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CCD photometry of the galactic star clusters Be 15, Be 71 and King 1

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Abstract. We present $UBVRI$ CCD photometry of three open star clusters Be 15, Be 71 and King 1 for the first time. Base on these data, optical colour-magnitude diagrams (CMDs) for the stars in the clusters down to $V = 22$ mag are studied. There are 1408, 1887 and 2485 stars located in the regions of Be 15, Be 71 and King 1 respectively. We also provide estimates of their fundamental parameters such as radius, reddening, distance and age. The radius values for the clusters Be 15, Be 71 and King 1 are 4.5, 3.0 and 4.0 arcmin respectively. The corresponding distances are 3.0±0.3,3.9±0.4 and 1.9±0.2 kpc respectively while the ages are log (age)=8.5±0.1, 8.8±0.1 and 9.2±0.1 respectively. The red giant clump is clearly visible in the CMDs of cluster King 1.

Keywords : open clusters: Be 15, Be 71 and King 1–colour-magnitude diagram

1. Introduction

Open clusters are excellent tools to define evolution and structure of our Galactic disc. The first comprehensive study of galactic star clusters was made by Trumpler (1930). The open cluster catalogue by Dias et al. (2003) include 1622 entries in which more than half are as yet virtually unstudied. The observations of distant unstudied open clusters become possible with the advent of charge couple device (CCD). The aim of the present study is, therefore, to acquire CCD data of open clusters and to estimate their fundamental parameters such as cluster's distance, age and interstellar reddening. To obtain these parameters we used colour-colour and colour-magnitude diagrams. This

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Table 1. Basic parameters of the open clusters.

Cluster	R. A. ($^{hh:mm:ss}$)	Decl. ($^{o:\prime:\prime\prime}$)	l (^{o})	b (^{o})	Trumpler class	Angular diameter (arcmin)
Be 15	05 02 05	44 30 00	162.33	1.61	I 2 m	9.0
Be 71	05 40 56	32 16 42	176.57	1.02	II 1 m	5.0
King 1	00 22 00	64 23 00	119.00	1.69	II 2 r	7.0

observational paper is a continuation of the work published earlier by Lata et al. (2004). In this paper, we have studied three clusters Be 15, Be 71 and King 1, located towards the anticentre direction of our Galaxy. The basic known parameters of these clusters are listed in Table 1. Be 15 is a strongly concentrated moderate size cluster of 9 arcmin in angular diameter while Be 71 and King 1 are more compact weakly concentrated clusters but clearly standing out against background. Fig. 1 shows their identification charts.

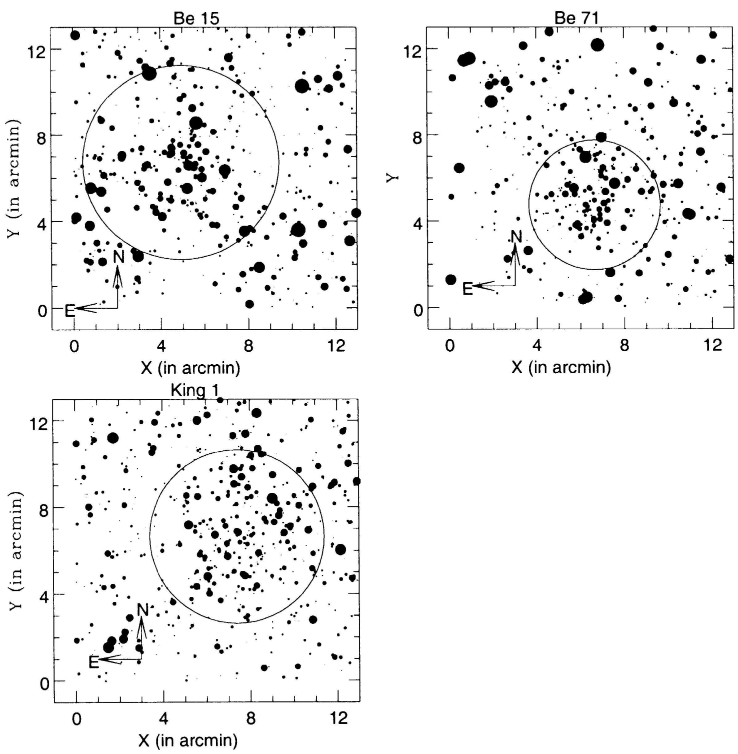

Figure 1. Identification chart for clusters Be 15, Be 71 and King 1. The circle represents radius of the cluster.

2. Observations and reductions

The broad band UBV Johnson and RI Cousins photometric observations for the clusters were carried out using CCD system at f/13 Cassegrain focus of the 104-cm Sampurnanad reflector of the Aryabhatta Research Institute of Observational-SciencES (ARIES), Nainital, during 2001 – 2002. The CCD detector is a square size of 2048 pixel and each square pixel of 24 μ size corresponds to 0.38 arcsec square on the sky. The entire chip covers a field of about 13×13 arcmin^2 on the sky. In order to improve signal to noise ratio observations were taken in binned mode of 2×2 pixel^2. Several bias and twilight flat field frames in all the filters have also been taken to clean the images. Multiple long and short exposures have been obtained for the cluster regions. For calibrating the cluster observations, Landolt (1992) standard stars in SA 92, PG0231 and PG0918 were also observed. The log of observations is listed in Table 2.

The data reduction was carried out using IRAF and MIDAS software packages installed on the computers of the ARIES, Nainital. Images of the cluster fields were aligned and co-added in each filter to optimize signal to noise ratio for the fainter stars. Short exposures have also been taken for estimation of extinction coefficients and also for measuring bright stars which were saturated on long exposure frames. The photometry was performed using DAOPHOT profile fitting software (Stetson, 1987, 1992). The instrumental magnitudes were converted to standard magnitudes using differential transformation equations. The typical zero-point errors derived from standard stars are 0.02, 0.02, 0.02, 0.02, 0.03 mag in V, $(B-V)$, $(V-R)$, $(V-I)$ and $(U-B)$ respectively. The errors listed in Table 3 and plotted in Fig. 2 are based on the signal to noise ratio of the image. This signal to noise ratio is affected by various factors such as brightness of the object, read out noise, average sky brightness etc. These errors are somewhat higher for brighter stars as they are derived only from the short exposure frames. The errors are of the order of about 0.02 mag upto V$\sim$20 mag but become very large at the limiting magnitude $V\sim$22. The measurements fainter than $V\sim$21 mag can therefore be considered unreliable.

The (X,Y) pixel co-ordinates, V, $(B-V)$, $(U-B)$, $(V-R)$ and $(V-I)$ magnitudes and colours of the stars observed in Be 15, Be 71 and King 1 are listed in Table 4. A sample of it is presented here. The entire data will be available only in electronic form at the CDS in Strasbourg and the WEBDA open cluster database website at http://obswww.unige.ch/webda/. It can also be obtained from the authors.

3. Colour-magnitude diagrams

The colour-magnitude diagrams for clusters Be 15, Be 71 and King 1 are shown in Fig. 3. The CMDs of the cluster show broad but well defined main sequence down to V=22 mag. But main sequence is highly contaminated by foreground/ background stars at fainter side for all the clusters. The V, $(V-I)$ diagram as shown in Fig. 3 is around 1.5 mag

Table 2. Log of CCD observations.

Region	Filter	Exposure time (seconds)	Date
Be 15 cluster	U	1500×4	29 November 2002
	U	600×3	30 November 2002
	B	900×3	29 November 2002
	B	200×3	30 November 2002
	V	300×3, 60×3	30 November 2002
	R	200×3, 30×3	”
	I	200×3	29 November 2002
	I	30×3	30 November 2002
Standard field(SA92)	U	500×3	29 November 2002
	B	150×3	”
	V	60×3	”
	R	30×3	”
	I	30×3	”
Be 71 cluster	U	1500×5, 500×6	17 November 2001
	B	1000×3	16 November 2001
	B	100×6	17 November 2001
	V	500×3, 50×3	” 2001
	R	300×4, 30×6	”
	I	300×3	16 November 2001
	I	30×6	17 November 2001
Standard field(PG0231)	U	500×3	17 November 2001
	B	200×3	”
	V	100×3	”
	R	50×3	”
	I	50×3	”
King 1 cluster	U	1800×4	29 November 2002
	U	400×5, 300	6 October 2002
	B	1000×3	5 October 2002
	B	150×6	6 October 2002
	V	600×3, 60×6	”
	R	200×3	5 October 2002
	R	30×6	6 October 2002
	I	200×3	5 October 2002
	IR	30×6	6 October 2002
Standard field(SA 92)	U	500×3	6 October 2002
	B	150×3	”
	V	60×3	”
	R	30×3	”
	I	30×3	”

fainter in comparison with the V, $(U-B)$, 0.5 mag with the V, $(B-V)$ and 0.3 mag with the V, $(V-R)$. All the clusters under discussion show evolutionary features. The MS turn-off point for cluster Be 15 is located at about $V \sim 14.4$ mag, $(B-V) \sim 0.80$ mag, for Be 71 it is at about $V \sim 16.0$ mag, $(B-V) \sim 0.96$ mag and for King 1 it is located at about $V \sim 15.5$ mag, $(B-V) \sim 1.10$ mag. The CMDs of cluster King 1 also

Table 3. Internal photometric errors as a function of brightness.

Cluster	magnitude range	σ_U	σ_B	σ_V	σ_R	σ_I
Be 15	< 12	-	0.007	0.003	0.006	0.006
	12-13	0.005	0.003	0.005	0.008	0.008
	13-14	0.003	0.004	0.006	0.010	0.010
	14-15	0.007	0.008	0.004	0.006	0.011
	15-16	0.008	0.007	0.004	0.007	0.012
	16-17	0.011	0.008	0.005	0.010	0.013
	17-18	0.013	0.009	0.007	0.012	0.016
	18-19	0.015	0.011	0.011	0.018	0.023
	19-20	0.022	0.015	0.020	0.033	0.037
	20-21	0.042	0.023	0.045	0.059	-
	21-22	0.079	0.046	0.088	0.070	-
Be 71	< 13	.003	0.004	0.007	0.010	0.011
	13-14	0.005	0.005	0.007	0.010	0.009
	14-15	0.006	0.007	0.008	0.009	0.008
	15-16	0.008	0.008	0.007	0.009	0.008
	16-17	0.007	0.006	0.008	0.010	0.009
	17-18	0.007	0.007	0.009	0.010	0.011
	18-19	0.010	0.007	0.009	0.012	0.019
	19-20	0.018	0.009	0.015	0.019	0.035
	20-21	0.037	0.015	0.032	0.037	0.070
	21-22	0.081	0.029	0.068	0.071	-
King 1	< 12	-	-	0.003	0.005	0.008
	12-13	0.007	0.004	0.005	0.008	0.008
	13-14	0.010	0.004	0.007	0.009	0.008
	14-15	0.009	0.005	0.007	0.009	0.008
	15-16	0.011	0.007	0.007	0.009	0.009
	16-17	0.011	0.008	0.008	0.010	0.011
	17-18	0.013	0.008	0.009	0.011	0.018
	18-19	0.017	0.009	0.010	0.014	0.026
	19-20	0.025	0.011	0.017	0.023	0.054
	20-21	0.045	0.019	0.035	0.046	-
	21-22	0.088	0.041	0.075	0.139	-

show red giant clump which is located at about $V \sim 14.0$ mag, $(B-V) \sim 1.70$ mag. The evolutionary features in the CMDs indicate that all the clusters under discussion are of intermediate age.

4. Cluster size

To determine the cluster size we derive the stellar surface density. This requires the knowledge of the cluster centre. For this the cluster centre has been derived iteratively by calculating average X and Y positions of stars within 100 pixels from an eye estimated centre, until it converged to a constant value. The (X, Y) coordinates of the cluster centre in arcmin are (4.9, 6.7), (6.7, 4.8) and (7.4, 6.7) for Be 15, Be 71 and King 1. An error

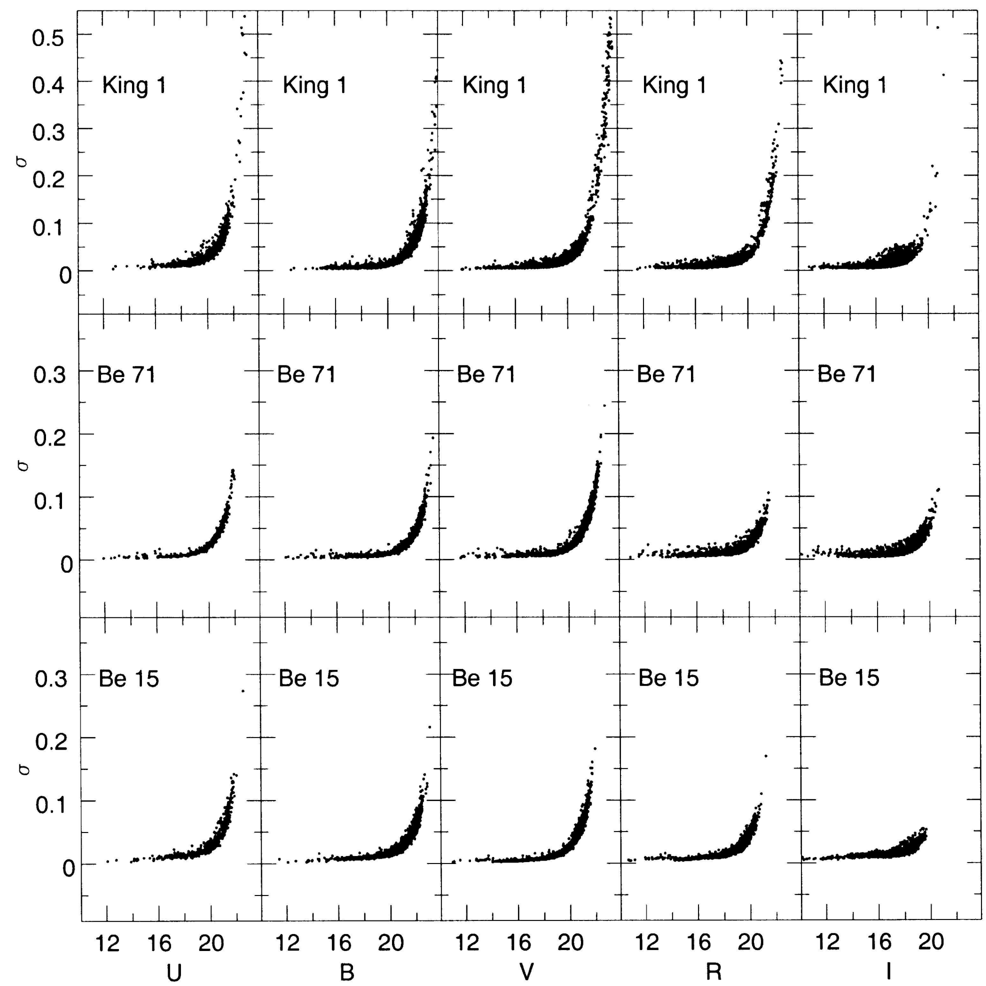

Figure 2. The errors of stars given by DAOPHOT as function of magnitude in different passbands.

of about 5 arcsec is expected in locating cluster centre. The radial density profile as a function of brightness is shown in Fig. 4. The radius at which density value becomes approximately equal to the field star density has been considered as cluster radius and it comes out to be about 4.5 arcmin for Be 15, 3.0 arcmin for Be 71 and 4.0 arcmin for King 1. Present radius value is in good agreement with the value given in Lyngå (1987) for cluster Be 15 while it is somewhat larger for clusters Be 71 and King 1. To estimate the core radius for these clusters the relation given by Kaluzny (1992) has been fitted to the data (Fig. 4). The model fits well to the observed data points. The best fit values obtained for the clusters under study are listed in Table 5 as function of brightness.

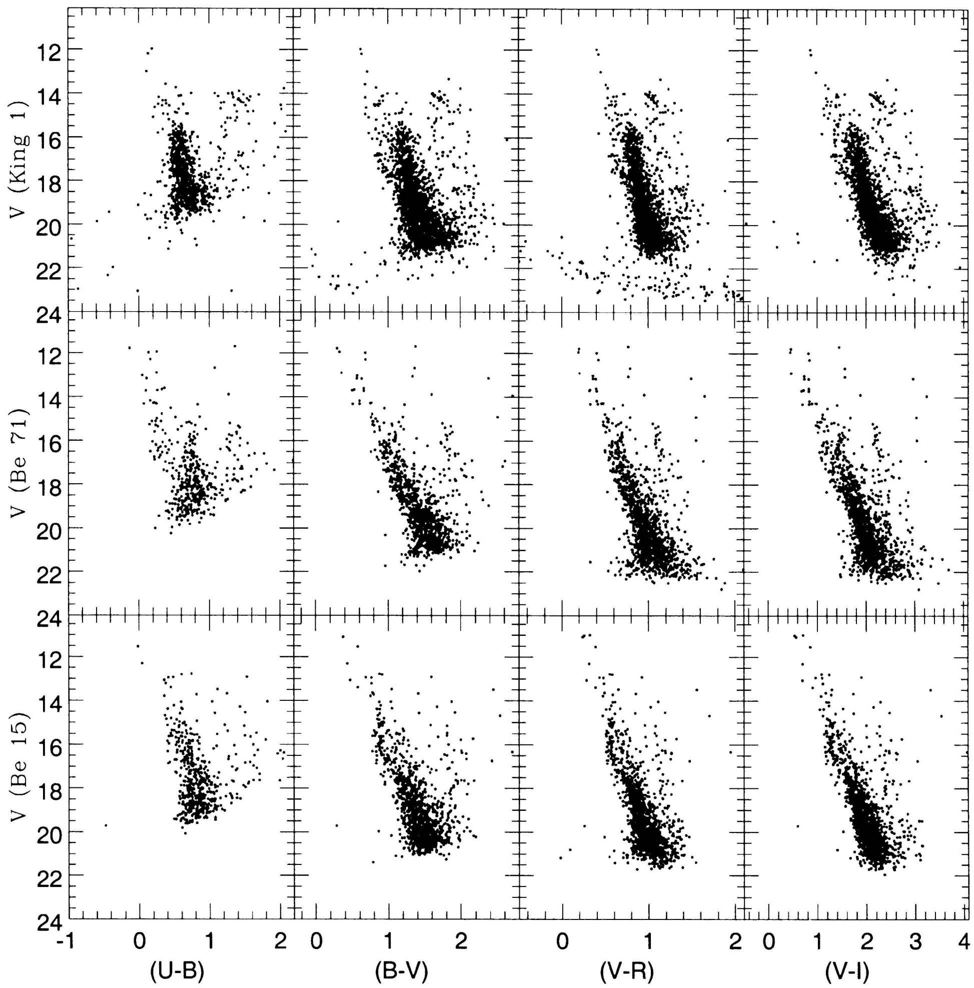

Figure 3. The CMDs for all stars in Be 15, Be 71 and King 1 regions.

These numbers indicate that about 78%, 67% and 87% foreground/background stars are present inside the cluster radius in Be 15, Be 71 and King 1 respectively. The percentage of probable members of clusters Be 15, Be 71 and King 1 with $V < 16$ mag inside cluster radius are 70%, 93% and 66% and with $V < 18$ mag inside cluster radius are 63%, 61% and 62% respectively. This indicates that percentage of cluster members is higher at brighter magnitudes and decreases with faintness becoming very small at the limiting magnitude of our observations. Therefore, for determination of cluster parameters we have used only those stars which were brighter than V=18 mag as they contain more than 50% cluster members.

Table 4. Sample of UBVRI photometric data of the stars in the clusters under study. The co-ordinates X and Y are in pixel, magnitude and colours are in mag.

No.	X	Y	V	$(U-B)$	$(B-V)$	$(V-R)$	$(V-I)$
Be 15							
64	44.7	1019.0	18.67	0.59	1.70	0.88	1.87
65	47.0	173.7	15.69	0.52	1.05	0.65	1.43
	*	*	*	*	*	*	*
	*	*	*	*	*	*	*
Be 71							
326	205.9	835.9	15.99	0.77	1.10	0.65	1.30
327	206.0	130.7	18.07	0.94	1.37	.090	1.85
	*	*	*	*	*	*	*
	*	*	*	*	*	*	*
King 1							
246	103.8	310.5	18.06	0.26	1.32	0.88	1.91
247	104.0	250.4	18.80	0.21	1.17	0.76	1.72
	*	*	*	*	*	*	*
	*	*	*	*	*	*	*

Table 5. Core radius and stellar surface density as a function of brightness.

Cluster	V < 16 mag		V < 18 mag		All stars	
	Core radius (arcmin)	Field density (stars/arcmin^2)	Core radius (arcmin)	Field density (stars/arcmin^2)	Core radius (arcmin)	Field density (stars/arcmin^2)
Be 15	0.8±0.1	0.24±0.07	1.4±0.1	0.91±0.15	1.5±0.1	7.55±0.24
Be 71	0.8±0.1	0.04±0.07	0.8±0.1	1.13±0.27	1.6±0.3	8.91±0.96
King 1	1.3±0.3	0.50±0.12	2.2±0.3	2.01±0.37	2.4±0.3	13.75±0.91

5. Fundamental parameters of the clusters

To estimate cluster parameters it is necessary to remove field star contamination and to check the completeness of data. But it is not possible to separate field stars from the cluster members only on the basis of their closeness to the main populated area of the CMDs, because field stars at cluster distance and cluster reddening may occupy the same area. For the separation of cluster members from the field stars, precise proper motion/radial velocity measurements of the stars are required. In the absence of such data for the clusters, we used radial distance and photometric criteria for cluster membership. The photometric criterion is based on the assumption that all the stars belonging to the cluster having the same chemical composition are formed at the same time should fall on a well defined evolutionary sequence in the colour-magnitude and the colour-colour diagrams. They also are supposed to be situated at the same distance, therefore, individual cluster members should not differ by more than ±0.5 mag from the mean distance modulus for the cluster (Walker, 1965). The completeness of data is necessary

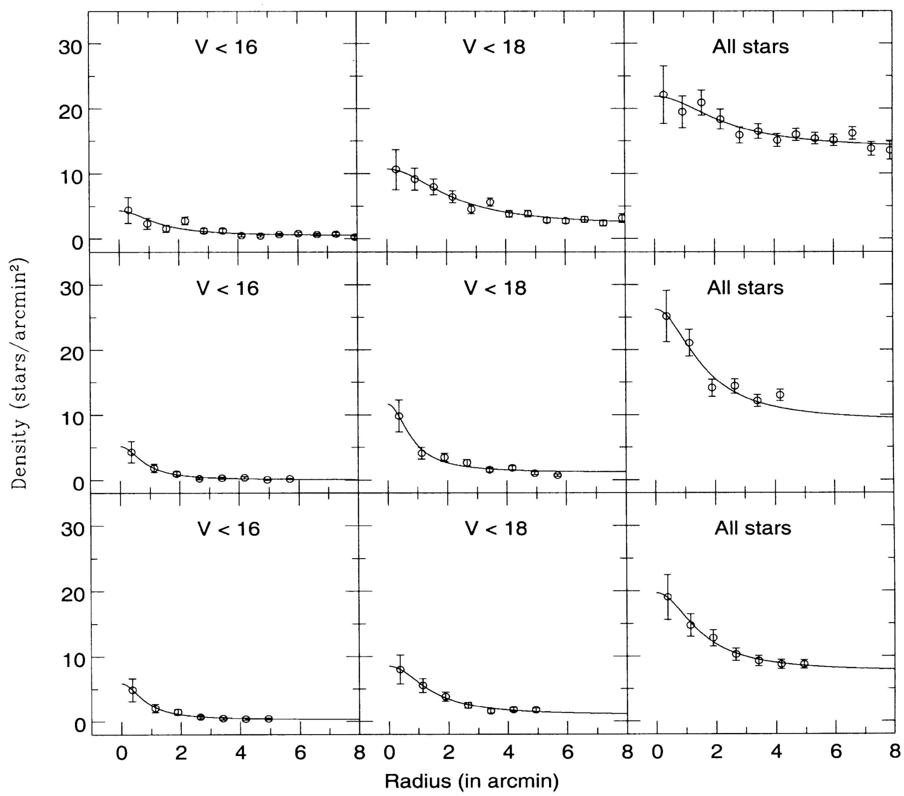

Figure 4. The variation of stellar surface density with radius for marked brightness ranges. The curve shows least square fit of the Kaluzny (1992) profile. The lower, middle and upper panels are for the clusters Be 15, Be 71 and King 1 respectively.

to make corrections in the sample that may occur because of various reasons such as crowded field which we observe. This increases for fainter stars of the cluster. Since we have taken only stars with V<18 mag, this correction is not as important in estimating the cluster parameters as is for the study of luminosity distribution of the stars in the cluster. A star located at a radial distance larger than the cluster radius is considered as a field star as for such stars, the probability of their being cluster members is relatively small. For photometric criterion, we fitted the theoretical isochrones by Girardi et al. (2002) to the cluster sequence in colour-magnitude diagram. The isochrones were brightened by 0.75 mag to take into account the maximum effects of binaries present in the cluster. This accounts for the broadening of the main sequence which may also be due to other reasons such as the photometric errors, internal reddening and spread in metallicity. The isochrones fitted in this way explain the presence of stars around the MS turn-off point and the red giant branch if present. The stars with V<18 mag lying along the main sequence within cluster radius are used to estimate cluster parameters.

5.1 Reddening and distance

The colour-colour diagrams ($U-B$, $B-V$) and the colour-magnitude diagrams (V, $U-B$), (V, $B-V$), (V, $V-R$) and (V, $V-I$) for stars with V<18 mag lying within the cluster radius are shown in Figures 5 and 6 respectively. They have been used to estimate reddening and distance modulus respectively. To derive the reddening and distance of the clusters we have used ZAMS given by Schmidt-Kaler (1982) and Walker (1985). The colour spread expected from the observational error as well as from binarity and peculiarities has been taken into account. The value of $E(B-V)$ and $E(U-B)$ has been calculated using the colour- colour diagram by fitting ZAMS given by Schmidt-Kaler (1982) to the observed data points which comes out to be 0.88±0.05 mag and 0.64±0.05 mag for cluster Be 15 and 0.85±0.05 mag and 0.62±0.05 mag for cluster Be 71 and 0.70±0.05 mag and 0.51±0.05 mag for cluster King 1. The value of $E(V-I)$ has been calculated using colour- magnitude diagram by fitting ZAMS given by Walker (1985) while the value of $E(V-R)$ was computed using colour-magnitude diagram by fitting ZAMS which was estimated using relation of $(V-R)_0$ with $(B-V)_0$ given by Caldwell et al. (1993). Thus, the value of $E(V-R)$ and $E(V-I)$ comes out to be 0.55±0.05 mag and 1.24±0.05 mag for cluster Be 15; 0.52±0.05 mag and 1.16±0.05 mag for cluster Be 71 and 0.50±0.05 mag and 1.17±0.05 mag for cluster King 1. The value of $E(U-B)/E(B-V)$ for Be 15, Be 71 and King 1 is 0.72. The values of $E(V-R)/E(B-V)$ for Be 15, Be 71 and King 1 are 0.63, 0.65 and 0.68 respectively. The values of $E(V-I)/E(B-V)$ for Be 15, Be 71 and King 1 are 1.41, 1.45 and 1.67 respectively. These values indicate that the reddening towards these clusters are not too different from the normal interstellar reddening.

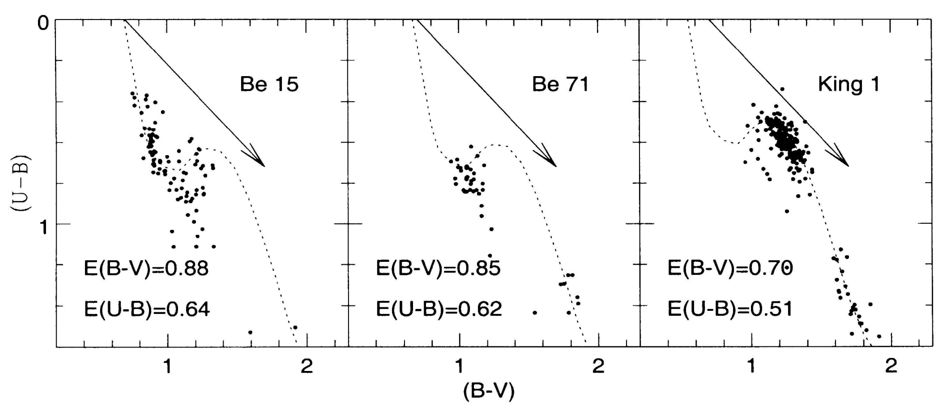

Figure 5. The colour-colour diagrams for stars with V<18 mag lying within the cluster radius. The curves show ZAMS given by Schmidt-Kaler (1982) for solar metallicity. The derived reddening values are in mag. The arrow represents the slope (0.72) and direction of the reddening vector.

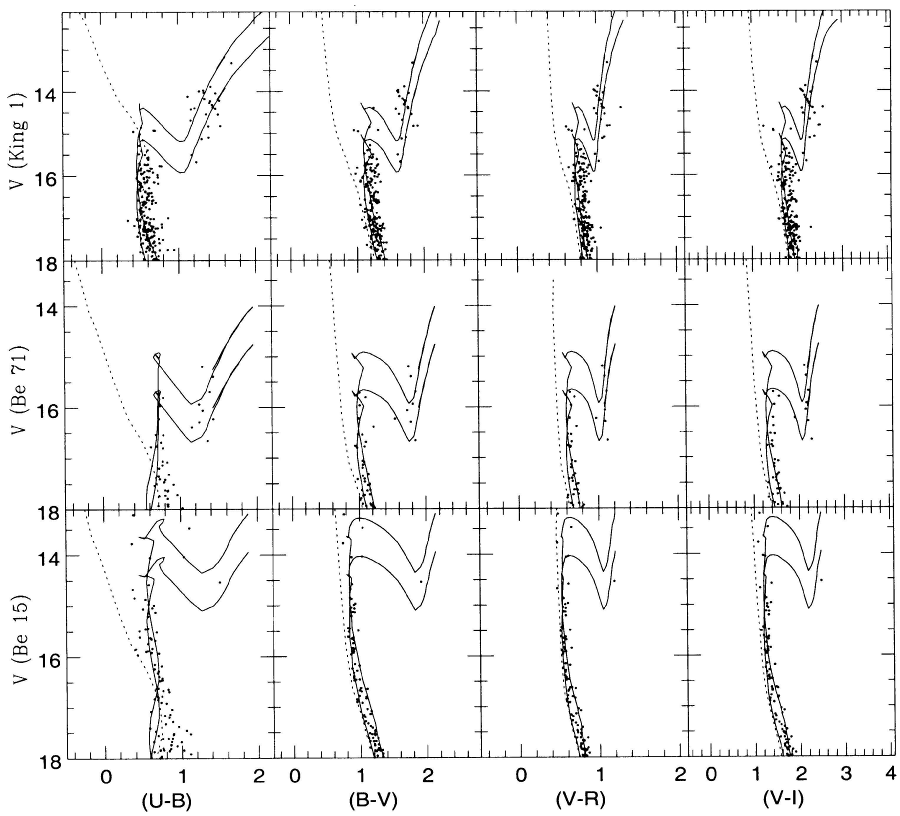

Figure 6. The CMDs for stars V<18 mag lying within the cluster radius. The solid curves show the isochrones given by Girardi et al. (2002) for solar metallicity and dotted curves are ZAMS fitted to the MS.

The distance modulus has been estimated by fitting ZAMS to the CMDs (Fig. 6) keeping constant value of reddening. In V, $(U-B)$ and V, $(B-V)$ diagrams, we have fitted ZAMS given by Schmidt-Kaler (1982) while that given by Walker was fitted in the V, $(V-I)$ diagram. For V, $(V-R)$ diagram, the ZAMS have been calculated as mentioned earlier. Thus, the distance moduli are 15.15, 15.60 and 13.55 for Be 15, Be 71 and King 1 respectively. We expect an uncertainty of about 0.2 mag in distance modulus. Adopting a normal value of total to selective absorption ratio R $(=A_V/E(B-V))$=3.1, we have determined distances to the clusters. These are 3.0, 3.9 and 1.9 kpc for Be 15, Be 71 and King 1 respectively.

5.2 Age

The age of the cluster has been estimated by fitting the theoretical isochrones given by Girardi et al. (2002) in Fig. 6. Ages for Be 15, Be 71 and King 1 are log(age)=8.5±0.1, 8.8±0.1 and 9.2±0.1 respectively. We have also estimated the ages of clusters using the relations between $(B-V)$ colour of the main-sequence turn-off point and age given by Meynet et al. (1993). The reddening free main-sequence turn-off colour indices for clusters Be 15, Be 71 and King 1 are estimated to be $(B-V) = -0.08 \pm 0.06$, 0.11 ± 0.06 and 0.40 ± 0.06 respectively. The corresponding ages are $\log t = 8.4 \pm 0.3$, 8.8 ± 0.3 and 9.3 ± 0.3 respectively. These are in very good agreement with the ages derived from fitting isochrones to the CMDs. Since King 1 has red giant clump, we can also estimate its age from the empirically determined relation given by Carraro & Chiosi (1994):

$$\log t = 0.45\delta V + 8.59$$

where δV is the difference between MS turn-off point and the red giant clump. The value of δV is 1.5±0.2 mag for King 1 and resulting value of log(age) is 9.3±0.1 which also matches well with those obtained above.

6. Integrated parameters

The integrated parameters have also been obtained for these clusters. The integrated absolute magnitude $I(M_V)$ and integrated intrinsic colours $I(B-V)_0$, $I(B-V)_0$, $I(B-V)_0$, $I(B-V)_0$ have been estimated using the procedures outlined earlier by Sagar et al. (1983) and recently by Lata et al. (2002). The parameters are listed in Table 6.

Table 6. Integrated parameters of clusters.

Cluster	$I(M_V)$ (mag)	$I(U-V)_0$ (mag)	$I(B-V)_0$ (mag)	$I(V-R)_0$ (mag)	$I(V-I)_0$ (mag)
Be 15	−4.65	0.07	0.08	0.08	0.16
Be 71	−3.01	0.73	0.44	0.34	0.64
King 1	−3.59	1.09	0.79	0.31	0.80

7. Conclusions

The paper presents for the first time CCD photometry in the Johnson UBV Cousins RI system for $\sim$ 5780 stars located in regions of the clusters Be 15, Be 71 and King 1. We have determined the distances, reddenings and ages of these clusters by analysing the colour-colour and colour-magnitude diagrams. We used ZAMS for determining the reddening and distances while for age estimation we used the isochrones given by Girardi et al. (2002). More weightage is given to the stars in the turn-off regions and giant branches, if present, since the lower main sequence are more heavily contaminated by field stars. All the clusters under discussion have well defined MS. Be 15, Be 71 and King 1 consist of 63%, 61% and 62% probable cluster members inside the cluster radius with V < 18 mag. In the absence of kinematical data, it is impossible to separate cluster members from field stars only on the basis of photometric criterion and present observations. The isochrones with solar metal abundance fits well to the observed diagrams for clusters under discussion. The cluster King 1 is older than Be 15 and B 71 while cluster Be 71 is the most distant object. The red giant clump in cluster King 1 is clearly visible while it is not visible in other two clusters. The CMDs of these clusters put them in the range of intermediate age. The $E(B-V)$ reddening values have been estimated from colour-colour diagrams of the clusters Be 15, Be 71 and King 1 are 0.88±0.05, 0.85±0.05 and 0.70±0.05 mag respectively. Be 15 is the most reddened cluster and lies at 3.0 kpc away from the Sun while Be 71 and King 1 are located about 3.9 and 1.9 kpc respectively from the Sun. All the clusters are located in the anticentre direction of Galaxy and above the galactic plane. The cluster Be 15, Be 71 and King 1 are at 11.4, 12.4 and 9.5 kpc away from Galactic centre assuming a galactocentric distance of Sun as 8.5 kpc. The corresponding distances above Galactic plane are 0.09±0.01, 0.07±0.005 and 0.05±0.005 kpc respectively. The linear diameter of clusters Be 15, Be 71 and King 1 are estimated to be 7.9, 6.8 and 4.3 pc respectively.

Acknowledgements

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