

The old open clusters Berkeley 32 and King 11[★]

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ABSTRACT

We have obtained CCD *BVI* imaging of the old open clusters Berkeley 32 and King 11. Using the synthetic colour–magnitude diagram method with three different sets of stellar evolution models of various metallicities, with and without overshooting, we have determined their age, distance, reddening and indicative metallicity, as well as distance from the Galactic Centre and height from the Galactic plane. The best parameters derived for Berkeley 32 are: subsolar metallicity ($Z = 0.008$ represents the best choice, $Z = 0.006$ or 0.01 is more marginally acceptable), age = 5.0–5.5 Gyr (models with overshooting; without overshooting the age is 4.2–4.4 Gyr with poorer agreement), $(m - M)_0 = 12.4$ – 12.6 , $E(B - V) = 0.12$ – 0.18 (with the lower value being more probable because it corresponds to the best metallicity), $R_{GC} \sim 10.7$ – 11 kpc and $|Z| \sim 231$ – 254 pc. The best parameters for King 11 are: $Z = 0.01$, age = 3.5–4.75 Gyr, $(m - M)_0 = 11.67$ – 11.75 , $E(B - V) = 1.03$ – 1.06 , $R_{GC} \sim 9.2$ – 10 kpc and $|Z| \sim 253$ – 387 pc.

Key words: Hertzsprung–Russell (HR) diagram – Galaxy: disc – open clusters and associations: general – open clusters and associations: individual: Berkeley 32 – open clusters and associations: individual: King 11.

1 INTRODUCTION

This paper is part of the BOCCE (Bologna Open Cluster Chemical Evolution) project, described in detail by Bragaglia & Tosi (2006). With this project, we intend to derive homogeneous measures of age, distance, reddening and chemical abundance for a large sample of open clusters (OCs), to study the present-day properties of the Galactic disc and their evolution with time.

As part of this project, we present here a photometric study of the two old OCs King 11 ($\alpha_{2000} = 23^{\text{h}}47^{\text{m}}40^{\text{s}}$, $\delta_{2000} = +68^{\circ}38'30''$, $l = 117^{\circ}2$, $b = +6^{\circ}5$) and Berkeley 32 ($\alpha_{2000} = 06^{\text{h}}58^{\text{m}}07^{\text{s}}$, $\delta_{2000} = +06^{\circ}25'43''$, $l = 208^{\circ}$, $b = +4^{\circ}4$), located in the second and third Galactic quadrants, respectively.

King 11 has been the subject of a few publications in the past. Kaluzny (1989) obtained a rather shallow colour–magnitude diagram (CMD) using the 0.9-m KPNO telescope. He found it old (about the same age of M67) and highly reddened, with a distance modulus $(m - M)_V \sim 15.3$, derived assuming $M_V(\text{clump}) = 0.7$ mag. Aparicio et al. (1991) acquired deep *UBVR* data at the 3.5-m tele-

scope in Calar Alto on a small field of view (2.7×4.3 arcmin²); they derived a reddening $E(B - V) = 1$, a distance modulus $(m - M)_0 \simeq 11.7$, a metallicity about solar (with some uncertainty, because different methods produced contrasting answers), and an age of 5 ± 1 Gyr. Phelps, Janes & Montgomery (1994) obtained not perfectly calibrated *BVI* photometry and measured a difference in magnitude between the main-sequence turn-off point and the red clump of $\delta V = 2.3$, that translates, using the so-called morphological age indicator (see Janes & Phelps 1994) into an age of 6.3 Gyr. From their recalibration of the δV –age relation, assuming $[\text{Fe}/\text{H}] = -0.23$, Salaris, Weiss & Percival (2004) infer an age of 5.5 Gyr. Note that the BDA¹ (Mermilliod 1995) used to indicate a spurious low age for this cluster (1.1 Gyr), directly taken from the Dias et al. (2002) catalogue, whose source is unclear. Finally, Scott, Friel & Janes (1995) obtained low-resolution spectra of 16 bright stars, from which an average cluster radial velocity (RV) was computed ($\langle \text{RV} \rangle = -35 \pm 16$ km s^{−1}). These spectra were later reanalysed by Friel et al. (2002), finding $[\text{Fe}/\text{H}] = -0.27$ (rms = 0.15) dex.

Be 32 has been photometrically studied by Kaluzny & Mazur (1991), Richtler & Sagar (2001) and Hasegawa et al. (2004). Be 32 seems to be quite old (age about 6 Gyr) and moderately metal poor ($[\text{Fe}/\text{H}]$ between -0.2 and -0.5). We have recently presented the RVs of about 50 stars in Be 32 and a preliminary analysis of the photometric data (D’Orazi et al. 2006, hereafter D06) based on

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¹ <http://www.univie.ac.at/webda/webda.html>

Table 1. Log of observations for the clusters and the control fields; exposure times are in seconds.

Field	α_{2000}	δ_{2000}	exposure time _B	exposure time _V	exposure time _I	UT date
Berkeley 32	06 ^h 58 ^m 07 ^s	+06°25′43″	600, 40, 5	480, 20, 2	480, 20, 1	26/11/2000, 14/02/2004
Be 32 – external	06 ^h 57 ^m 27 ^s	+06°08′26″	600, 240, 40	300, 120, 20	300, 120, 20	26/11/2000
King 11	23 ^h 47 ^m 39 ^s	+68°38′25″	300, 1200, 240, 40	120, 600, 120, 20	120, 600, 120, 20	25/11/2000, 26/11/2000
King 11 – external	23 ^h 47 ^m 40 ^s	+68°08′18″	1200, 300, 40	600, 1280, 20		25/11/2000

isochrone fitting and the magnitude of the red clump. In D06 we also discussed the literature related to Be 32 available at the time, and we will not repeat it here. We now refine our determinations, applying the synthetic CMD method, as done for all the clusters in the BOCCE project. Finally, Sestito et al. (2006) presented an analysis of high-resolution FLAMES@VLT spectra of nine red clump giants in Be 32, finding an average metallicity $[\text{Fe}/\text{H}] = -0.29$ dex (rms 0.04 dex), in very good agreement with that found by D06.

The paper is organized as follows. Observations and reductions are presented in Section 2, a description of the resulting CMDs can be found in Section 3; the derivation of the cluster parameters using the synthetic CMD technique is discussed in Section 4, while conclusions and summary are given in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

Observations in the *BVI* Johnson–Cousins filters of Be 32 and King 11 were performed at the Telescopio Nazionale Galileo (TNG) in 2000 November (plus three additional exposures in 2004 February for Be 32). We also acquired associated control fields to check the field stars contamination, as detailed in Table 1 and D06. We used DOLORES (Device Optimized for the LOW RESolution), with scale of 0.275 arcsec pix⁻¹, and a field of view 9.4×9.4 arcmin². Of the two November nights, only the first one resulted photometric. Fig. 1 shows the position of our pointings for King 11 and the associated control field.

A description of the data and reduction procedure for Be 32 can be found in D’Orazi (2005) and in D06; we report here briefly the analysis of King 11, which is absolutely equivalent to that of Be 32. The standard IRAF² routines were utilized for pre-reduction, and the IRAF version of the DAOPHOT-II package (Stetson 1987; Davis 1994) was used with a quadratically varying point spread function (PSF) to derive positions and magnitudes for the stars. Output catalogues for each frame were aligned in position and magnitude, and final (instrumental) magnitudes were computed as weighted averages of the individual values. Even with the shortest exposure times we did not avoid saturation of the brightest red giants in the *I* filter; unfortunately, we could not obtain additional exposures as we did for Be 32 (D06), so we will mostly concentrate in the following on the *V, B – V* CMD.

The final catalogues have been created including all the objects identified in at least two filters, after applying a moderate selection in the shape-defining parameter sharpness ($|\text{sharpness}| \leq 2$) and on the goodness-of-fit estimator χ^2 ($\chi^2 \leq 10$). To the two final catalogues, one for the cluster and one for the comparison field, we applied the transformation to astrometrize the α and δ coordinates, using software written by P. Montegriffo at the Bologna Observatory.

After application of a correction to the PSF magnitudes to bring them on the same scale of the aperture magnitudes of the standard stars, we calibrated our catalogues to the standard Johnson–Cousins *BVI* system. We adopted the calibration equations that can be found in D06, since King 11 was observed in the photometric night beginning on UT 2000 November 25 when Be 32 was observed too.

Finally, we determined our completeness level using extensive artificial stars experiments: we iteratively added, one at a time, about 50 000 simulated stars to the deepest frames and repeated the reduction procedure, determining the ratio of recovered over added stars (see Tosi et al. 2004, for a more detailed description). The results for Be 32 are given in Table 2 and those for King 11 in Table 3.

We checked the quality of the calibration comparing our photometry for both clusters with that presented in previous literature papers, that is, with Kaluzny & Mazur (1991) for *B, V* and with Richtler & Sagar (2001) for *VI* in Be 32, and with Aparicio et al. (1991) for King 11 (only for *B, V*, since there are no other sources to compare the *I* photometry with). Fig. 2 shows the differences with these photometries for the stars in common; the comparison is particularly favourable with the work by Kaluzny & Mazur (1991), but is good in all cases.

3 THE COLOUR–MAGNITUDE DIAGRAMS

The CMDs for Be 32 were described in D06 and the data are already available at the BDA. Fig. 3 shows the *V, B – V* CMD of the stars at various distances from the centre of Be 32 and of the control field. It is apparent that contamination is quite high, with about half the stars likely to be foreground/background objects even in the central regions. However, in the area with a radius of 3 arcmin from the cluster centre the main sequence (MS), the turn-off (TO) and the subgiant branch (SGB) are well defined. The MS extends more than 5 mag below the TO. With the additional help of the available RVs (from D06 and Randich et al., in preparation, see next section) to select the most probable cluster members, we can satisfactorily identify the TO ($V = 16.3, B - V = 0.52$ and $V - I = 0.60$), the SGB, the red giant branch (RGB) and the red clump ($V = 13.7, B - V = 1.07$ and $V - I = 1.10$).

For King 11, the final, calibrated sample of cluster stars (which will also be made available through the BDA) consists of 1971 objects, and the external field catalogue comprises 880 stars. The corresponding CMDs are shown in Fig. 4. In spite of a contamination lower than that in Be 32, the location of the foreground/background objects in the CMD makes the definition of the evolutionary sequences more complicated. We can improve the definition by using the information on membership of a few giant stars from Scott et al. (1995), which perfectly define the red clump position. If we consider the CMDs of regions with increasing distance from the cluster centre displayed in Fig. 5, it is apparent that a safe identification of the main evolutionary loci becomes difficult beyond a radius of 2 arcmin. Within such radius, the cluster main sequence extends for almost 4 mag and the RGB and red clump are well delineated. The

² IRAF is distributed by the National Optical Astronomical Observatory, which are operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation.

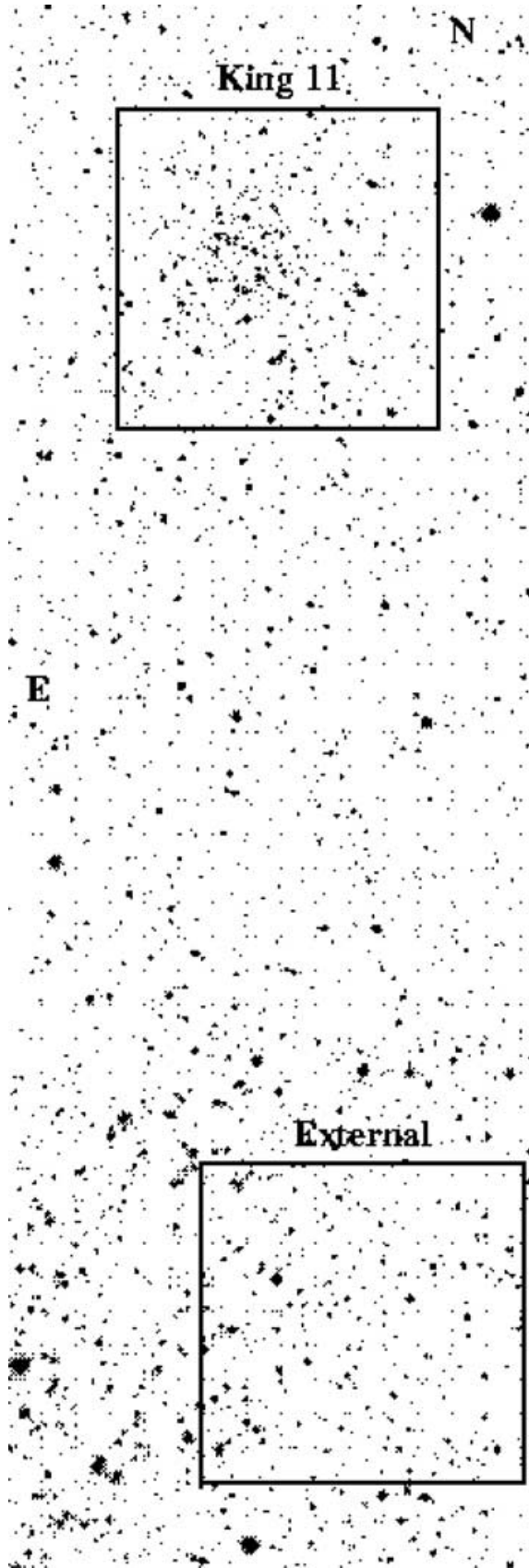


Figure 1. Approximate positions of our pointings on King 11 and the control field. The map is 15×45 arcmin², has north to the top and east to the left-hand side.

Table 2. Completeness level for the central (Columns 2–4) and external (Columns 5–7) fields of Be 32; mag is the calibrated *B*, *V* or *I* magnitude.

mag	c_B	c_V	c_I	c_B	c_V	c_I
16.00	1.00	1.00	1.00	1.00	1.00	1.00
16.50	1.00	0.95	0.92	1.00	0.99	0.95
17.00	0.92	0.94	0.88	0.99	0.98	0.94
17.50	0.91	0.93	0.85	0.97	0.97	0.92
18.00	0.89	0.92	0.78	0.97	0.94	0.87
18.50	0.88	0.91	0.68	0.96	0.93	0.84
19.00	0.86	0.87	0.54	0.93	0.93	0.73
19.50	0.82	0.85	0.37	0.91	0.90	0.52
20.00	0.77	0.80	0.21	0.89	0.86	0.29
20.50	0.66	0.74	0.09	0.85	0.78	0.11
21.00	0.51	0.60	0.03	0.69	0.58	0.04
21.50	0.32	0.39	0.01	0.42	0.32	0.01
22.00	0.16	0.19	0.00	0.22	0.15	0.00
22.50	0.06	0.09	0.00	0.07	0.05	0.00

Table 3. Completeness level for the central (Columns 2 and 3) and external (Columns 4 and 5) fields of King 11; mag is the *B* or *V* calibrated magnitude.

mag	c_B	c_V	c_B	c_V
16.5	1.0	1.0	1.0	1.0
17.0	1.0	0.99	1.0	0.99
17.5	1.0	0.97	0.99	0.98
18.0	1.00	0.97	0.98	0.95
18.5	1.00	0.95	0.99	0.94
19.0	0.98	0.94	0.96	0.94
19.5	0.97	0.93	0.94	0.93
20.0	0.97	0.92	0.91	0.90
20.5	0.97	0.87	0.88	0.87
21.0	0.95	0.87	0.81	0.82
21.5	0.93	0.74	0.78	0.70
22.0	0.91	0.56	0.63	0.43
22.5	0.88	0.27	0.38	0.21
23.0	0.74	0.06	0.15	0.04
23.5	0.45	0.00	0.02	0.00
24.0	0.18	0.0	0.00	0.0
24.5	0.02	0.0	0.0	0.0
25.0	0.00	0.0	0.0	0.0

turn-off point is at $V = 18.2, B - V \simeq 1.3$, while the red clump is at $V = 16.0, B - V \simeq 1.8$.

In the $V, V - I$ CMD of King 11 we lack the brightest RGB stars, because they were saturated even in the shortest image, and the MS is less well defined. For this reason, we refer to the $V, B - V$ CMD to derive the cluster distance, reddening and age, and use the I data only to discriminate in metallicity among degenerate solutions (see next section).

4 CLUSTER PARAMETERS

Age, distance and reddening of King 11 and Be 32 have been derived with the same procedure applied to all the clusters of our project (see Bragaglia & Tosi 2006, and references therein), namely, the synthetic CMD method originally described by Tosi et al. (1991). The best values of the parameters are found by selecting the cases providing synthetic CMDs with morphology, colours, number of stars in the various evolutionary phases and luminosity functions

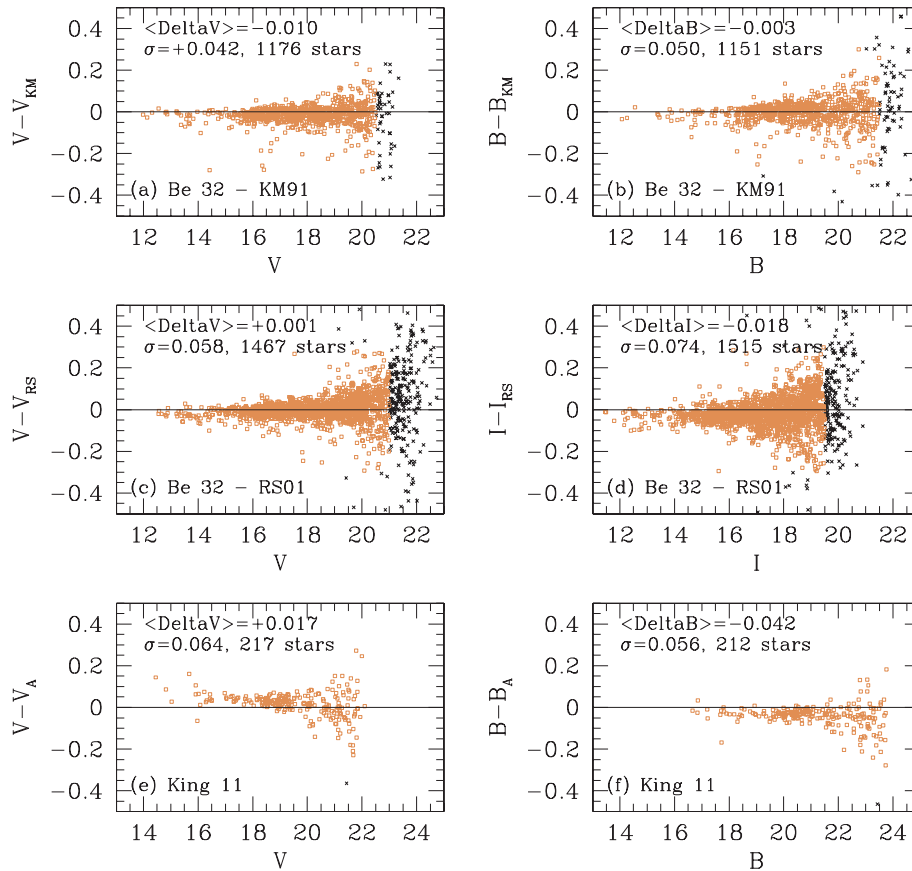


Figure 2. Comparison between our photometry and literature data: (a) and (b) are for Be 32 by Kaluzny & Mazur (1991); (c) and (d) are for Be 32 by Richtler & Sagar (2001); (e) and (f) for King 11 by Aparicio et al. (1991). The horizontal lines are on zero; stars used to compute the average differences are indicated by (orange) open squares, while the ones discarded are indicated by crosses.

(LFs) in better agreement with the observational ones. As for the other clusters of this series, to estimate the effect on the results of different stellar evolution assumptions, we have adopted three different sets of stellar models, with various assumptions on the metallicity, treatment of convection, opacities and equation of state. The adopted models are listed in Table 4.

In addition to the usual synthetic CMD method, the cluster parameters have also been searched by means of statistical tests. The problem of comparing CMDs (and two-dimensional histograms in general) is still unsolved in astrophysics. However, several approaches have been explored. For instance, in Cignoni et al. (2006) the *entire* CMD is used: data and model CMDs are binned and a function of residuals is minimized. In Gallart et al. (1999), the number of stars in *a few regions* (representative of the most important evolutionary phases) is controlled through a χ^2 test. The goal of those papers was to recover a complex star formation history. Here, the nature of the problem is in principle simpler (single stellar generation), thus we follow a more classical approach: the luminosity and the colour distribution of each model are independently compared with the data using a Kolmogorov–Smirnov (KS) test (Press et al. 1995). One of the advantages of using also the colour distribution lies in the fact that the major drawback of using the LF alone, that is, the degeneracy among parameters (distance, reddening, age and metallicity) can be mitigated. Moreover, the KS does not require to bin the data; therefore, arbitrary parametrizations of the CMD (typical of the χ^2) can be avoided. In order to reduce the Poisson noise, which is the dominant uncertainty in our LFs, the model CMDs are built with a

large number of stars. Only CMDs yielding a KS probability larger than 5 per cent both for the LF and for the colour distribution are accepted.

Unavoidably, poorly populated CMD regions like the core helium burning region or the RGB are often underrepresented by a similar analysis (washed out by Poisson noise). However, also in these cases, a good KS probability still indicates that the most populous stellar phases (e.g. MS and TO) are well matched. In other words, the adopted statistical procedure provides a quick tool to *exclude* those solutions for which the synthetic CMD does not reproduce the properties of MS and TO stars. Then, the remaining parameter space is explored with a traditional analysis: (i) exploiting the difference in luminosity between the lower envelope of the subgiants and the red clump; (ii) fitting the SGB; (iii) matching the RGB colour.

4.1 King 11

As already said in Section 3, for King 11 we have mainly used the $V, B - V$ CMD because the $V, V - I$ lacks the brighter part of the RGB. To minimize contamination from field stars we have selected as reference field the region within a radius of 2 arcmin from its centre. Since this region contains 531 stars, and the control field of the same area contains 143 stars, we assume the cluster members to be 388. Incompleteness and photometric errors are those inferred from the data and described in Section 2. In order to minimize the Poisson noise of the models, all available field stars (~ 880) are used: hence the synthetic CMDs are built with 3259 synthetic stars

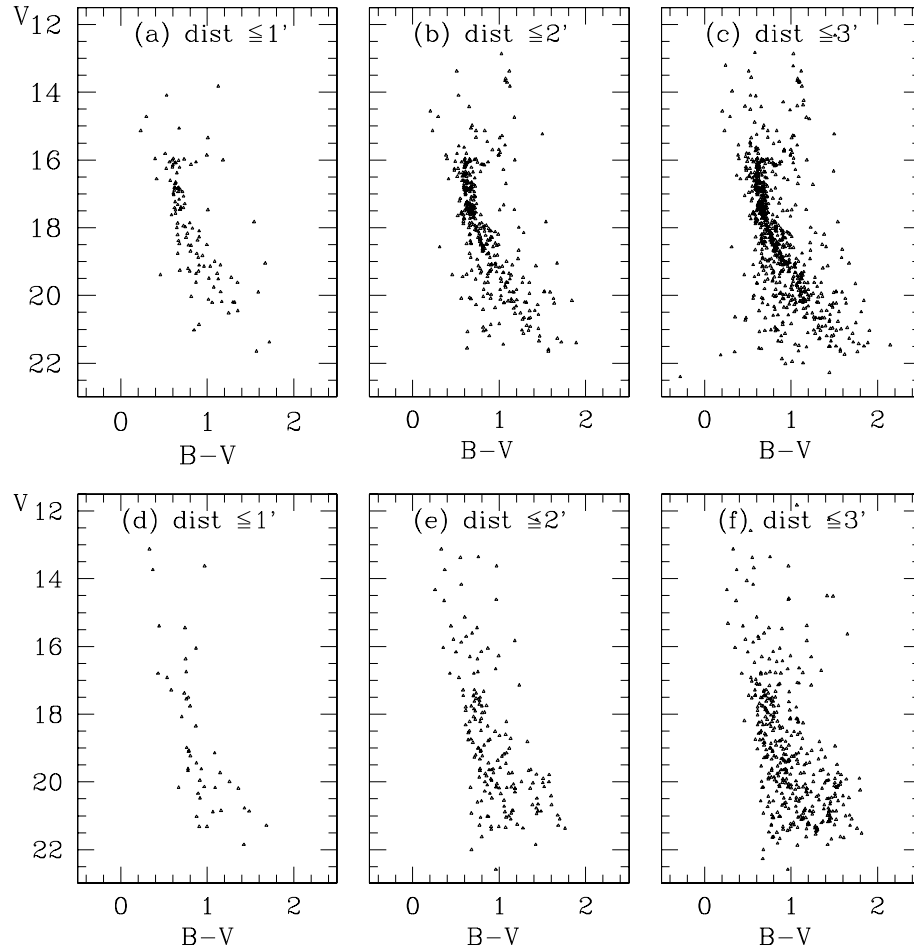


Figure 3. Radial CMDs for Be 32 (upper panels) and equal areas in the comparison field (lower panels); we plot stars within distances of 1, 2, 3 arcmin from the cluster and field centres. The CMDs contain 133, 444, 903 objects in panels (a), (b), (c), respectively, and 57, 229, 524 in panels (d), (e), (f), respectively.

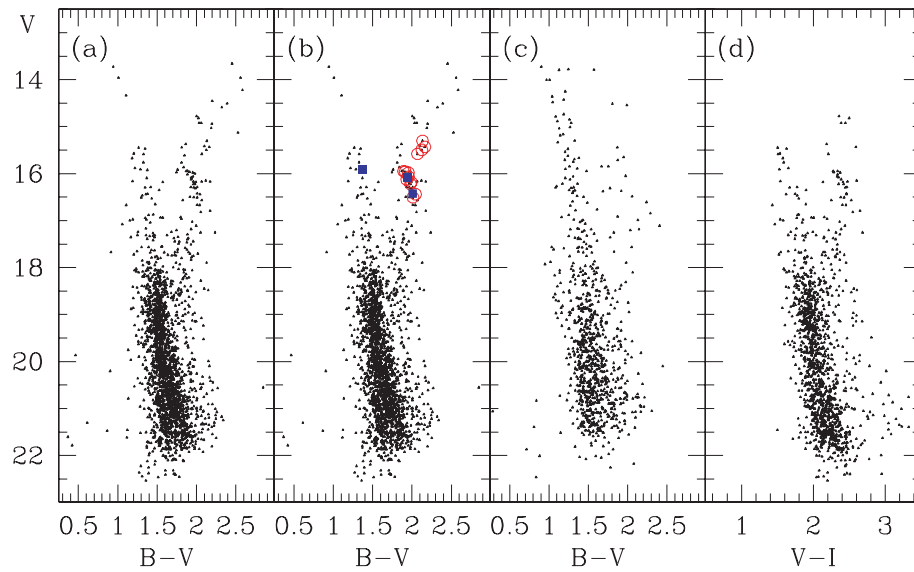


Figure 4. (a) $V, B - V$ CMD for King 11; (b) the same CMD, with stars member (open circles, red in the electronic version) and non-member (filled squares, blue in the electronic version) according to the RVs in Scott et al. (1995); (c) $V, B - V$ CMD for the comparison field; (d) $V, V - I$ CMD for King 11.

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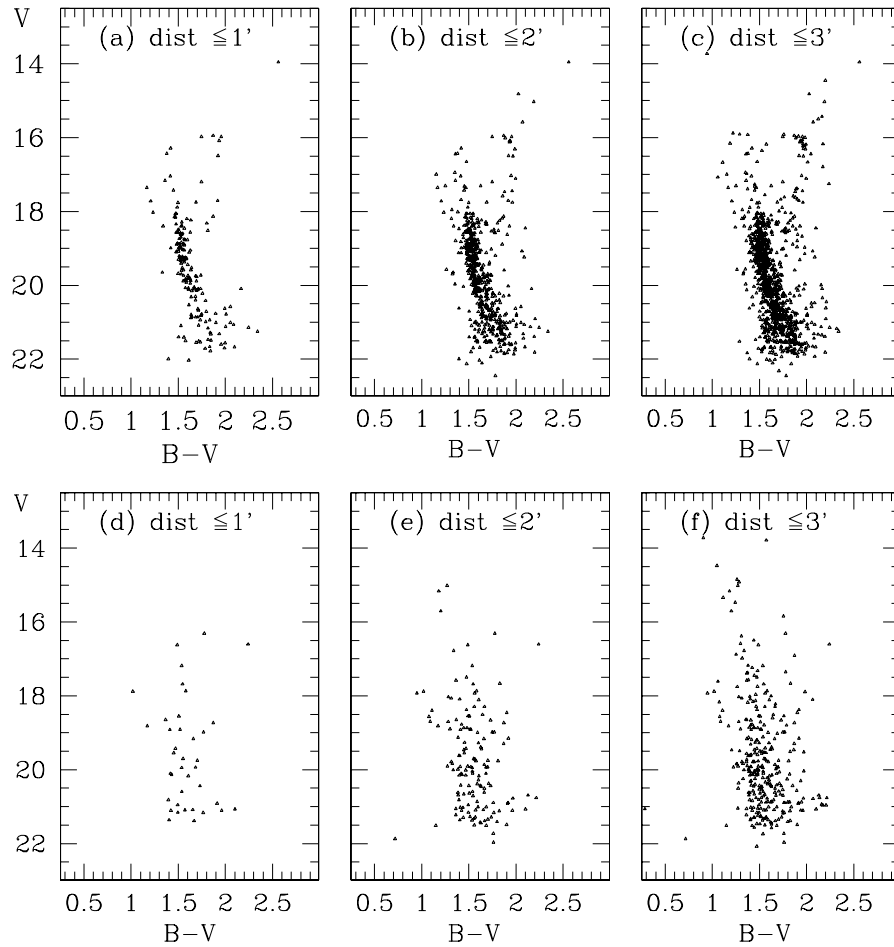


Figure 5. Radial CMDs for King 11 (upper panels) and equal areas of the comparison field (lower panels); we plot stars within distances of 1, 2, 3 arcmin from the cluster and field centres. The CMDs contains 173, 531, 941 objects in panels (a), (b), (c), respectively, and 38, 143, 317 in panels (d), (e), (f), respectively.

Table 4. Stellar evolution models adopted for the synthetic CMDs. The FST models actually adopted here are an updated version of the published ones (Ventura, private communication).

Set	Metallicity	Overshooting	Reference
BBC	0.008	Yes	Fagotto et al. (1994)
BBC	0.004	Yes	Fagotto et al. (1994)
BBC	0.02	Yes	Bressan et al. (1993)
FRA	0.006	No	Dominguez et al. (1999)
FRA	0.01	No	Dominguez et al. (1999)
FRA	0.02	No	Dominguez et al. (1999)
FST	0.006	$\eta = 0.00, 0.02, 0, 03$	Ventura et al. (1998)
FST	0.01	$\eta = 0.00, 0.02, 0, 03$	Ventura et al. (1998)
FST	0.02	$\eta = 0.00, 0.02, 0, 03$	Ventura et al. (1998)

(in order to preserve the ratio cluster members/field stars). Only afterwards we randomly extract from the whole sample of synthetic stars 388 objects, as attributed to the cluster central region.

Almost all models have been computed assuming a fraction of binary stars of 20 per cent³ [following Bragaglia & Tosi (2006),

prescriptions] and a power-law initial mass function (IMF) with Salpeter's exponent. The KS test is applied to the stars brighter than $V \approx 20$. The constraint on the KS probability does not guarantee a unique solution, mostly because the statistics is dominated by MS stars fainter than the TO, less affected than other evolutionary phases by small parameter variations. We have then decided to validate only models with acceptable KS probabilities *and* with a predicted clump within 0.05 mag of the observed clump (whose membership is also confirmed by RV estimates). Fig. 6 shows the results;⁴ error bars correspond to ages for which an appropriate combination of distance and reddening exists. Considering our findings, one can provisionally accept a range of ages between 3 and 5 Gyr. Only BBC models for $Z = 0.004$ are rejected by the KS test for all ages (meaning that no solution for age, reddening and distance has been found). Figs 7–9 show a selection of our best synthetic CMDs. To further proceed in the selection, we have used the morphology of the RGB (a poorly populated region, therefore ignored by our statistical test) to give additional constraints on the parameter space. An examination of this evolutionary phase reveals that: (1) the residual BBC models ($Z = 0.02$ and 0.008) are all rejected, because they

³ The low number of observed TO stars does not permit to infer the actual fraction.

⁴ FRANEC models for $Z = 0.006$ and 0.01 , providing the same age of $Z = 0.02$, are not shown in the figure.

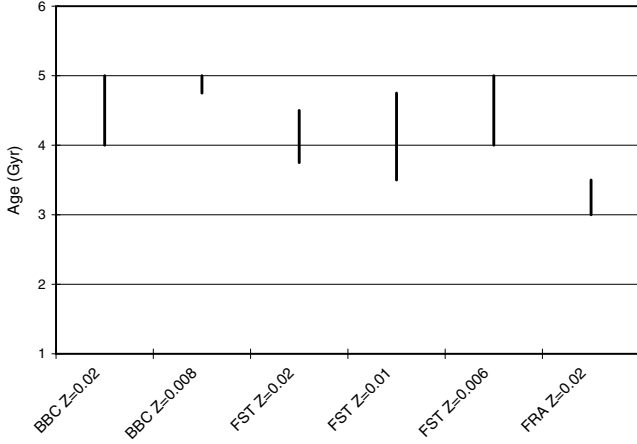


Figure 6. The range of statistically acceptable ages for King 11. Results for different sets of tracks are shown.

predict excessively red RGBs [the upper panel of Fig. 7 shows the best BBC model: age = 4.5 Gyr, $Z = 0.02$, $E(B - V) = 0.93$ and $(m - M)_0 = 11.85$]; (2) the same problem exists with the FRA models: the RGB is systematically too red [the lower panel of Fig. 7 shows the best FRA model: age = 3 Gyr, $Z = 0.02$, $E(B - V) = 1.01$ and $(m - M)_0 = 11.95$]; (3) the FST models seem in good agreement with the data independently of the adopted metallicity. We thus restrict the next considerations only to the FST models.

Fig. 8 shows the theoretical FST CMDs that best reproduce the $V, B - V$ data. The best-fitting parameters turn out to be: $Z = 0.02$, age 4 Gyr, $E(B - V) = 0.94$ and $(m - M)_0 = 11.95$ (panel a); $Z = 0.01$, age 4.25 Gyr, $E(B - V) = 1.04$ and $(m - M)_0 = 11.75$ (panel b); $Z = 0.006$, age 4.75 Gyr, $E(B - V) = 1.09$ and $(m - M)_0 = 11.65$ (panel c).

To solve the degeneracy we have made use of the $V, V - I$ CMD: although not complete in the bright part, it remains useful, since only models of the right metallicity can fit the observed CMDs in all passbands (see also the case of Be 32). Because of the very large reddening, we adopt the reddening law by Dean, Warren & Cousins (1978, see appendix, equation A1): $E(V - I) = 1.25 \times E(B - V) \times [1 + 0.06(B - V)_0 + 0.014E(B - V)]$, which takes into account a colour dependence. This relation tends to the usual $E(V - I) = 1.25 \times E(B - V)$ for $B - V \rightarrow 0$ and $E(B - V) \rightarrow 0$.

In Fig. 9 we show the synthetic cases of Fig. 8 both in the $V, B - V$ and $V, V - I$ diagrams and with no photometric error, to allow for a more immediate visualization of the theoretical predictions. We can see from Fig. 9 that the three competing models, indistinguishable in $B - V$ (left-hand panel), do separate in $V - I$ (right-hand panel): the best fit is reached for $Z = 0.01$. The solar composition seems definitely ruled out (the MS is too blue), but the $Z = 0.006$ model lies only slightly too red and cannot be completely excluded. This seems to confirm the findings by Friel et al. (2002), who based the analysis on spectroscopic indices. In contrast, Aparicio et al. (1991) preferred a solar abundance on the basis of their CMDs, but in this case different stellar models have been employed. While we are rather confident on a subsolar metallicity, a definitive answer will require analysis of high-resolution spectra.

The assumption of different levels of core overshooting ($\eta = 0.2$ or 0.3) has a minor effect on the results, as expected: King 11 is a sufficiently old cluster that the upper MS stars have masses with small

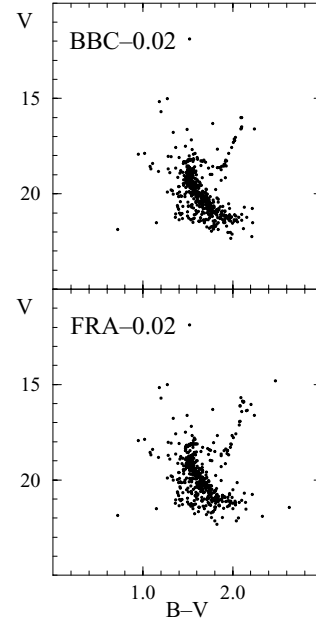


Figure 7. The upper panel shows the best solution for King 11 for BBC models: age = 4.5 Gyr $Z = 0.02$, $E(B - V) = 0.93$ and $(m - M)_0 = 11.85$; the lower panel shows the best FRANEC model: age = 3 Gyr, $Z = 0.02$, $E(B - V) = 1.01$ and $(m - M)_0 = 11.95$. Both these models predict RGBs that are too red.

convective cores, and therefore with small overshooting. Comfortably, the predicted number of stars in RGB and clump phase is close to the observed one, confirming that the evolutionary lifetimes of the theoretical models are correct.

Finally, in order to evaluate the contribution of the adopted binary fraction and IMF, we performed several tests. Larger fractions of binaries could help to fit the MS, yielding slightly larger distance moduli (with minor effects on the age). Vice versa, if distance, reddening and age are fixed, the stellar multiplicity that is consistent with the data is wide (between 10 and 60 per cent). In fact, only fractions higher than 60 per cent produce an evident plume over the turn-off region, which is not observed. If the same test (fixing distance, reddening and age) is performed also for the IMF, the results allow us to rule out only exponents larger than 3.3, for which the synthetic RGBs appear underpopulated.

In conclusion, the best parameters for King 11 can be summarized in the following intervals:

- (i) $Z = 0.01$;
- (ii) age between 3.5 and 4.75 Gyr;
- (iii) distance modulus between 11.67 and 11.75;
- (iv) reddening $1.03 \leq E(B - V) \leq 1.06$.

4.2 Berkeley 32

For Be 32, we have chosen as reference CMDs those of the region within 3 arcmin from the cluster centre (top panels in Fig. 10), which contains 608 stars with magnitudes measured in all the three B, V, I bands. The same area in the control field contains 332 stars with B, V, I . Taking this contamination into account, as well as the circumstance that 27 of the stars within the central area are shown by the RVs not to belong to Be 32, we assume the cluster members to be 249. The top panel of Fig. 10 shows the CMD of the stars

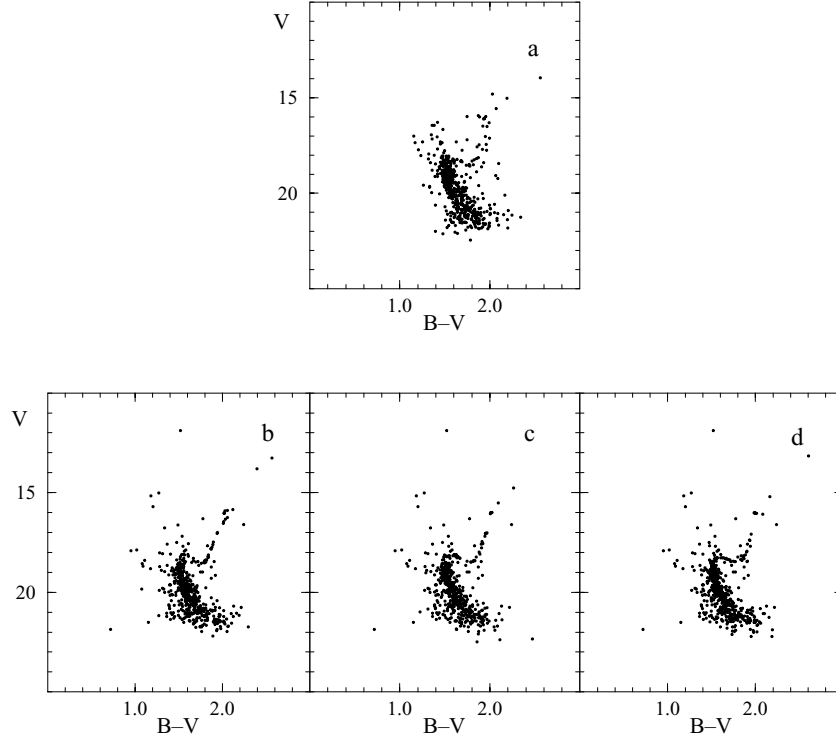


Figure 8. Comparison between observational and synthetic CMDs for King 11. Panel (a) shows the data CMD for the central 2 arcmin radius region. Panels (b), (c) and (d) show the CMDs of the best-fitting cases (FST tracks): (b) age 4 Gyr, $E(B-V) = 0.94$ and $(m-M)_0 = 11.95$; (c) $Z = 0.01$, age 4.25 Gyr, $E(B-V) = 1.04$ and $(m-M)_0 = 11.75$; (d) $Z = 0.006$, age 4.75 Gyr, $E(B-V) = 1.09$ and $(m-M)_0 = 11.65$.

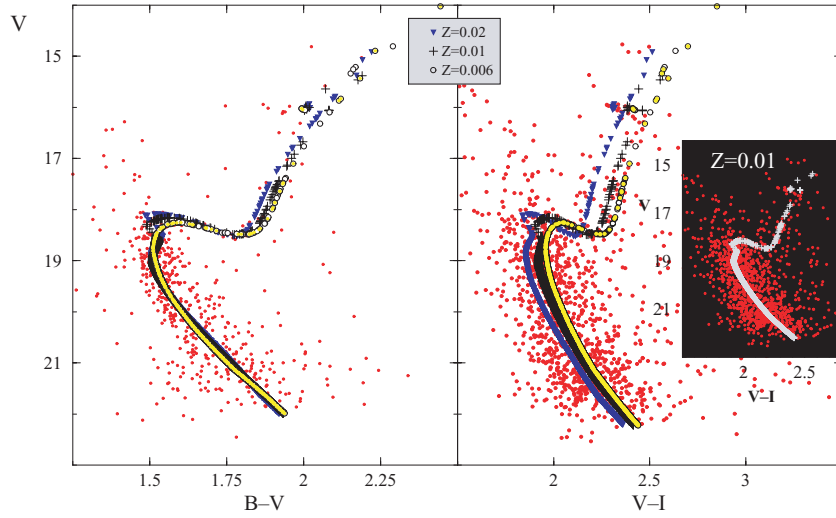


Figure 9. Choice of the metallicity for King 11: the left-hand panel shows the $V, B-V$ data and the three best solutions (at $Z = 0.006, 0.01, 0.02$) that all reproduce the observed CMD of the central zone, while the right-hand panel shows the same models overimposed on the $V, V-I$ data (in this case stars from the whole field are shown). Only the solution at $Z = 0.01$ (for an easier understanding it is isolated in the small panel on the right-hand side) can well fit at the same time the two different CMDs.

located within 3 arcmin from the cluster centre, with the larger symbols indicating the 48 objects whose RVs indicate most probable membership. To help in the RGB definition, also the two brightest RGB members are shown, although outside the selected 3 arcmin radius.

The synthetic CMDs have been generated with 249 objects, the incompleteness of Table 2 and the photometric errors described

by D06. We have generated the synthetic CMDs with and without binary systems. As for most of our sample clusters, a fraction of 30 per cent of binaries seems more consistent with the data, for all sets of stellar models. We notice, though, that binaries are not sufficient to cover the whole colour extension of the MS: a differential reddening of about $\Delta E(B-V) = \pm 0.01$ would provide a better reproduction of the MS thickness.

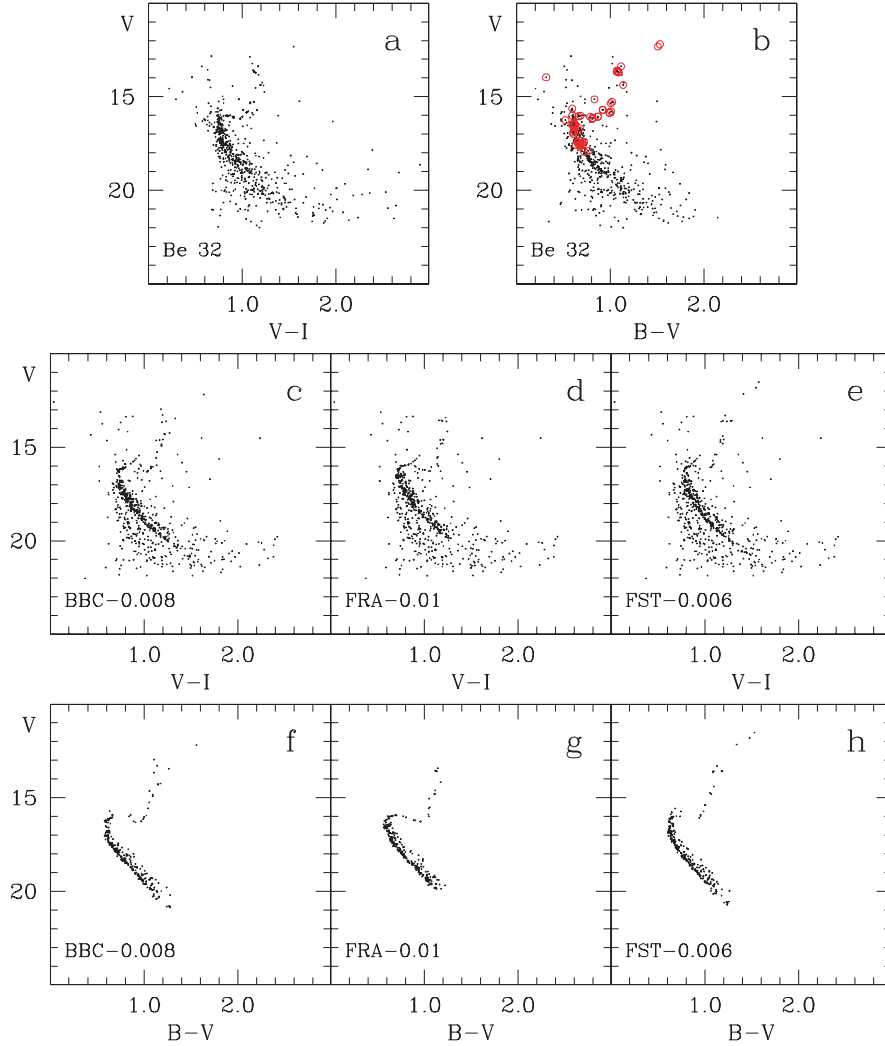


Figure 10. Comparison between observational and synthetic CMDs for Be 32. Panels (a) and (b) show the stars measured in B, V, I in the central 3 arcmin radius region. The larger symbols (red in the electronic version) in panel (b) indicate the objects with higher membership probability from the RVs (see text for details). Panels (f), (g) and (h) show the $B - V$ CMDs of the best-fitting case, mentioned in the text, for each type of stellar models. Panels (c), (d) and (e) show the corresponding $V - I$ CMDs, overimposed to the CMD of the same area in the control field for a more direct comparison.

The results of our analysis are the following. A solar metallicity is out of the question, because the synthetic CMDs show $V - I$ colours definitely too blue for all cases when the $B - V$ colours are correct. Of all the synthetic models, only those with metallicity $Z = 0.008$ are always able to simultaneously reproduce both the $B - V$ and $V - I$ colours of all the evolutionary phases. For $Z < 0.008$, if $B - V$ is reproduced, $V - I$ tends to be too red, while for $Z > 0.008$, if $B - V$ is fine, $V - I$ tends to be too blue. Unfortunately, $Z = 0.008$ is available only for the BBC tracks. For the FRA models, an acceptable colour agreement is achieved for $Z = 0.006$, but when we take into account also the shape of the MS and the TO, $Z = 0.01$ may be better. With the FST models, instead, $Z = 0.006$ seem slightly better than $Z = 0.01$. This ambiguity further suggests that the actual metallicity is in between, that is, $Z = 0.008$.

In order to obtain an in-depth exploration of the preferred metallicity $Z = 0.008$, we have also applied our statistical procedure. Although the contamination by field stars is quite high, the turn-off region, also thanks to the partial cleaning from non-members by the RVs, appears better defined than in King 11. The KS test is simultaneously applied to the $V, B - V$ and $V - I$ distributions,

selecting only models giving a KS probability above 5 per cent. The only acceptable models resulted to have age between 5 and 6.1 Gyr, distance moduli $(m - M)_0 = 12.5$ – 12.6 and reddening $0.085 < E(B - V) < 0.12$.

Whatever the metallicity, it is not easy to reproduce the shape of all the evolutionary phases covered by the stars in Be 32. The BBC models, in spite of the excellent reproduction of the colours, shape and position of MS, SGB and RGB, do not fit precisely the morphology of the TO and predict a clump slightly too bright. The FRA models are the only ones with a TO hooked enough to fit the bluest supposed member of Fig. 10 (which however is in the tail of the RV distribution and is the least safe member), but not for the ages which better reproduce the other CMD sequences. When the TO morphology is fine, the clump is too bright and vice versa. Moreover, the MS of the FRA models is slightly too red at its faint end. The FST models, independently of the overshooting choice η , have TO not much hooked and excessively vertical RGBs, whose brightest portion is therefore too blue.

As usual, models without overshooting (FRA) lead to the youngest age. The FST models with maximum overshooting $\eta =$

0.03 provide results totally equivalent to those with $\eta = 0.02$; this has been noted also for King 11 and all OCs old enough to have stars with small (or no) convective cores. The best compromise for each set of stellar models is:

- (i) $Z = 0.008$, age 5.2 Gyr, $E(B - V) = 0.12$, $(m - M)_0 = 12.6$ (BBC);
- (ii) $Z = 0.01$, age 4.3 Gyr, $E(B - V) = 0.14$, $(m - M)_0 = 12.6$ (FRA);
- (iii) $Z = 0.006$, age 5.2 Gyr, $E(B - V) = 0.18$, $(m - M)_0 = 12.4$ (FST).

The CMDs corresponding to these three best cases are shown in Fig. 10, where in $V, B - V$ we plot only the synthetic stars to allow for a direct comparison of the different models, while in $V, V - I$ we overplot the control field objects on the synthetic stars to facilitate the comparison between theoretical and observational CMDs.

The uncertainties mentioned above obviously affect the identification of the best age; however, all our independent tests consistently favour an age between 5.0 and 5.5 Gyr with overshooting models (both BBC and FST, although the BBC ones perform better, possibly because of the more appropriate metallicity $Z = 0.008$).

Finally, another useful piece of information can be inferred from the comparison of the pure synthetic CMDs of the bottom panels of Fig. 10 with the observational ones of the top panels. The synthetic MSs do not reach magnitudes fainter than $V \simeq 21$ for BBC and FST and $V \simeq 20$ for FRA. This limit corresponds to the minimum stellar mass available in the adopted sets of models: $0.6 M_\odot$ in the BBC and FST sets and $0.7 M_\odot$ in the FRA ones. In the central row panels, where the external field CMD is overimposed to the synthetic one, the faintest portions are therefore populated only by foreground/background stars. Yet, the synthetic LFs do not differ too much from the observational one, suggesting that contamination dominates at that magnitude level.

5 SUMMARY AND DISCUSSION

The context of this work is the large BOCCE project (Bragaglia & Tosi 2006), devoted to the systematic study of the Galactic disc through OCs. Distance, reddening and physical properties of the OCs King 11 and Be 32 have been explored. To this end, synthetic CMDs have been built and compared with data using both morphological and statistical criteria. A morphological analysis exploits all the evolutionary phases, but leads to some level of subjective-

ness. On the other hand, a pure statistical treatment can establish the significance for each model (reducing the subjectiveness of the comparison), but is truly selective only in case of very well-defined TOs.

In order to extract the maximum level of information, we have used both approaches: (1) we generate synthetic CMDs to best reproduce the main CMD features, especially the late evolutionary phases (RGB, red clump luminosity, SGB); (2) TO and main sequence are explored by KS test (LF and colour distribution). The final results come from the intersection of these.

During the analysis, King 11 and Be 32 have presented different problems. For King 11, whose metallicity is unknown, the statistical treatment has the advantage to explore very quickly a multidimensional parameter space. Nevertheless, King 11 has a very noisy TO, therefore, a morphological analysis plays a key role in refining the results. On the other hand, Be 32 is characterized by well-defined TO and MS (and a well-defined metallicity), and the statistical approach has provided an independent estimate of the parameters.

For King 11, our analysis has produced the following results: (1) the FST tracks give the best chance to reproduce the LF, the colour distribution and the morphological constraints (the clump luminosity, the bottom of the RGB and the RGB colour); (2) the metallicities $Z = 0.006, 0.01, 0.02$ all produce synthetic $V, B - V$ CMDs whose goodness of fit are indistinguishable but the use of the I band permits to select the right cluster metallicity, that is, $Z = 0.01$; (4) the synthetic CMDs generated with the FST tracks are consistent with a reddening $1.03 \leq E(B - V) \leq 1.06$, a distance modulus between 11.67 and 11.75, a cluster age between 3.5 and 4.75 Gyr (the best fit is obtained with 1.04, 11.75 and 4.25, respectively).

Our results confirm that King 11 is among the true ‘old OC’, contradicting the Dias et al. (2002) value, but in line with all past direct determinations. For an immediate comparison, Table 5 shows our results together with literature ones. Our derived ages are consistent with the Aparicio et al. (1991) finding (age 5 ± 1 Gyr). The difference (our estimates are systematically younger) may be easily ascribed to the input physics: Aparicio et al. (1991) adopted the Bressan, Bertelli & Chiosi (1981) tracks, characterized by strong core overshooting: although King 11 masses are only marginally affected by this phenomenon, a conspicuous amount of overshooting goes in the direction of rising the estimated age. A similar age is recovered also by Kaluzny (1989), but that work is based on a very shallow sample. Salaris et al. (2004), adopting $[\text{Fe}/\text{H}] = -0.23$, provide an age of about 5.5 Gyr from their recalibration of the re-

Table 5. Comparison of our results and selected literature data for the two clusters.

Authors	Age (Gyr)	Z or $[\text{Fe}/\text{H}]$	$(m - M)_0$	$E(B - V)$	Notes
King 11					
This work	3.5–4.75	0.01	11.67–11.75	1.03–1.06	<i>BVI</i>
Kaluzny	~ 5		$(m - M)_V \sim 15.3$		Shallow <i>BVR</i> , comparison to M67/red clump mag
Aparicio et al.	5 ± 1	0.02	11.7	1.00	<i>BVR</i> , synthetic $V, B - V$ CMD
Salaris et al.	5.5	-0.23 ± 0.15			δV , $[\text{Fe}/\text{H}]$ from literature, age–metallicity– δV relation
Berkeley 32					
This work	5.0–5.5	0.008	12.4–12.6	0.12	<i>BVI</i>
Kaluzny & Mazur	6	-0.37 ± 0.05	12.45 ± 0.15	0.16	Morphological age ratio/MS fitting
D’Orazi et al.	6.3	0.008	12.5–12.6	0.10	<i>BVI</i> , isochrone fitting/red clump mag
Richtler & Sagar	6.3	-0.2	12.6 ± 0.15	0.08	<i>VI</i> , isochrone fitting/red clump mag
Sestito et al.		-0.29 ± 0.04		0.14	High-resolution spectra

lation between δV , metallicity and age, based on 10 clusters. The large reddening we have found is in good agreement with literature values, in particular with the $E(B - V) = 0.98$ derived by the Schlegel, Finkbeiner & Davis (1998) maps. Our choice of metallicity is in good agreement with the one by Friel et al. (2002) and slightly discrepant with the other derivation based on photometry (Aparicio et al. 1991), which, however, is more uncertain since those authors found discrepant results with different methods.

In the case of Be 32 our CMDs constrain fairly well the cluster metallicity. The BBC tracks for $Z = 0.008$ reproduce all the stellar phases in all bands, while other metallicities have problems to simultaneously best fit both the $V, B - V$ and the $V, V - I$ diagrams. This is in perfect agreement with the finding by Sestito et al. (2006), based on high-resolution spectra ($[\text{Fe}/\text{H}] = -0.29 \pm 0.04$). The best estimate of the age ranges between 5.0 and 5.5 Gyr, slightly older than King 11. The age derived by D06 with isochrone fitting was 6.3 Gyr, consistent with what we find here once we consider the coarseness of the isochrone grid. Slightly older ages (6.3 and 6.0 Gyr, respectively) were found also by Richtler & Sagar (2001) and Kaluzny & Mazur (1991), while Hasegawa et al. (2004) reach exactly our same conclusion (5.2 Gyr).

In addition, the present data for Be 32 suggests a distance modulus $(m - M)_0 = 12.4\text{--}12.6$, in fair agreement with past studies, and reddening most likely around 0.12. The latter is consistent but slightly larger than the $E(B - V) = 0.10$ we determined in D06 assuming an older age, and slightly smaller than the value $E(B - V) = 0.16$ quoted by Kaluzny & Mazur (1991). A clearly lower reddening [$E(B - V) = 0.08$] was found by Richtler & Sagar (2001), but we recall that their study was based only on two passbands and may be plagued by uncertainties like the ones we found in the case of our analysis of King 11. The comparison to the Schlegel et al. (1998) maps is too uncertain, given the very low latitude of the cluster. We suggest the possibility of a differential reddening of the order of $\Delta E(B - V) \simeq 0.02$.

We have computed the distances of the two OCs adopting the preferred distance moduli: King 11 has a distance of about 2.2–3.4 kpc from the Sun and about 9.2–10 kpc from the Galactic Centre (assuming the Sun to be at 8 kpc from the centre), with a height above the Galactic plane of 253–387 pc; the corresponding values for Be 32 are 3.0–3.3, 10.7–11 kpc and 231–254 pc, respectively. Neither cluster is far enough from the Galactic Centre to be of relevance in the current debate about the metallicity distribution in the outer disc. However, both contribute to enlarge the still smallish number of old OCs and their metallicity (specially once that of King 11 is confirmed by dedicated high-resolution spectroscopy studies) will be important in defining the (possible) variation of the radial metallicity distribution over the Galactic disc lifetime.

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