Bull. Astr. Soc. India (2001) **29**, 389–396

Photometric studies of intermediate and old age galactic star clusters

Alok K. Durgapal

U.P. State Observatory, Manora Peak, Naini Tal 263129, India

Abstract. We present a detailed analysis of five intermediate / old age open star clusters, based on the CCD UBVRI data. We have used a new colour index parameter (CIP), which is the difference in colour index between the blue turn off point (BTO) of the main sequence and the colour at the base of the red giant branch (BRGB), to estimate morphological age of the cluster. This parameter is useful for the clusters which have no noticeable red giant clump. We find that morphological features of the colour magnitude diagram (CMD) are better understood in terms of convective core overshooting. Age of the clusters under study ranges between 0.6-5 Gyr. We have studied the mass function and structure of all the clusters. Mass function slopes for three clusters are in agreement with the Salpeter (1955) value. Spatial variation of mass function along the clusters is also studied. Mass segregation is observed in three clusters. Since all these clusters are dynamically relaxed, the observed mass segregation is therefore most likely due to the dynamical evolution processes.

Key words : Open clusters, photometry, mass segregation, mass function, cluster structure

1. Introduction

Open clusters have long been recognized as important tools in the study of the Galactic Disk. Within the large population of known open clusters, the old ones are an interesting minority. The system of galactic open clusters, in particular the oldest members serve as excellent probes of the structure and evolution of the Galactic Disk (Janes & Phelps, 1994). In addition, the intermediate age open clusters are well suited to study the issue of convective core overshooting (e.g., Mazzei & Pigatto, 1988 and references therein). These clusters have turnoff mass near the critical value separating the domain of core He flash from that of mild He-ignition. A comparison of the HR diagram of the observed clusters with the evolutionary models of the same chemical composition can be used to test core overshooting and classical stellar models. Spatial and age distribution of open clusters provide an insight into the processes of cluster formation and destruction that have allowed substantial number of old open clusters to survive.

Recently much interest has been shown by various groups to determine accurate ages for intermediate and old open clusters (see e.g., Kaluzny, 1994 and Phelps et al., 1994) with the aim of setting a lower limit to the age of the Galactic Disk. An understanding of their properties (age, metallicity and kinematics) is mandatory for many studies such as the history of star formation in the Galactic Disk, the structure of the Disk etc.

2. Observations and reductions

The UBVRI photometric observations for the clusters Be 64, Be 69, King 5, King 7 and BVRI observations for the cluster Be 20 were carried out using the photometric CCD system at f/13 Cassegrain focus of the 104-cm Sampurnanand reflector of the Uttar Pradesh State Observatory (UPSO), Naini Tal, during 1990 to 1996. Two CCDs having size 384 x 576 and 1024 x 1024 pixel^2 were used for the observations. In order to improve the S/N ratio, the observations were taken in binning mode of 2 x 2 pixel^2. In this setup each pixel 384 x 576 and 1024 x 1024 pixel^2 CCDs corresponds to 0.66 arcsec and 0.7 arcsec respectively whereas these chips cover a field of ~ 2 x 3 and ~ 6 x 6 arcmin respectively. The details of the observations of these clusters are given in our previous papers (Pandey et al. 1997, Durgapal et al. 1997 and Durgapal et al. 2001).

A number of bias and twilight flat-field frames were also taken during the observing runs. The frames were cleaned employing the standard procedures using ESO-MIDAS software running on the computer systems of the Observatory. The photometry of co-added frames was carried out using DAOPHOT package by Stetson (1987). The PSF was obtained for each frame using several uncontaminated stars and the PSF magnitudes were suitably tied to aperture photometry magnitudes. One star of the cluster field was taken as comparison star and differential magnitude and colours of each star were obtained. The differential magnitudes were then standardized using Landolt (1983) stars.

3. Morphological age of the clusters

Age of an open cluster is obtained by fitting theoretical isochrones to its colour-magnitude diagrams. This requires however, a knowledge of cluster metallicity and reddening. Distance modulus can be determined simultaneously with age. The difficulties encountered in fitting theoretical isochrones to observed cluster CMDs when no information about reddening and/or metallicity is available, have prompted some indirect methods for age estimation of open clusters. These methods use the visible differences in the CMDs of star clusters for different ages (see e.g., Kaluzny 1994; Phelps et al., 1994), the position of red giant clump, main sequence blue turnoff (BTO) and red turnoff.

We have derived morphological age of the clusters using colour index parameter (CIP) which is a difference in (B-V) colour index of the BRGB and the BTO (cf. Pandey et al., 1997);

$$CIP = (B - V)_{BRGB} - (B - V)_{BTO} \tag{1}$$

Table 1. Morphological features of the CMDs of the clusters.

Cluster	BTO (B − V)	BRGR (B − V)	CIP	Age (Gyr) (estimated from CIP)
Be 64	1.05	1.7	0.65	1.0
Be 69	0.75	1.30	0.55	1.0
King 7	1.25	2.00	0.75	0.5
King 5	1.00	1.57	0.57	1.2-1.6
Be 20	0.55	0.90	0.35	5.0

This parameter is useful for the clusters which have no noticeable red giant clump. Pandey et al. (1997) have derived CIP as a function of age using the model of VandenBerg (1985) and convective overshoot model of Bertelli et al. (1994). Although CIP of a cluster slightly depends on the metallicity, yet the ages obtained from the two stellar models are almost the same. The BTO and BRGB for one of the clusters (Be 20) are marked in Fig. 1. Error in the estimation of CIP is approximately of the order of ± 0.1 mag. For a value of CIP = 0.65 ± 0.1 mag, age estimate varies from log τ =8.7 to log τ = 9.2. However, age estimated in this way is just a first approximation.

3. Colour Magnitude Diagrams (CMDs)

The CMDs of the clusters under discussion show a well defined, broad main sequence (MS). The broadness of the MS may be due to various causes, among which are the photometric error, the presence of unresolved binary stars, possible spread in reddening and metallicity. In order to estimate the contamination due to field stars, we have observed the surrounding regions ~ 30′ away from the cluster and removed them statistically using the following procedure. For each star in the V, $(V - I)$ CMD of the field region, the nearest star in the cluster region within $V \pm 0.25$, $(V - I) \pm 0.10$ of the field star, was removed. CMDs for one of the clusters (Be 20) are shown in Fig. 1.

Recently comparison of stellar evolutionary models with observations of old open clusters has yielded interesting results because the CMD of old open clusters is sensitive to the effects of convective core overshoot mixing. Now it is possible to compare models computed without overshoot e.g., those by VandenBerg (1985) with models incorporating overshoot (e.g., Bertelli et al. 1994). We found that for some clusters under discussion, morphological features of the CMDs are better explained in terms of convective core overshooting rather than the classical ones. This discrepancy is shown in Fig. 2.

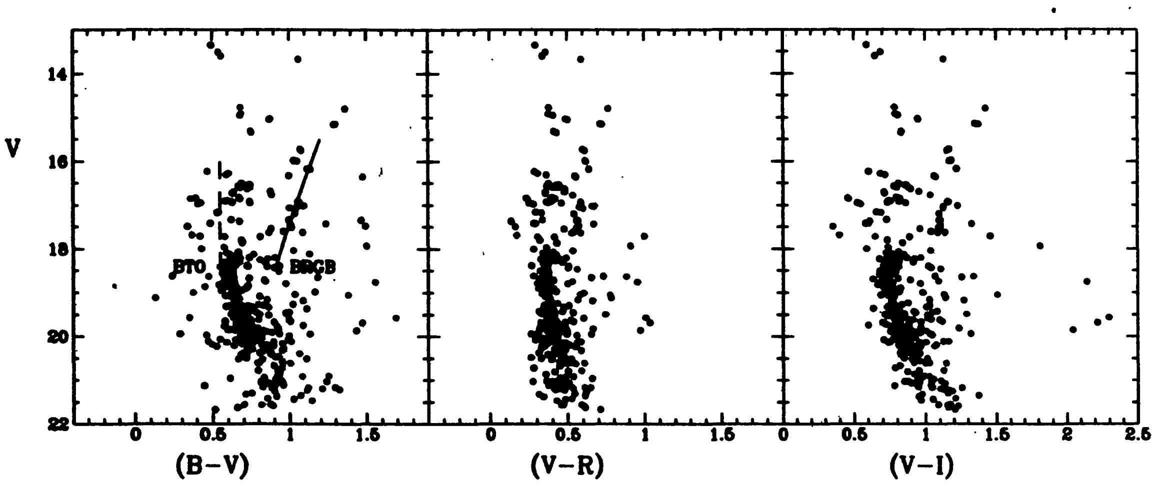

Figure 1. The CMDs for the stellar content of Be 20. The location of BTO (shown by dotted line) and BRGB are also marked in the (B-V) CMD

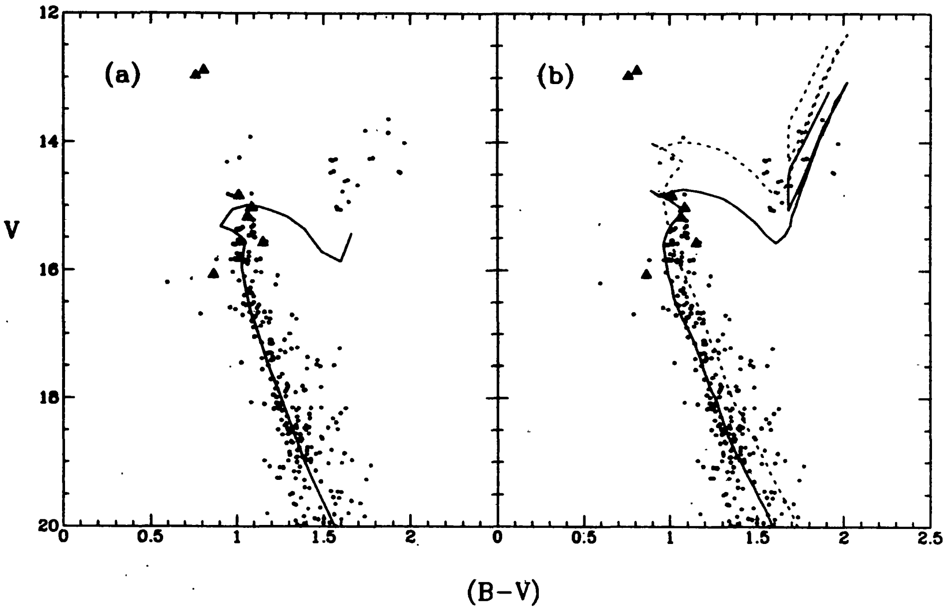

Figure 2. In the CMDs, overplotted are the best fit evolutionary model by VandenBerg (1985) (a) and convective core overshooting model by Bertelli et al., 1994 (b). The dotted curve shows the isochrone brightened by 0.75 mag to take into account the contribution of binaries. Probable variable stars and blue stragglers are shown by filled triangles.

4. Structure, mass function and dynamical state of the clusters

In order to study the stellar distribution we computed the radial density profile by counting all stars lying in concentric rings at increasing distance from the cluster center. The star counts have been normalized to the area of each ring. We tried to fit the empirical model of King (1962) to the projected stellar density distribution of the clusters. It has been found that the radial structure of three clusters namely King 5, King 7 and Be 20 can be well explained by the King's empirical model, whereas other two clusters (Be 64 and Be 69) show an irregular structure. Cluster radius (r_{est}) is estimated from the radial density profile, which is the radius at which the stellar density culminates with the field star density. To compare density profiles of the clusters under discussion, we normalised the densities and radial extent of the clusters. The cluster Be 64 is excluded as it shows an irregular radial density profile. It is found that the evolution of the core of the clusters under discussion is rather same whereas structure of the corona of cluster differs (Fig. 3, left panel). This may be due to various effects e.g., (i) the dynamical relaxation, which causes mass segregation in the clusters, (ii) the external environments as we know that the corona of the clusters are moulded by the galactic tidal fields (Mathieu, 1985). A large sample of clusters is needed to study in detail the evolution of coronae of the clusters (cf. Durgapal & Pandey, 2001).

The distribution of stellar masses in a cluster is termed as the mass function (MF) and can be expressed as a power law, $N(\log m) \propto m^{\Gamma}$. The slope of the mass function is given as ;

$$\Gamma = \frac{d \log N(\log m)}{d \log m} \tag{2}$$

where N(log m) is number of stars per unit logarithmic mass interval. The Salpeter value (1955) for the slope of IMF is $\Gamma = -1.35$. The Luminosity functions were converted to the MFs using the theoretical models of Bertelli et al. (1994). Three clusters namely Be 64, Be 69 and King 5 have MF slope, which are in agreement, within error, with the Salpeter value. The cluster King 7 shows a steeper slope of MF whereas slope for Be 20 comes out to be almost flat.

In the literature there are evidences for spatial variations of MF within a cluster (see e.g, Pandey et al. 1992 and references therein). The data for three clusters (King 5, King 7 and Be 20) were divided into subregions to investigate spatial variation of the MF within the clusters. The data for Be 64 and Be 69 are not sufficient to study the spatial variation of MF in these clusters. The outer region of the cluster King 7 shows a steeper slope ($\Gamma = -2.62 \pm 0.14$) than that obtained for the outer region of King 5 ($\Gamma = -1.7 \pm 0.8$) whereas the MF is rather flat in the outer region of the cluster Be 20. The MF of Be 20, in the inner as well as outer region, shows a truncation at ~ 0.9 $M_{\odot}$. The MF in the inner region of the cluster King 5 also indicate a turnover in the MF at ~ 1.0 $M_{\odot}$. These features seems to be real as we have corrected the data for incompleteness which is not very severe (~ 0.80) (cf. Durgapal & Pandey, 2001).

Dynamical relaxation is one of the possible reasons for spatial variations in the slope of the mass function. At the time of formation, the cluster may have a uniform spatial stellar mass distribution, which may be modified due to dynamical evolution of the clusters. Because of

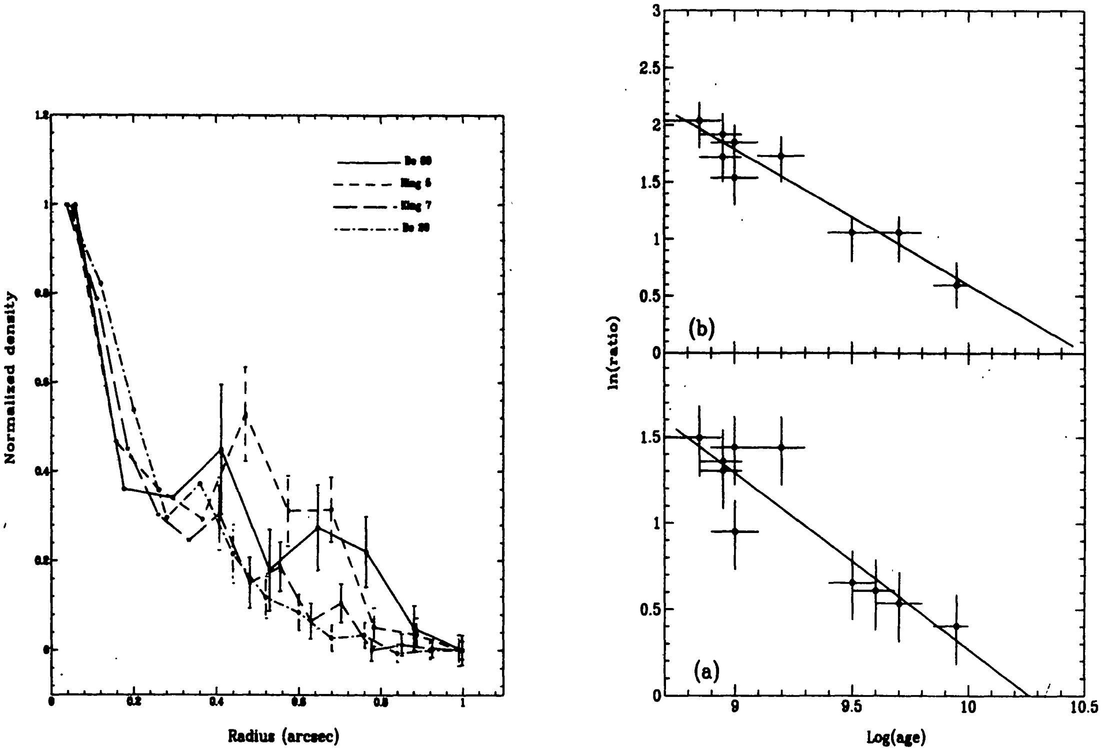

Figure 3. Left panel : Normalized radial density profiles of the clusters Be 69, King 7, King 5 and Be 20. Right panel (a) Variation of ratio (limiting radius/estimated radius) with cluster age. Only observed stellar mass is considered in calculating limiting radius. (b) Same as above but unseen mass is also considered in calculating the limiting radius.

dynamical relaxation, low mass stars in a cluster may possess largest random velocities, consequently these will try to occupy a larger volume than the high mass stars (cf. Mathieu & Latham, 1986; McNamara & Sekiguchi, 1986; Mathieu, 1985). Thus mass segregation developes in the time scale required to exchange energy between stars of different mass by scattering. To study mass segregation in the sample of clusters under discussion, we constructed cumulative radial stellar distribution of main-sequence stars for two or three luminosity ranges depending upon the available data. Mass segregation is observed in three clusters King 5, King 7 and Be 20 (cf. Durgapal and Pandey, 2001).

The limiting radius of a cluster moving in the field of the Galaxy is defined as the distance from the cluster center at which the attraction of a given star to the cluster is balanced by the attraction of external masses (Kholopov, 1969). The limiting radius of a bound cluster can be determined from the relation given by King (1962).

$$r_{lim} = R_p \, (M_{cluster}/3.5 \, M_G)^{1/3} \tag{3}$$

Table 2. Various parameters of the clusters under study.

Cluster	Galactocentric]Distance (kpc)	Z (pc)	E(B-V) (mag)	Age (Gyr) estimated from isochrone fitting	Distance (kpc)
Be 64	11.46 ± 0.40	310 ± 40	1.05 ± 0.05	0.8 - 1.0	3.88 ± 0.48
Be 69	11.35 ± 0.30	–900 ± 10	0.65 ± 0.05	0.8 - 1.0	2.86 ± 0.31
King 7	10.46 ± 0.25	40 ± 8	1.25 ± 0.05	0.6 - 0.8	2.20 ± 0.34
King 5	10.09 ± 0.25	–141 ± 10	0.82 ± 0.05	1.0	1.90 ± 0.10
Be 20	17.11 ± 0.45	–2700 ± 120	0.1 ± 0.05	5	9.03 ± 0.48

where, R_p is the peri-galactic distance of the cluster and M_G is the mass of the Galaxy. We calculated limiting radius for the cluster under discussion as well as for another five clusters namely Tr 5 (Kaluzny, 1998), NGC 6791 (Kaluzny & Udalski, 1992), Be 81, Be 99 and NGC 7044 (Sagar & Griffiths, 1998) for which data are taken from literature. R_p is taken as galactocentric distance of the cluster and the mass of the Galaxy $M_G \sim 2 \times 10^{11}$. The ratio of the limiting radius (r_{lim}) to the estimated radius of the cluster (r_{est}) as a function of age is shown in Fig. 3 (Right panel). The ratio is found to decrease with the age of the clusters and can be represented by a power law as

$$r_{lim}/r_{est} = Ae^{B\ \log\tau} \tag{4}$$

where τ is the age of the cluster. The cluster will become gravitationally unbound when their radius reaches to the limiting radius (i.e., ratio = 1). An extrapolation of the present observational data indicate that these clusters need at least ~ 18 ± 5 Gyr to attain the limiting radius.

5. Conclusions

A detailed study of five intermediate and old age open star clusters has revealed the following: (i) Morphological features of the clusters are better understood in terms of convective core overshooting. (ii) The radial structure of three clusters namely King 5, King 7 and Be 20 can be well explained by the King's empirical model (1962), whereas other two clusters (Be 64 and Be 69) show an irregular structure. (iii) A comparison of radial density profile of these clusters indicate that evolution of the central region of the clusters is same whereas outer region of the clusters are modified by the external forces of the Galaxy as well as dynamical evolutionary processes. (iv) Mass segregation, in the sense that massive stars tend to lie near the cluster center, is observed in the clusters King 5, King 7 and Be 20. (v) The slope of the MF (for the entire cluster region) of three clusters (Be 64, Be 69 and King 5) are in agreement with the Salpeter value. (vi) There are indications for spatial variations of the MF in the two clusters (viz, King 5 and King 7). The cluster Be 20 shows a flat MF akin to MFs of older clusters.

Since all the clusters are dynamically relaxed (cf. Durgapal & Pandey, 2001) therefore the observed mass segregation is most likely due to the dynamical evolution process. It is interesting to note that the ratio of the limiting radius to the present radius of the cluster decreases with the age of the cluster. Various parameters obtained for the clusters under discussion are summarized in Table 2.

Acknowledgements

I am grateful to Dr. A.K. Pandey, my Ph.D. thesis supervisor, for valuable guidance and constant encouragement throughout my thesis work. Thanks are also due to Prof. Ram Sagar and Dr. Vijay Mohan for their keen interest and valuable suggestions to improve the contents of my thesis.

References

Bertelli G., Bressan A., Chiosi C., Fagotto F., Nasi E., 994, A&AS 106, 275
Durgapal A.K., Pandey A.K., Mohan V., 1997, BASI 25, 489
Durgapal A.K., Pandey A.K., Mohan V., 2001, A&AS (in press)
Durgapal A.K., Pandey A.K., 2001, A&A (Submitted)
Janes K.A. Phelps R.L., 1994, AJ 108, 1773
Kaluzny J., 1994 A&AS 108, 151
Kaluzny J., 1998, A&AS 133, 25
Kaluzny J., Udalski A., 1992, Acta astronomica 42, 29
Kholopov P.N., 1969, Soviet Astr 12, 625
King I., 1962, AJ 67, 471
Landolt A.U., 1983, AJ 88, 439
Mathieu R.D., 1985, Dynamics of star clusters 113, 427 J. Goodman and P. Hut (eds).
Mathieu R.D., Latham D.W., 1986, AJ 92, 1364
Mazzei D., Pigatto L., 1988, A&A 193, 148
McNamara B.J.a nd Sekiguchi K., 1986, ApJ 310, 613
Pandey A.K., Mahra H.S., Sagar R., 1992, Bull. Astr. Soc. India 20, 295
Pandey A.K., Durgapal A.K., Bhatt B.C., Mohan V., Mahra H.S., 1997, A&AS 122, 111
Phelps R.L., Janes K.A., Montgomery K.A., 1994, AJ 107, 1079
Sagar R., Griffiths W.K., 1998, MNRAS 299, 1
Salpeter E.E., 1955, ApJ 121, 161
Stetson P.B., 1987, PASP 99, 191
VandenBerg D.A., 1985, ApJs 58, 711