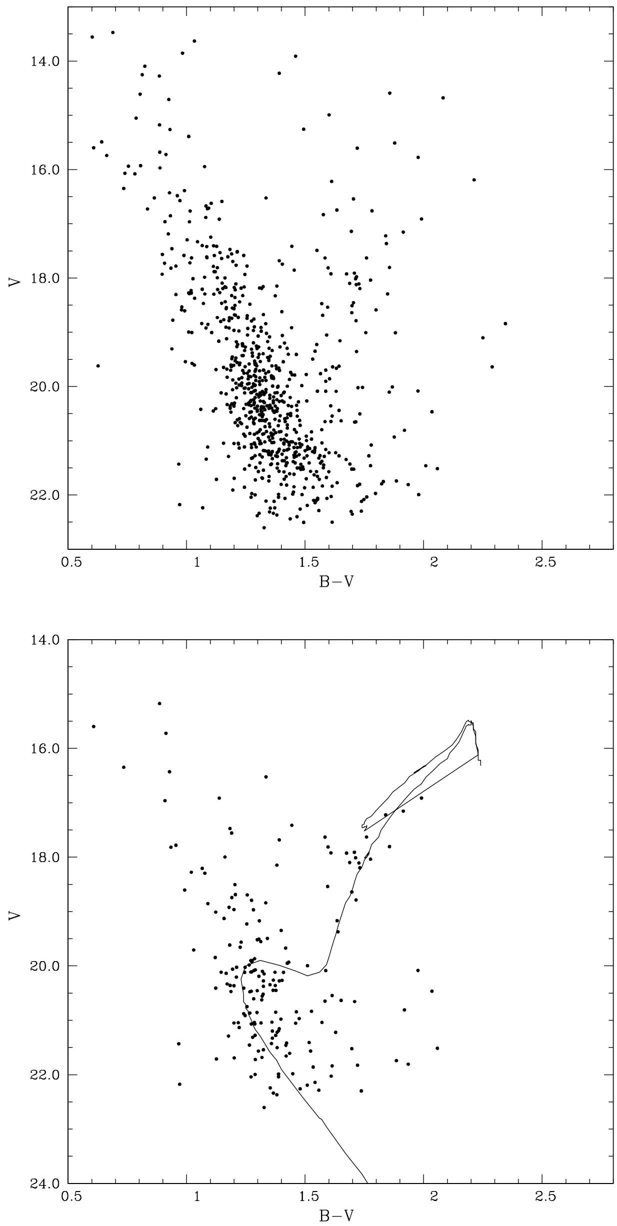

Fig. 10. V, $B-V$ diagram of PWM 4: **a)** whole field **b)** diagram corresponding to an extraction of $r < 72''$. An isochrone of 6.3 Gyr is overplotted on the diagram.

Adopting the distance to the Galactic center as $R_\odot = 8.0$ kpc (Reid 1993; Eisenhower et al. 2003), the Galactocentric coordinates ($X < 0$ means our side of the Galaxy) are derived and reported in Table 4.

4.1. Ages

We used Padova isochrone fitting to the data in two ways: (i) an overall best fit, where a horizontal match of colour difference between MS and giant branch is optimized; (ii) the magnitude difference between TO and giant clump ΔV^{TO}_{clump} (vertical method) is optimized. The resulting ages are however significantly different with Method (ii) giving younger ages, because the giant clump appears systematically lower than in the theoretical isochrones in Method (i).

The MAI method gives results compatible with the colour match method, within uncertainties, despite the fact that giant clumps are systematically fainter relative to predicted loci from the isochrones. CC94 tends to give ages younger than the colour match and MAI, but older than Method (ii).

The ΔV^{TO}_{clump} method is based on a more reliable physics. The systematic difference between the ages from the clump position and the MS TO fit using the isochrones may suggest that the colour transformation from theoretical models to the observational plane is uncertain. On the other hand, most old age galactic open clusters do not show a clear clump due to statistics and field contamination. Therefore ages from the overall fit, used more often in the literature, form a more uniform set of results.

Clusters located beyond the solar circle at galactocentric distances of 12 to 14 kpc probably have sub-solar metallicities, down by about 0.3 dex, according to Friel et al. (2002) and Salaris et al. (2004). We also tested the effect of using lower metallicity isochrones ($Z = 0.008$) in the fits. The net result is that reddening values increase by $\Delta E(B-V) \approx 0.11$, while ages do not change significantly. This is expected because the ΔV^{TO}_{clump} for different metallicities at a fixed age is negligible. The increase in reddening instead results in shorter distances by about 0.5 kpc.

We also tried the set of isochrones from Yonsei-Yale Y^2 (Kim et al. 2003, and references therein). A comparison between isochrones from the two sets (Padova and Y^2) is shown in Fig. 11. For a given age, the Y^2 isochrones are bluer by about 0.1 mag in the RGB and slightly less at the TO. The Y^2 isochrones are in fact not yet suitable to fit most of open clusters, given that the clump is only included in the calculations for older ages. A fit to Be 24 showed an increase in reddening of $\Delta E(B-V) = 0.07$ with respect to the Padova fit (Fig. 6), whereas the distance modulus and age remain the same.

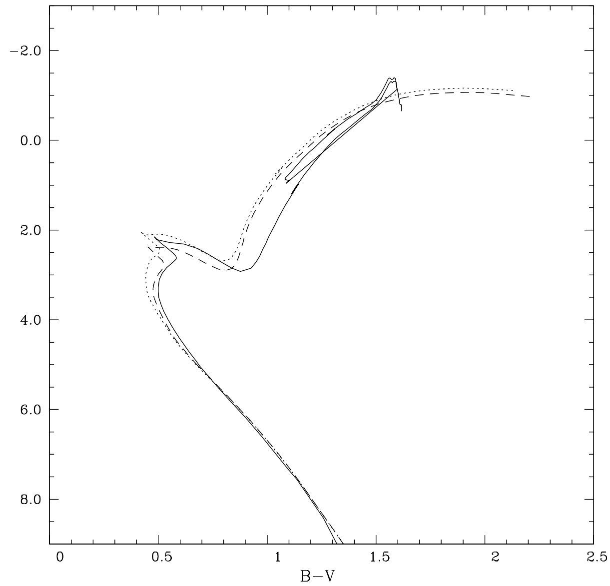

Fig. 11. V, $B-V$ isochrones for solar metallicity and ages of 2.5 Gyr (short-dashed) and 3.0 Gyr (long-dashed) of Y^2 and 2.5 Gyr (solid line) of Padova.

5. Conclusions

We carried out BV photometry of five old open clusters: Be 24, Be 35, Be 78, PWM 1 and PWM 4. From a best fit of solar metallicity isochrones, reddening values of $E(B-V) = 0.4$, 0.0, 0.01, 0.94, and 0.62, respectively were derived. They are all very distant clusters at ∼11.5 to 13.5 kpc from the Galactic center. PWM 4, despite its large Galactocentric distance $R_{GC} \approx 13.5$ kpc and old age, is located close to the plane.

The absolute age determination of old open clusters is more often derived from isochrone fits to the data. The presence of a giant clump in 3 of the sample clusters, indicated that their location is systematically lower relative to the theoretical expectation in the isochrone overall best fits. If the giant clump is well fitted in luminosity, then ages are younger. Different methods of age determination found in the literature are discussed.

The updated sample of old open clusters now amounts to 108 objects by adding the present 5 objects to those described in Ortolani et al. (2005). The number of clusters older than 6 Gyr is still very small with only 8 objects, as can be seen in the age histogram shown in Fig. 11 of Ortolani et al. (2005). In our sample, PWM 4 can be identified as one of these, with 6.3 Gyr.

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