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CCD photometry of the unstudied galactic star clusters Be 10, Be 67 and To 5

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Abstract. We present the broad band Johnson UBV and Cousins RI CCD photometric observations for open clusters Be 10, Be 67 and To 5. So far no photometric study of these clusters is published. The colour-magnitude diagrams indicate that all the three clusters are of intermediate age. The reddening E(B-V), estimated from colour-colour diagrams/colour-magnitude diagrams, is 0.87±0.05 mag for Be 10, 0.79±0.05 mag for Be 67 and 0.80±0.05 mag for To 5. The comparison of colour magnitude diagrams with the stellar models with convective overshoot by Girardi et al. (2002) produces a good fit for a metallicity Z = 0.008 for cluster Be 10 and Z = 0.02 for clusters Be 67 and To 5. Ages for Be 10, Be 67 and To 5 are log (age) = 8.8±0.1, 9.0±0.1 and 8.3±0.2 respectively. The corresponding distances for these clusters are 2.29±0.21, 2.45±0.23 and 1.75±0.16 kpc respectively. Analysis of the radial distribution of stellar surface density indicates that radius values for Be 10 , Be 67 and To 5 are 6.0, 3.5 and 6.0 arcmin respectively.

Keywords : Open clusters: Be 10, Be 67 and To 5–colour-magnitude diagram

1. Introduction

The Galactic star clusters are important tools for the studies of a host of present day astrophysical problems including the theories of star formation and stellar and galactic evolution. For such studies, a knowledge of cluster parameters and stellar content are mandatory but these are lacking for more than 60% of the star clusters in our Galaxy. We therefore observed a number of unstudied star clusters from both northern and southern

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hemispheres and published their studies in a series of papers (see Mohan et al., 1992; Bhatt et al., 1993; Pandey et al., 1994; Sagar & Cannon 1994; Durgapal et al., 1996; Durgapal et al., 1998; Nilakshi et al., 1998; Sagar& Griffiths 1998; Subramaniam & Sagar 1999; Sagar et al., 2001a and Sagar et al., 2001b). In this paper we present the first deep CMDs of Be 10, Be 67 and To 5. A brief description of the clusters, along with earlier informations, is given below.

Berkeley 10 (Be 10) : This cluster is also known as OCL 370 (α = 3^h $39^m.45$, δ = 66^o $32'.0$ (2000); l = $138^o.58$, b = $8^o.91$). Its angular diameter is about 12 arcmin and Trumpler classification is II2m (Lyngå 1987). However, Ruprecht (1966) has classified it as II3p.

Berkeley 67 (Be 67) : The cluster is also known as OCL 400 (α = 4^h $38^m.13$, δ = 50^o $44'.97$ (2000); l = $154^o.88$, b = $2^o.51$). The angular diameter of the cluster is about 7 arcmin while Trumpler classification is III1m (Lyngå 1987). However, Ruprecht (1966) has classified it as IV1p.

Tombaugh 5 (To 5) : The cluster is also known as OCL 385 (α = 3^h $47^m.8$, δ = 59^o $03'.22$ (2000); l = $143^o.94$, b = $3^o.58$). The angular diameter and distance of the cluster are 17 arcmin and 1800 pc respectively. Trumpler has classified it as III2r (Lyngå 1987) while Ruprecht (1966) has classified it as III2m.

To determine cluster parameters reliably, deep and accurate photometric observations of the clusters are desired and the same have been provided here. The details of present observations and data reduction are given in the next section while radial distribution of surface density and parameters of the clusters are presented in the remaining part of the paper.

2. Observations and Reductions

The broad band UBVRI photometric observations for the clusters Be 10 , Be 67 and To 5 were carried out using CCD system at f/13 Cassegrain focus of the 104-cm Sampurnanad reflector of the State Observatory, Nainital, during 1999 – 2001. The CCD detector is a square of 2048 pixel size and each pixel of 24μ square size corresponds to 0.38 arcsec. 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 98 were also observed. As cluster diameter for To 5 is 17 arcmin, we observed the cluster by dividing it in 4 sub-regions namely North-West, South-East, South-West and North-East. Fig. 1 shows their identification maps. The log of observations is listed in Table 1.

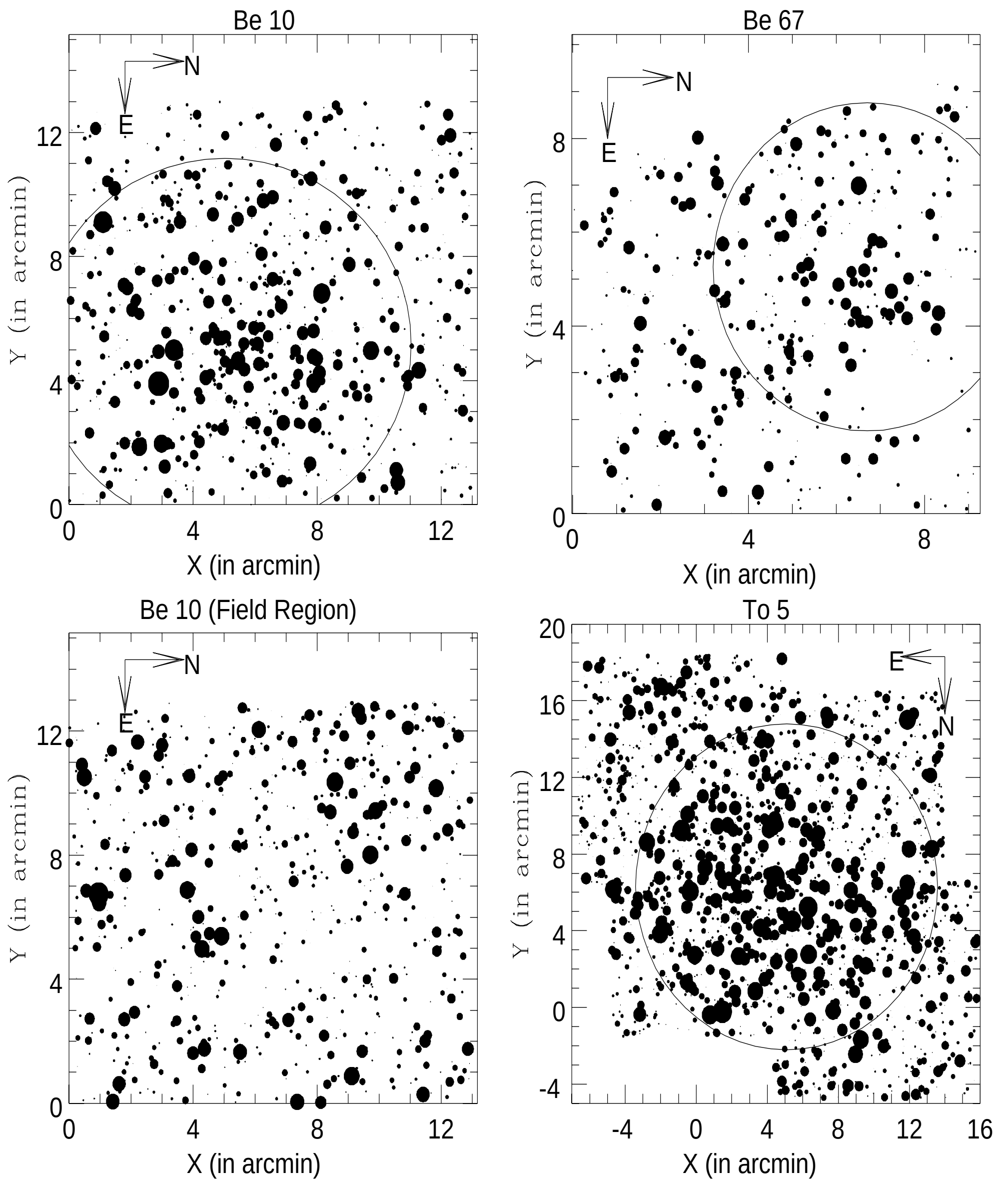

Figure 1. Identification chart for cluster Be 10, Be 67 and To 5 and for field region of Be 10. The circle represents radius of cluster.

Table 1. Log of CCD observations.

Cluster	Filter	Exposure time (seconds)	Total Exposure time (seconds)	Date
Be 10	U	600×6	3600	20 October 2001
	U	300×3		16 November 2001
	B	600×4	2400	20 October 2001
	B	100×3		16 November 2001
	V	300×4	1200	20 October 2001
	V	60×3		16 November 2001
	R	200×3	600	20 October 2001
	R	30×3		16 November 2001
	I	200×3	600	20 October 2001
	I	30×3		16 November 2001
Standard field(SA 98)				
	U	300×8		16 November 2001
	B	100×8		"
	V	50×8		"
	R	30×8		"
	I	30×8		"
Be 67	U	1500×4	6000	27 October 2000
	B	900×3, 600	2700	"
	V	500×3, 300	1500	25 October 2000
	R	300×2, 200	800	"
	I	300×3	900	25 October 2000
Standard field(SA 98)	U	300×4		26 January 2001
	B	100×4		"
	V	60×2, 50, 30		"
	R	30×4		"
	I	30×4		"
To 5				
South-East Region	U	900×3, 1000, 500	3700	5 November 1999
	B	600×3, 300×2	1800	4 November 1999
	V	300×2, 100×2	600	"
	R	300×2, 100×2	600	5 November 1999
	I	300×2, 100×2	600	4 November 1999
South-West Region	U	1000×2, 900×2	3800	6 December 1999
	B	600×3, 100×2	1800	12 December 1999
	V	300×3, 50×2	900	6 December 1999
	R	300×2, 50×2	600	12 December 1999
	I	300×3, 100×3	900	11 December 1999
North-West Region	U	900×4	3600	12 December 1999
	B	600×3	1800	4 January 2000
	V	300×3	900	5 January 2000
	R	300×3	900	"
	I	300×3	900	12 December 1999

The data reduction was carried out using IRAF and MIDAS software packages installed on the computers of the State Observatory, Nainital. Images of the cluster fields were aligned and co-added in each filter to optimize signal to noise ratio. Short exposures have also been taken for estimation of extinction coefficients and also for measuring bright stars which were saturated in 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

Table 1. *continued.*

Cluster	Filter	Exposure time (seconds)	Total Exposure time (seconds)	Date
North-East Region	U	900×6	5400	19 October 2001
	B	600×4	2400	”
	V	300×4	1200	”
	R	200×4	800	”
	I	200×2, 300	700	”
Central Region	U	300×8		12 December 1999
	B	100×8		”
	V	40×8		”
	R	40×8		”
	I	40×8		”
Standard field (SA 98)	U	300×2, 100		”
	B	100×2, 60		”
	V	30×3		”
	R	30×3		”
	I	30×3		”

typical errors for standard stars are 0.02, 0.02, 0.02, 0.03 mag in V, $(B-V)$, $(V-R)$, $(V-I)$ and $(U-B)$ respectively.

Table 2a. Sample of UBVRI photometric data of the stars in the cluster Be 10. The co-ordinates X and Y are in pixel, magnitude and colours are in mag.

No.	X	Y	V	$(U-B)$	$(B-V)$	$(V-R)$	$(V-I)$	σ_U	σ_B	σ_V	σ_R	σ_I
5263	227.8	308.1	11.26	0.32	0.37	0.25	0.49	.003	.005	.016	.008	.021
5645	86.3	719.4	12.23	0.26	0.76	0.52	0.96	.006	.006	.012	.025	.013
5362	266.6	393.5	12.32	1.47	1.47	0.86	1.60	.013	.006	.024	.009	.016
5491	643.0	537.6	12.79	0.28	0.73	0.45	0.86	.010	.007	.014	.010	.020
5359	768.3	392.1	13.25	0.22	0.67	0.45	0.85	.008	.011	.015	.010	.021
5115	235.2	155.3	13.54	0.21	0.77	0.48	0.91	.015	.011	.017	.012	.027
	*	*	*	*	*	*	*	*	*	*	*	*
	*	*	*	*	*	*	*	*	*	*	*	*
	*	*	*	*	*	*	*	*	*	*	*	*

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 10, Be 67 and To 5 along with their DAOPHOT errors have been listed in Tables 2a, 2b and 2c respectively. The format of all the Tables 2a, 2b and 2c is similar and for 2a it is presented here. The entire data will be available only in electronic form at the CDS in Strasbourg and the WEBDA open cluster data base website at http://obswww.unige.ch/webda/. It can also be obtained from the authors. The DAOPHOT errors in different passbands as a function of standard magnitudes have been plotted in Fig. 2. In Table 3, we list these errors as a function of brightness.

3. Radius and spatial structure of the clusters

To determine cluster radius and to study the spatial structure, we plot the radial variation of the stellar surface density. For this it is necessary to fix the cluster centre first. To

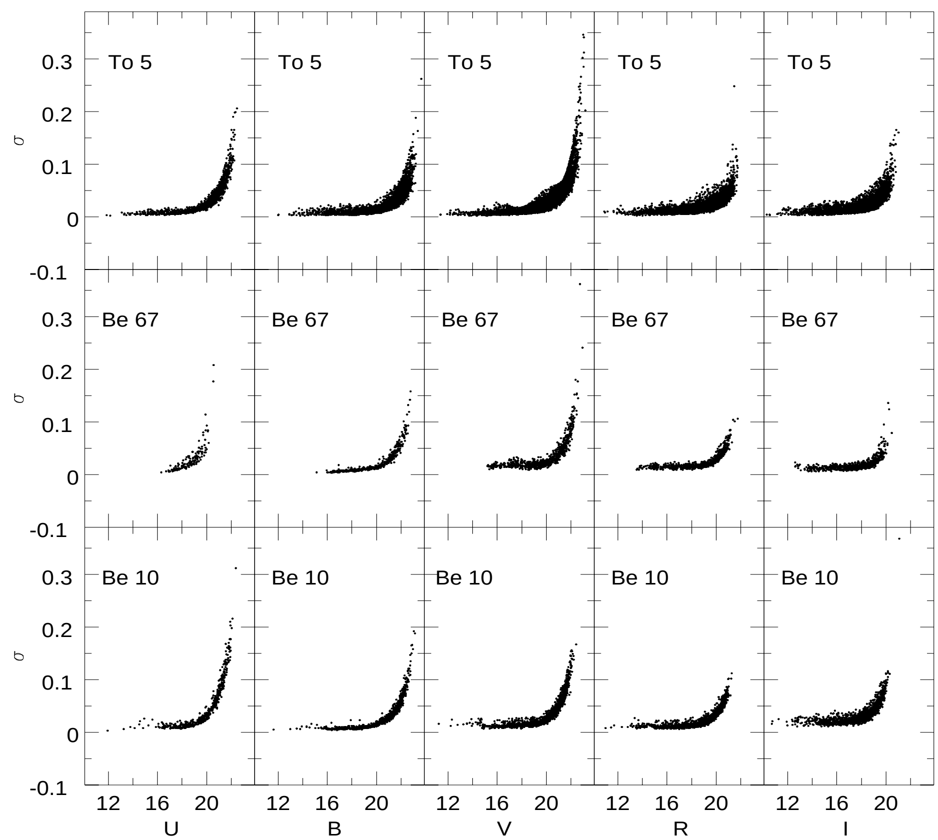

Figure 2. The errors of stars given by DAOPHOT as function of magnitude.

minimize contamination due to field stars in determination of the cluster centre, relatively bright stars within a small strip of eye estimated centre have been used (for Be 10, V<18 mag and within 100 pixels and for To 5, V<19 mag and within 100 pixels). We have estimated co-ordinates of cluster centre by fitting the gaussian function in the star distribution and considering the peak to be centre of the cluster. For cluster Be 67 we could not estimate the cluster centre by fitting gaussian function because there is deficiency of stellar density towards NE direction due to presence of some gaseous clouds in front of the cluster. For this cluster we have derived cluster centre iteratively by calculating average X and Y positions of stars within 100 pixels from eye estimated centre, until it converged to a constant value. An error of a few arcseconds is expected in locating the cluster centre. For determining the radial surface density of stars, the imaged area has been divided into a number of concentric circles with respect to above estimated cluster centre in such a way that each zone contains at least 10 stars. The

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

Cluster	magnitude range	σ_U	σ_B	σ_V	σ_R	σ_I
Be 10	< 13	0.003	0.006	0.017	0.009	0.021
	13-14	0.008	0.008	0.017	0.013	0.021
	14-15	0.016	0.012	0.015	0.012	0.022
	15-16	0.016	0.009	0.012	0.011	0.021
	16-17	0.012	0.007	0.013	0.012	0.022
	17-18	0.011	0.008	0.015	0.013	0.024
	18-19	0.014	0.009	0.016	0.016	0.033
	19-20	0.025	0.012	0.019	0.026	0.058
	20-20.5	0.039	0.019	0.029	0.043	0.100
	20.5-21	0.063	0.024	0.043	0.063	-
	21-21.5	0.096	0.034	0.063	0.090	-
	21.5-22	0.147	0.050	0.095	-	-
	22-22.5	0.242	0.075	0.141	-	-
Be 67	< 16	-	0.005	0.016	0.014	0.013
	16-17	0.006	0.006	0.017	0.015	0.013
	17-18	0.011	0.007	0.020	0.015	0.014
	18-19	0.022	0.009	0.018	0.016	0.018
	19-20	0.043	0.012	0.020	0.023	0.034
	20-20.5	0.073	0.016	0.024	0.036	0.082
	20.5-21	-	0.022	0.034	0.051	-
	21-21.5	-	0.034	0.048	0.075	-
To 5	<12	0.003	-	0.004	0.009	0.009
	12-13	0.004	0.004	0.007	0.009	0.008
	13-14	0.006	0.006	0.006	0.008	0.010
	14-15	0.006	0.008	0.008	0.010	0.011
	15-16	0.008	0.009	0.008	0.011	0.012
	16-17	0.008	0.009	0.010	0.012	0.012
	17-18	0.009	0.010	0.010	0.013	0.015
	18-19	0.011	0.010	0.013	0.016	0.022
	19-20	0.018	0.012	0.019	0.022	0.036
	20-20.5	0.029	0.014	0.027	0.030	0.061
	20.5-21	0.039	0.020	0.035	0.039	0.105
	21-21.5	0.059	0.027	0.045	0.055	0.160
	21.5-22	0.086	0.038	0.068	0.107	-
	22-22.5	0.142	0.053	0.104	-	-

number density of stars, ρ_i, in i^{th} zone has been evaluated as

$$\rho_i = N_i/A_i$$

Where N_i is the number of stars in area A_i of the i^{th} annulus. The radial density profile (RDP) thus obtained for clusters are shown in Fig. 3. The error bars are derived assuming that the number of stars in a zone follows Poisson statistics. Following Kaluzny (1992), we described the $f(r)$ of an open cluster as

$$f(r) = f_0/(1 + (r/r_c)^2)$$

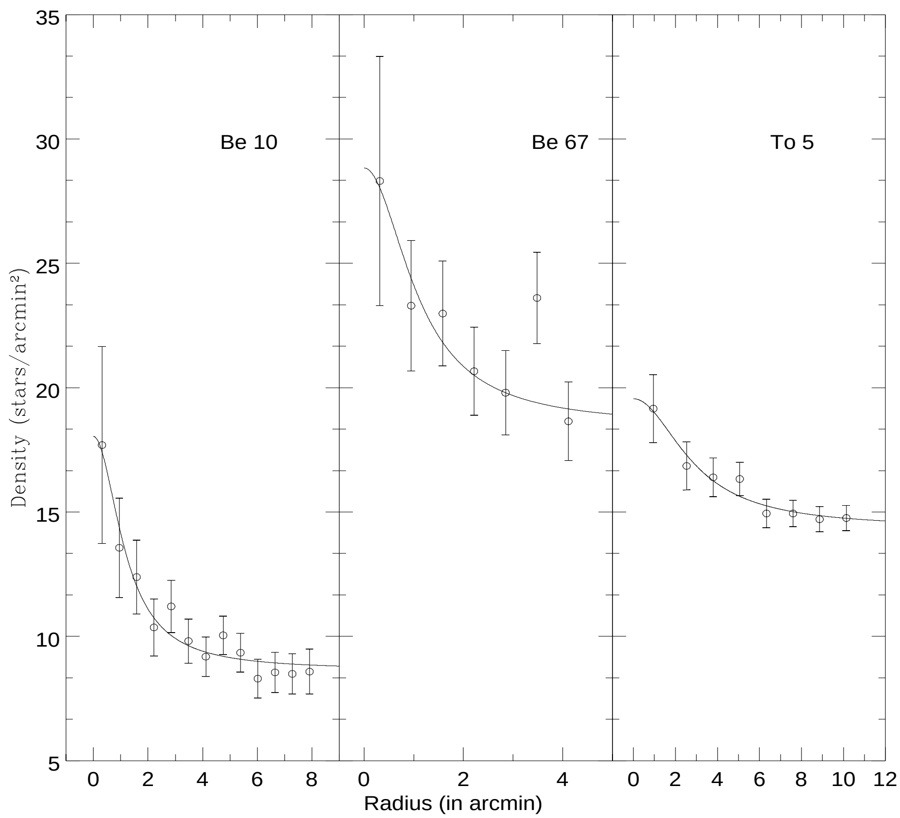

Figure 3. The variation of stellar surface density with radius. The curve shows least square fit of the Kaluzny (1992) profile.

where the cluster core radius r_c is the radial distance at which the value of $f(r)$ becomes half of the central density f_0. We fit this function to the observed data points of each cluster and use χ^2 minimisation technique to determine r_c and other constants. As can be seen in Fig. 3, the fitting of the function is satisfactory for clusters. This yields $r_c = 1.19 \pm 0.19$ arcmin ($\chi^2 = 0.4077$) for Be 10, 1.09 ± 0.28 arcmin ($\chi^2 = 0.9618$) for Be 67 and 2.89 ± 0.51 arcmin ($\chi^2 = 0.1665$) for To 5. The radius at which the value of density becomes constant has been considered as cluster radius and it comes out to be 6 arcmin for Be 10, 3.5 arcmin for Be 67 and 8.5 arcmin for To 5. The (X_c, Y_c) pixel co-ordinates of the cluster centre along with radius are listed in Table 4.

Table 4. Pixel coordinates of the cluster centres with their radius estimate.

Cluster	X_c (pixel)	Y_c (pixel)	r (pixel)	r (arcmin)
Be 10	397	408	474	6.0
Be 67	529	415	276	3.5
To 5	402	497	671	8.5

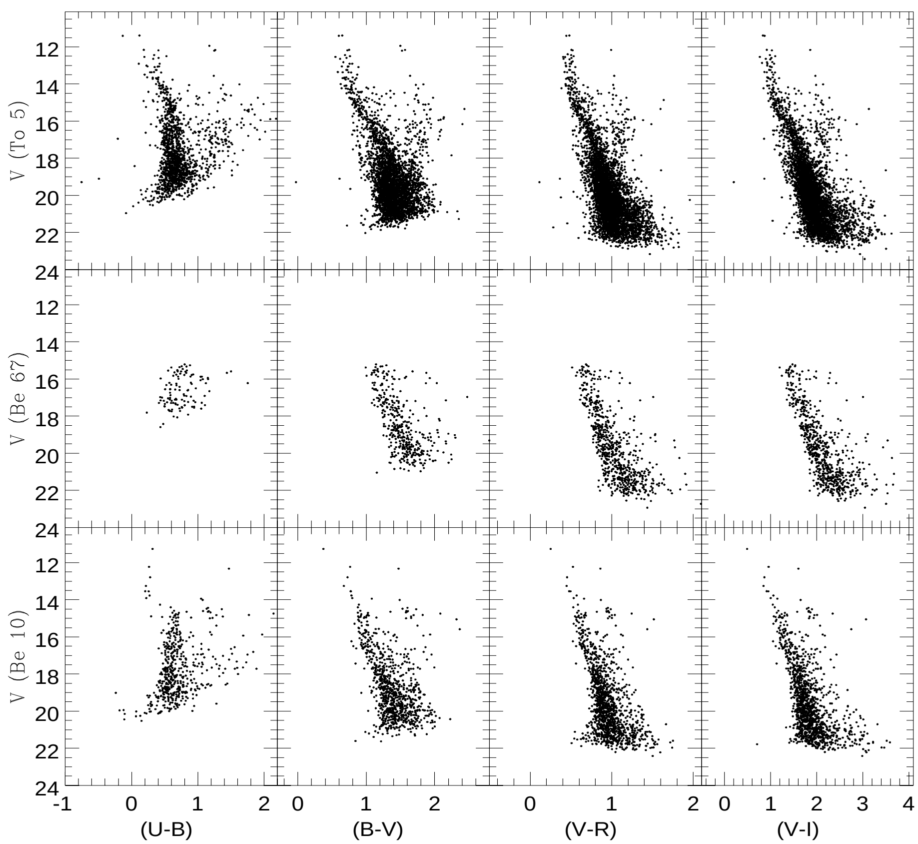

Figure 4. The CMDs for all stars in Be 10, Be 67 and To 5.

4. Cluster Parameters

The apparent colour-magnitude diagrams (CMDs) generated from the present data for the clusters are shown in Fig. 4 and CMD for a nearby field region of Be 10 is plotted in Fig 5. The CMDs of the clusters show cluster main sequence (MS) contaminated by field

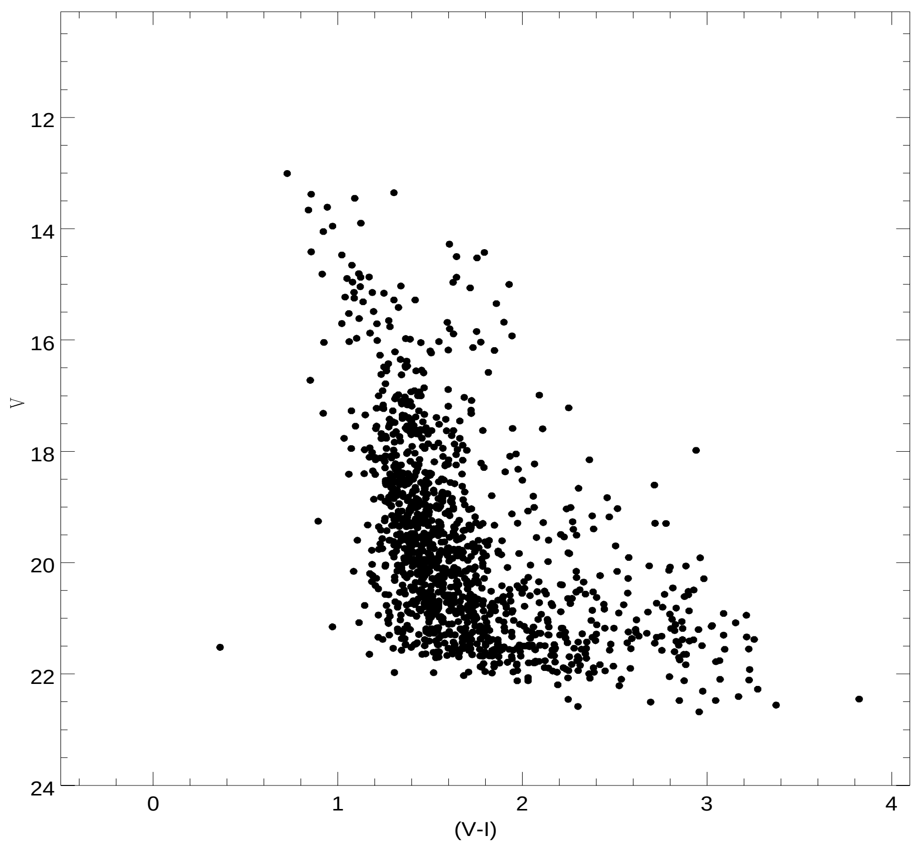

Figure 5. The CMD of field region of Be 10.

stars down to V ≈ 21 mag. The cluster sequences fainter than V ≈ 18 mag have large scatter due to larger photometric errors and field star contaminations. 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. A star located at a radial distance larger than the cluster radius determined above is considered as a field star. For stars lying outside the cluster radius, the probability of such stars being members is relatively small.

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 lying within the cluster radius for clusters

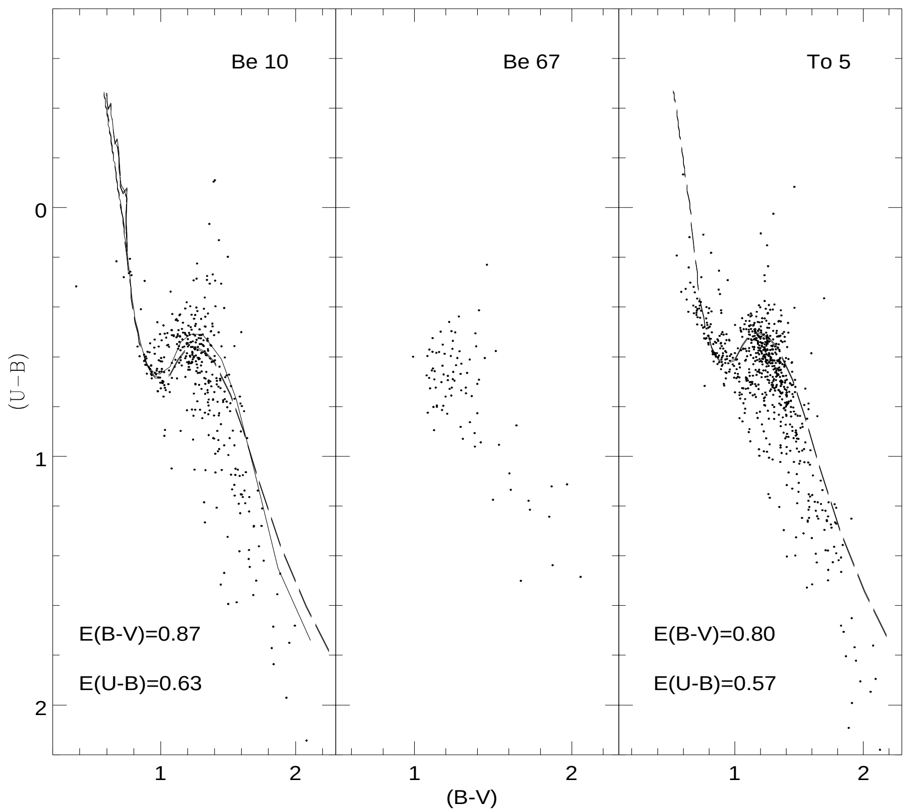

Figure 6. The colour-colour diagrams for cluster Be 10, Be 67 and To 5. Dashed curve shows model given by Girardi et al. (2002) of metallicity Z=0.02 and solid curve is for Z=0.008.

under study are shown in Figures 6 and 7 respectively. Theoretical stellar evolutionary models given by Girardi et al. (2002) have been used to estimate the cluster parameters. Since we do not know about metal abundances of these clusters, we have used theoretical ZAMS and isochrones of different metallicities to estimate the best fit in colour-colour and colour magnitude diagrams simultaneously. For To 5 and Be 67 models with metallicity Z=0.02 produce a good fit but for Be 10 models with Z=0.008 produce a better fit than models with Z=0.02 as shown in Figure 6. For To 5 and Be 10 we could estimate the reddening based on (U-B, B-V) colour-colour diagram but in case of Be 67 the reddening could not be determined from the colour-colour diagram and so we have estimated it while fitting the isochrones in (V, B-V) colour-magnitude diagram.

The apparent distance modulus and age of the clusters have been obtained by fitting isochrones to the colour magnitude diagrams. These have been plotted in Figures 7a, 7b and 7c. For estimation of E(V-R) and E(V-I), we have used the relations E(V-R) = 0.60×E(B-V) and E(V-I) = 1.25×E(B-V) (Dean et al., 1978). The reddening values thus estimated are given in Table 5.

Table 5. Reddening for the clusters.

Cluster	$E(B-V)$ mag	$E(U-B)$ mag	$E(V-R)$	$E(V-I)$
Be 10	0.87±0.05	0.63±0.05	0.57±0.05	1.15±0.05
Be 67	0.79±0.05	–	0.47±0.05	0.99±0.05
To 5	0.80±0.05	0.57±0.05	0.50±0.05	1.03±0.05

To obtain true distance modulus, the relation A_v = 3.1×E(B-V) has been used. We also draw the MS brightened by 0.75 mag to take into account physical/optical binary stars and scatter due to the photometric errors and stellar peculiarities etc. We consider those stars as probable cluster members which lie within the envelopes around the MS in the apparent CMDs of the cluster. The linear diameter of the cluster has been obtained by using the distance of the cluster and its angular radius estimated in section 3. The ages, distances and cluster diameters thus obtained have been listed in Table 6. The galactocentric distance (R_g) and distance above galactic plane (z) have also been estimated which are also listed in Table 6. Piatti et al. (1995) have obtained age-metallicity-position relation. From using this relation Z values for clusters Be 10, Be 67 and To 5 come out to be 0.011, 0.014 and 0.014 with error 0.004 respectively.

Table 6. Ages, distances and diameters of clusters.

Cluster	log t (t in years)	($m-M_v$) (mag)	(m_0-M_v) (mag)	Distance (kpc)	Diameter (pc)	R_g (kpc)	z (kpc)
Be 10	8.80±0.10	14.50	11.80±0.20	2.29±0.21	8.00	10.31	0.35±0.03
Be 67	9.00±0.10	14.40	11.96±0.20	2.45±0.23	4.98	10.78	0.11±0.01
To 5	8.30±0.20	13.70	11.22±0.20	1.75±0.16	8.65	9.90	0.11±0.01

4.1 Integrated parameters

The integrated parameters for clusters under study have been obtained by using the method given by Gray (1965). The uncertainty in integrated absolute magnitude could be ± 0.5 mag and in colours it could be ± 0.2 mag. We have estimated total cluster mass considering magnitude range $14<V\leq21$ mag for Be 10, $15<V\leq22$ for Be 67 and $11<V\leq19$ for To 5 by using the relation(log M -$I(M_V)$) given by Battinelli et al. (1994) and also cluster age from the relation ($I(U-V)_0$ - log (age)) obtained by Lata et al. (2002). Ages thus determined are in good agreement with those obtained by fitting models. These integrated parameters along with mass and age are listed in Table 7.

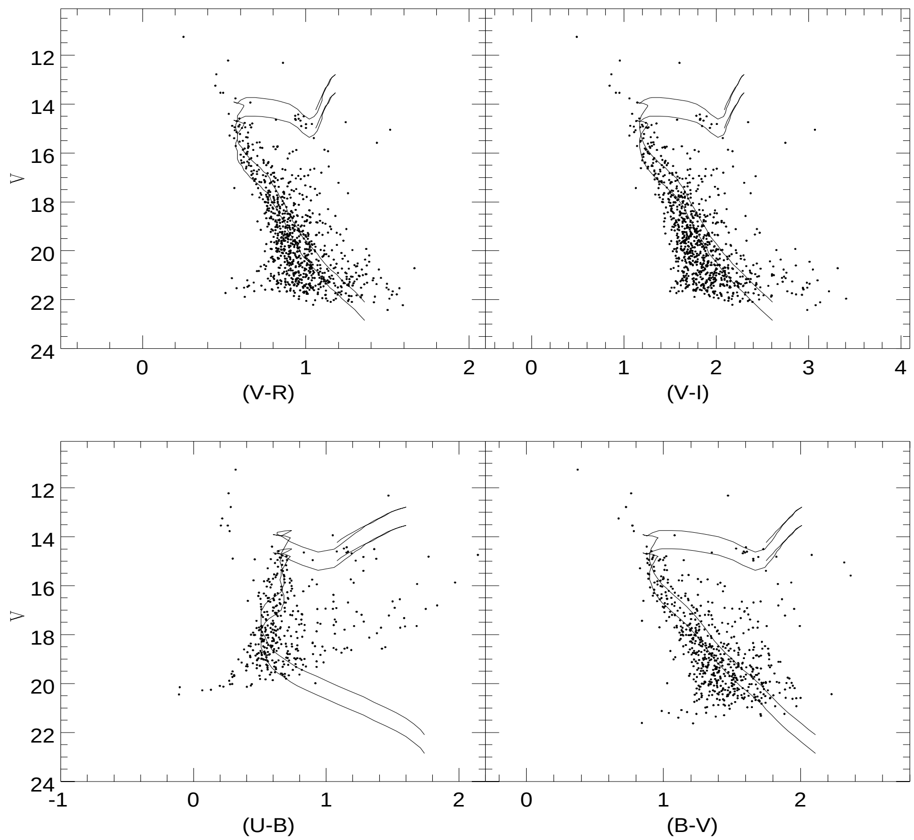

Figure 7a. The CMDs for stars lying within cluster radius in Be 10. The curves show the isochrones of log (age) = 8.80 and brighter one is the isochrone for the binary stars.

Table 7. 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)	M ($M_\odot$)	log t (t in years)
Be 10	−4.22	0.36	0.27	0.19	0.34	116 ± 2	8.70±0.38
Be 67	−3.26	0.77	0.53	0.31	0.66	83±2	9.24±0.38
To 5	−5.58	−0.16	0.03	0.06	0.11	185±2	8.00±0.38

5. Discussion and Conclusions

We have presented the photometry of clusters Be 10, Be 67 and To 5 down to V∼21 mag for the first time. From this database we have estimated fundamental parameters of

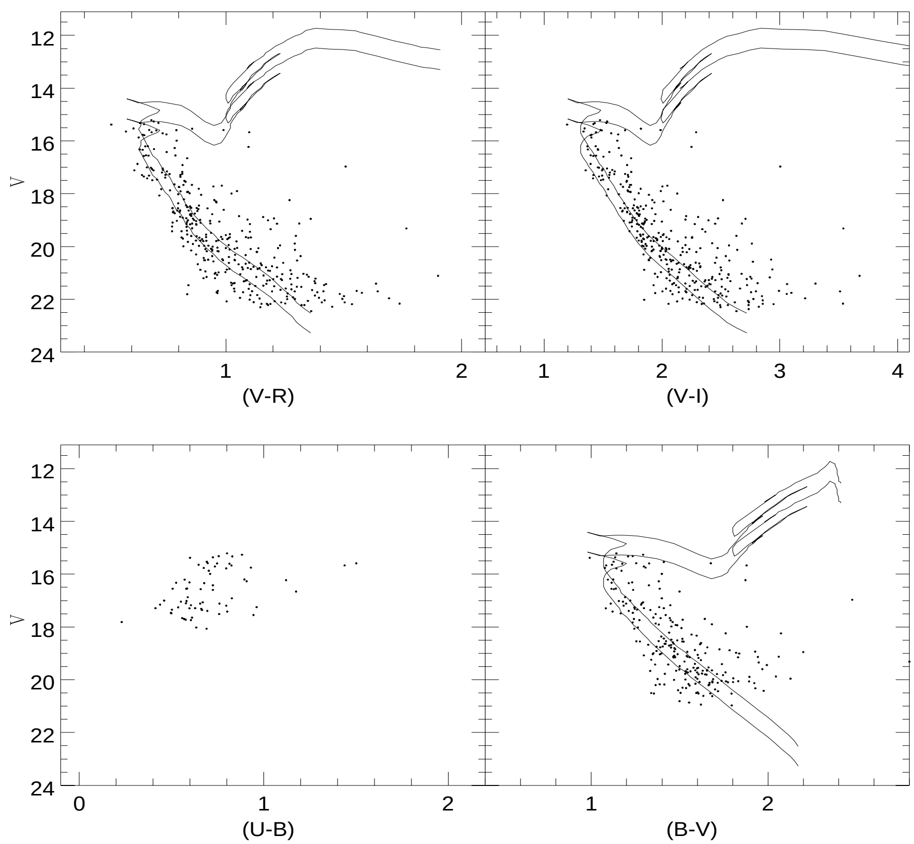

Figure 7b. The CMDs for stars lying within cluster radius in Be 67. The curves show the isochrones of log (age) = 9.00 and brighter one is the isochrone for the binary stars.

clusters by visual fitting of theoretical stellar isochrones. For Be 10, cluster parameters have been obtained by fitting isochrones of metallicity Z=0.008 instead of solar metallicity because it fits better than solar metallicity. The clusters Be 10, Be 67 and To 5 are at distance of 2.29±0.21, 2.45±0.23 and 1.75±0.16 kpc respectively. The age varies for cluster sample from log(age) = 8.0 to 9.1 in which To 5 is the youngest while Be 67 is the oldest. The reddening values for clusters Be 10 and Be 67 have been estimated from colour-colour digrams while for Be 67 it is estimated from CMD of the cluster. The location of the turn-off point in the CMDs indicate that all the clusters under study are of intermediate age. All the clusters have well defined and broad main sequence. The broadening of main sequence is due to photometric errors, binaries and presence of field stars etc. The radial distribution of stellar surface density by fitting the model gives the core radii for clusters Be 10, Be 67 and To 5 which are 1.19±0.19, 1.09±0.28 and

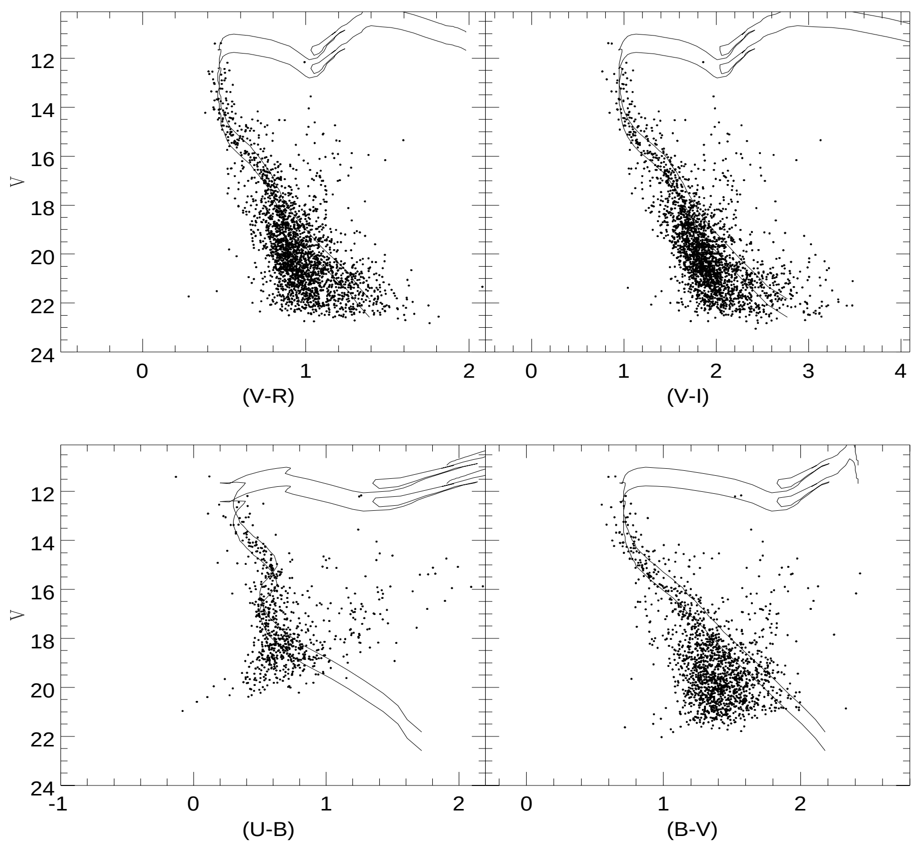

Figure 7c. The CMDs for stars lying within cluster radius in To 5. The curves show the isochrones of log (age) = 8.30 and brighter one is the isochrone for the binary stars.

2.89±0.51 arcmin respectively. The cluster radii obtained here are in good agreement with those given in the catalogue of Lyngå (1987). The Clusters under study are located in the galactic anticenter direction and lie above the galactic plane. A comparison of the CMDs of cluster Be 10, To 5 with the CMD of the nearby field region of Be 10 indicates that the stars located towards the redward of the MS are probably field stars.

We have also computed integrated parameters for all the clusters under study. The integrated colours indicate the age of cluster. We have also computed age and mass of clusters from these integrated parameters. The age obtained from colour-age relation is in agreement with that obtained by fitting isochrones.

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