The structure and dynamics of young star clusters: King 16, NGC 1931, NGC 637 and NGC 189

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Homogeneous samples of photometric data, coupled with uniform methods of data analysis are essential to make statistical inferences based on the fundamental parameters of clusters. These studies can contribute to understanding the galactic disk, formation and evolution of clusters, molecular cloud fragmentation, star formation and evolution. In this work, we study a sample of young clusters viz. King 16, NGC 1931, NGC 637 and NGC 189 using photometric data from the Two Micron All Sky Survey (2MASS) (Skrutskie et al. 2006). The 2MASS covers 99.99% of the sky in the near-infrared $J$ ($1.25 \, \mu m$), $H$ ($1.65 \, \mu m$) and $K_s$ ($2.16 \, \mu m$) bands (henceforth $K_s$ shall be refered to as $K$). Hence the 2MASS database has the advantages of being homogeneous, all sky (enabling the study of the outer regions of clusters where the low mass stars dominate) and covering near infrared wavelengths where young clusters can be well observed in their dusty environments.

Dutra and Bica (2001) discovered 42 objects at infra-red wavelengths using the 2MASS survey. Many papers devoted to the study of clusters using the 2MASS have been presented in the past few years (Bica et al. 2003, 2006; Tadross 2007; Kim 2006) showing the potential of this database.

We use the 2MASS database to study the sample of four young clusters, to investigate the structure and dynamical state of these clusters close to their time of formation. The sample is selected on the basis that all the four clusters have an age of $\approx 10$ Myr reported in literature (see Table 1) and have been formed in different environments. We study the structures and dynamical states of our sample of clusters and determine their mass functions (MFs) and degree of mass segregation in various regions of the clusters. To study the sample, we
construct radial density profiles (RDPs), color–magnitude diagrams (CMDs),
color–color diagrams, luminosity functions (LFs) and MFs. Such studies are not
possible using heterogenous datasets where unknown biases may be present.

The initial mass function (IMF) is the distribution of stars of varying masses
from the original parent cloud. The universality of the IMF and the influence of
environment on star formation is still a matter of debate. As these clusters are
very young (age ≤ 10 Myr), their MF may be approximated as the IMF. The
sample of clusters have been made from differing initial conditions and subject
to varied influences of external interactions with the galactic field, thus leading
to observable differences, which we explore. However, from a recent study of
Kroupa (2007), even in the case of very young clusters, there is a change in the
MF due to the dynamics of young clusters which loose a significant fraction of
their stars at an early age.

Mass segregation is the redistribution of stars according to their masses,
thus leading to the concentration of high mass stars near the centre and the low
mass ones away from the centre. This has been observed in a variety of clusters,
both young and old. The variation of the MF of these clusters is determined
in different regions of the clusters and their values are compared. Further, we
estimate from the value of $\tau = t_{\text{age}}/t_{\text{relax}}$, the degree of mass segregation expected
due to dynamical effects and compare it with our observations. The relaxation
time $t_{\text{relax}}$ is a characteristic time in which there is an equipartition of energy
and the high mass stars with lesser kinetic energy sink to the core and the
low mass stars move to the outer regions of the cluster (Binney and Tremaine
2008). The value of $\tau$ indicates whether an excess of high mass stars in the
cores of clusters is a result of dynamical evolution or the imprint of the star
formation process itself. The parameter $\tau$ has been described as an evolutionary parameter (Bonatto and Bica 2005) which indicates the extent to which the cluster has relaxed. It relates to the core and overall MF flattening. For large values of $\tau$, the high mass stars sink to the centre and the low mass stars with high velocities move towards the outskirts and hence the MFs of clusters show large-scale mass segregation and low-mass stars evaporation. We report the presence of gaps in the main sequence associated to physical processes in stars (Kjeldsen and Frandsen 1991).

The plan of the paper is as follows: Section 2 describes the clusters in our sample and shows the corresponding RDPs and the values obtained for the limiting radii for these clusters. Section 3 describes the method of selecting cluster members and the corresponding values of fundamental parameters obtained. LFs and MFs are described in Section 4 and a comparative study of these clusters is in the concluding Section 5.

2. Basic Data and Earlier Observations

The RGB images of the target clusters using the DPOSS images are shown in Figure I and their parameters are given in Table I (Dias et al. 2007).

Fig. 1.— Cluster areas (a) King 16 ($JOE$ bands) $(13.37' \times 13.35')$ (b)NGC 1931 ($JKN$ bands)$(13.37' \times 13.35')$ (c)NGC 637($JKN$ bands) $(13.37' \times 13.35')$ (d)NGC 189 ($JKN$ bands)$(11.87' \times 11.87')$

King 16 has been studied by Maciejewski and Niedzielski (2007) using $BV$ photometry and they obtained a reddening value $E(B - V) = 0.89$, age 10 Myr and distance 1920 pc. It lies close to the clusters Dias 1 and Berkeley 4.
The young cluster NGC 1931 is situated in the extension of the Perseus arm (Pandey and Mahra 1986). The cluster shows variable reddening with $\Delta E(B-V) = 0.45$ and is at a distance of 2170 pc and an age 10 Myr (Bhatt et al. 1994). The nebulous cloud in the central region is in the background as inferred by Pandey and Mahra (1986) based on the reddening determinations in different regions of the cluster.

NGC 637 has been studied by Grubissich (1975) in the RGU photographic system. Photoelectric observations in the $UBV$ system were made by Huestamendia et al. (1991) to obtain a distance of 2500 pc, reddening 0.66 and age 15 Myr. Phelps and Janes (1994) also observed this cluster and obtained a younger age of 0–4 Myr. A conspicuous gap was found in its color–magnitude diagram, which is not a result of incompleteness of data. Pietrukowicz et al. (2006) presented $VI$ photometry of this cluster and monitored the cluster for variables.

NGC 189 is a young compact cluster in the vicinity of Stock 24 and Do 12. It has been studied by Balazs (1961) and the distance to this cluster was found to be 790 pc.

In this paper, we have used the 2MASS database. The point-source $S/N = 10$ limit is achieved at or fainter than $J = 15.8^m$, $H = 15.1^m$ and $K = 14.3^m$ for virtually the entire sky and hence we have used the above criteria to extract the 2MASS data using Vizier.\footnote{http://vizier.u-strasbg.fr/cgi-bin/VizieR?-source=II/246} Further, we have also added the constraint that photometric errors in each band are $\leq 0.2^m$.
2.1. Determination of Radial Density Profiles

For accurate determination of the cluster parameters, it is essential to have the knowledge of the radial extent of the clusters. Mass segregation might lead to a larger ‘true’ cluster size than stated in the Dias et al. (2007) catalogue. As the 2MASS data offers all sky coverage we have the opportunity to study farther reaches of the clusters.

The centers of the clusters are determined using a program which, given an eye estimated center and radius, counts the number of stars and calculates the average $\bar{X}$ and $\bar{Y}$ of the stars within the radius. If the difference in the position $(\bar{X}, \bar{Y})$ from the eye estimated center is smaller than a given tolerance value (a pixel), then the eye estimated center is taken as the center. If larger, then $(\bar{X}, \bar{Y})$ is taken as the new approximate center. The same procedure is repeated iteratively until the difference in the position $(\bar{X}, \bar{Y})$ and the center lies within the tolerance value (Sagar and Griffiths 1998). An error of a few arc seconds is expected in locating the center.

For the determination of the radial surface density of stars $\rho(r)$ in a cluster, a number of concentric circles with respect to the estimated center are made in such a way that each annular region contains statistically significant number of stars. The number density of stars, $\rho_i$ in the $i^{th}$ region is calculated as $\rho_i = N_i / A_i$, where $N_i$ is the number of stars in the $i^{th}$ region of area $A_i$. The RDPs for the clusters are shown in the Fig. 2. The $\chi^2$ minimization technique was used to fit the RDPs to the function

$$\rho(r) = \frac{\rho_0}{1 + (r/r_c)^2}$$

Fig. 2.— Radial density profiles (a) King 16 (b) NGC 1931 (c) NGC 637 (d) NGC 189
(King 1962) to determine $r_c$ and other constants. The cluster’s core radius $r_c$ is the radial distance at which the value of $\rho(r)$ becomes half of the central density, $\rho_0$. Probable members are selected from all the stars in the cluster area which satisfy the photometric criterion [Walker (1965)] described in the next section. The best fits are shown in the figures with dotted lines for all the stars in the cluster field and solid lines for probable members. The reduced $\chi^2$ (variance of residuals) for the fits to the clusters King 16, NGC 1931, NGC 637 and NGC 189 were 0.95, 1.14, 0.98 and 0.89 respectively. The limiting radius of the cluster is the distance from the centre at which the star density becomes approximately equal to the field star density. As is evident from the Fig. 2, we obtained a radius of 7′ and 6′ in the case of King 16 and NGC 637. In the case of NGC 1931, due to the presence of the obscuring nebula, a large number of cluster stars are hidden and hence the RDP was plotted using field stars and we obtained a size of 12′. In the case of NGC 189, we obtained a size of 5′.

The new sky coordinates of the cluster centers for epoch 2000, core and limiting radii and background densities obtained by fitting to King’s profile are given in Table 2.

3. Membership, Color–Magnitude and Color–Color Diagrams

VizieR was used to extract $J$, $H$ and $K$ 2MASS photometry of the stars in a circular area of radius 30′ from the approximate center obtained in the earlier section. The apparent CMDs for the clusters obtained by extracting stars from the areas equal to the sizes obtained from the RDPs and an offset field of the same area are shown in the Fig. 3. In the case of King 16, we extracted data for the cluster within a radius of 7′ and an the offset area made up of a concentric
Table 1: Basic cluster parameters [Dias et al. (2007)]

| Parameter                     | King 16     | NGC 1931    | NGC 637     | NGC 189     |
|-------------------------------|-------------|-------------|-------------|-------------|
| RA (2000) (h:m:s)             | 00 43 45    | 05 31 25    | 01 43 04    | 00 39 35    |
| Decl. (2000) (d:m)            | +64 11 08   | +34 14 42   | +64 02 24   | +61 05 42   |
| Galactic longitude            | 122.09°     | 173.89°     | 128.54°     | 121.49°     |
| Galactic latitude             | +01.32°     | +00.28°     | +01.73°     | –01.74°     |
| Ang. diameter                 | 17.6′       | 5′          | 3′          | 5′          |
| Distance (pc)                 | 1920        | 3086        | 2160        | 752         |
| $E(B-V)$ (mag)                | 0.89        | 0.738       | 0.634       | 0.42        |
| log(age)                      | 7.00        | 7.002       | 6.980       | 7.00        |

Table 2: Structural parameters from RDPs

| Parameter                  | King 16 | NGC 1931 | NGC 637 | NGC 189 |
|----------------------------|---------|----------|---------|---------|
| RA (h:m:s)                 | 00 43 24| 05 30 4.8| 01 43 12| 00 40 05|
| Decl (d:m:s)               | +64 11 00| +34 13 22| +64 02 19.8| +61 05 00|
| Field density              | 0.97 ± 0.27| 1.26 ± 0.03| 0.08 ± 0.04| 0.42 ± 0.36|
| Core radius                | 0.89 ± 0.37| 0.63 ± 0.16| 0.36 ± 0.13| 1.38 ± 0.85|
| Limiting radius            | 7 ± 1.2 | 12 ± 0.5 | 6 ± 0.2 | 5 ± 0.6 |
ring of radius $29.17'$ to $30'$. For NGC 1931, the cluster size determined from the RDP was $12'$ and the extracted offset area was made up of a concentric ring of radius $27.49'$ to $30'$. In the case of NGC 637, the cluster area was within a radius of $6'$ and the offset area of $29.4'$ to $30'$. In the case of NGC 189, as Stock 24 and Do 12 are very close to the cluster, we marked out a field area at a distance of $7'$ to the south-west of the cluster.

To study the intrinsic cluster CMDs, we use the field star decontamination procedure similar to the one applied by Bonatto et al. (2006); Bica et al. (2006). In this method, we divide the CMD into cells and count the number of stars in the field and in the cluster area. Assuming that the number of field stars is constant, we randomly remove in each cell, candidate field stars equal to the number expected in the field to obtain a ‘clean’ cluster CMD. Considering that the solid area in the offset area is different from that in the cluster area, we multiply the number of stars of the offset field by a constant. Figure 3 shows the field star decontaminated or ‘clean’ cluster CMDs. In crowded field regions, the field star density at fainter magnitudes may be larger than that of the cluster area, thus artificially truncating the main sequence. As this method artificially removes stars and distorts the RDPs, we used this method only to uncover the cluster CMDs and color–color diagrams. To study the cluster structure, LF and MF we use the probable members obtained by the photometric criterion.

Fig. 3.— Apparent color–magnitude diagrams for the clusters and an offset field 1(a) King 16; 1(b) Offset Field for King 16 1(c) ‘Clean’ CMD of King 16; 2(a) NGC 1931; 2(b) Offset Field for NGC 1931 (c) ‘Clean’ CMD of NGC 1931; 3(a) NGC 637; 3(b) Offset Field for NGC 637(c) ‘Clean’ CMD of NGC 637; 4(a) NGC 189; 4(b) Offset Field for NGC 189(c) ‘Clean’ CMD of NGC 637
The observed data has been corrected for interstellar reddening using the coefficients given by Dutra et al. (2002) where
\[ A_J = 0.856 \times E(B-V), \]
\[ A_H = 0.546 \times E(B-V), \]
\[ A_K = 0.366 \times E(B-V), \]
\[ E(J-H) = 0.31 \times E(B-V), \]
\[ E(H-K) = 0.18 \times E(B-V) \]
where \( E(B-V) \) denotes the color excess for the cluster. The clusters King 16, NGC 189 and NGC 637 show uniform reddening and hence reddening values have been obtained by isochrones fits.

In the case of King 16, the only spectroscopic data we have is that of BD 6384 which has a reddening value of 0.91 and distance modulus (DM) 11.26. Using isochrone fits to the CMD, we get a reddening of 0.85 and a DM of 11.3, which also agrees with the values obtained by Maciejewski and Niedzielski (2007).

In the case of NGC 1931, which shows differential reddening (Pandey and Mahra 1986; Bhatt et al. 1994), the entire cluster region was divided into 9 regions for which the reddening values were determined individually by isochrone fits. Stars were then corrected for their reddening values depending on their spatial location. We obtained reddening values \( E(B-V) \) ranging from 0.65–0.85 and a distance of 3062 pc to the cluster.

For NGC 637 and NGC 189 isochrone fits to the CMDs gave reddening values of 0.6 and 0.53 and distances of 2270 pc and 912 pc respectively.

To determine the membership we use two criteria: the radial extent and the photometric criterion described by Walker (1965). The photometric criterion is made by plotting a color–magnitude filter along the isochrone with a width of

Fig. 4.— NGC 1931: Differential reddening
≈ 0.1 in the \((J - H)\) direction and ≈ 1.0 in the \(J\) direction. Thus we identify main sequence members which may have have been displaced from the main sequence track either due to photometric errors, effects of binarity, etc. Similar filters have also been made in the \(H\) vs \((J - H)\) and \(K\) vs \((J - K)\) planes. The Walker method is valid only for main sequence stars while other luminosity classes and groups require different methods for member identification.

The absolute CMDs with the isochrones used to determine their ages are shown in the Fig. 5. The clusters show a well-defined main sequence, with even the most massive stars still on the main sequence.

It is interesting to note that three of the cluster CMDs show a gap for early type stars. A gap in the main sequence is loosely defined as a band, not necessarily perpendicular to the main sequence, with no or very few stars. Mermilliod (1976) pointed out a gap at \((B - V)_0 = -0.1\), \((J - H)_0 = -0.05\) possibly related to the way in which the Balmer jump and the Balmer lines behave in late \(B\) or early \(A\) stars. In the CMDs of King 16 a gap is noticeable at \(M_J = -3\), \((J - H)_0 = -0.1\). NGC 1931 has a gap at \(M_J = -2.5\), \((J - H)_0 = -0.1\) and NGC 637 has a gap at \(M_J = -1.5\), \((J - H)_0 = -0.1\). All these are associated to \(OB\) type stars.

The unreddened color–color diagrams \((J - H)_0\) versus \((H - K)_0\) for the field star decontaminated clusters are shown in the Fig. 6, indicating the appropriate reddening correction. In the case of NGC 1931, the plot clearly shows the differential reddening and the possible classical T Tauri stars in the cluster (Lada and Adams 1992).

Fig. 5.— Absolute CMDs (a) King 16 (b) NGC 1931 (c) NGC 637 (d) NGC 189
Table 3 shows the values of the fundamental parameters of reddening, distance and age obtained for the clusters using the isochrones (Girardi et al. 2002) and compares it to that obtained by earlier authors.

4. Luminosity and mass functions

The LF obtained for clusters using observations has to be corrected for the following three factors: (i) fraction of cluster area studied (ii) completeness of data (iii) field star contamination. As the 2MASS data has 99.99% completeness for the magnitude range considered and we have extracted the complete cluster area, we only had to correct the LF for field star contamination. The LF was found for members based on the photometric criterion (Walker 1965) in the $J$ vs $(J - H)$ plane using color–magnitude filters. These filters are lines parallel to the isochrone track with a width of $\approx 0.1$ in the $(J - H)$ direction and $\approx 1.0$ in the $J$ direction. A similar color–magnitude filter was applied for the apparent CMDs of the field area shown in Fig 3. Thus, we obtain the approximate number of stars which are probable non-members, but still lie within our color–magnitude filter. The number of field stars in each magnitude bin was then subtracted from the number of stars in the cluster area. The LFs in other bands were found by using color–magnitude filters in the $H$ vs $(J - H)$ and the $K$ vs $(J - K)$ plots to identify probable members. Similar filters were also made for the offset field to correct for field star contamination. Figure 7 shows the uncorrected (dotted line) and corrected (solid line) LFs for the four clusters in the $J$, $H$ and $K$ bands.

Fig. 6.— Two–color diagrams (a) King 16 (b) NGC 1931 (c) NGC 637 (d) NGC 189
Table 3: Parameters estimated for King 16, NGC 1931, NGC 637 and NGC 189

| Cluster      | Reddening | Distance(pc) | Age(Myr) | Reference               |
|--------------|-----------|--------------|----------|-------------------------|
| King 16      | 0.89      | 1920         | 10       | Maciejewski and Niedzielski (2007) |
|              | 0.85      | 1786         | 6        | This work               |
| NGC 1931     | 0.33-1.2  | 2160         |          | Pandey and Mahra (1986)  |
|              | 0.55-1.0  | 2170         | 10       | Bhatt et al. (1994)      |
|              | 0.738     | 3086         | 10       | Loktin et al. (2001)     |
|              | 0.65-0.85 | 3062         | 4        | This work               |
| NGC 637      | 0.63      | 2160         | 9.5      | Grubissich (1975)        |
|              | 0.66      | 2500         | 15       | Huestamendia et al. (1991) |
|              | 0.65      | 2884         | 4        | Phelps and Janes (1994)  |
|              | 0.55      | 2679-3221    | 4        | Pietrukowicz et al. (2006) |
|              | 0.6       | 2270         | 4        | This work               |
| NGC 189      | 790       |              |          | Balazs (1961)            |
|              | 0.53      | 912          | 10       | This work               |

Fig. 7.— Luminosity functions (a) King 16 (b) NGC 1931 (c) NGC 637 (d) NGC 189 ($J$ in blue, $H$ in green and $K$ in red)
The MFs were constructed from the LFs using the isochrones of Girardi et al. (2002) with the appropriate ages and distances and fitting them to a fourth order polynomial to find the mass–luminosity relation. The mass function, \( \phi(M) = dN/dM \propto M^{-(1+\chi)} \), is an indicator of the star formation process. The relaxation times for the core and overall clusters have been calculated using the formula \( t_{relax} = \frac{N}{8nN} \times t_{cross} \) where \( t_{cross} = R/\sigma_v \), \( N \) is the number of stars, \( R \) is the radius and \( \sigma_v \) is the velocity dispersion. We have used the value \( \sigma_v = 3 \) km s\(^{-1} \) (Binney and Merrifield 1998).

The clusters were divided into regions so as to obtain a significant number of stars in each region. For King 16, we obtained a core radius 0.89 ± 0.24. We divided the cluster into three regions: core (0′ - 0.89′), halo1 (0.89′ - 3′) and halo2 (3′ - 7′). In the case of NGC 1931, we divided the cluster into three regions: halo1 (0′ - 4′), halo2 (4′ - 8′) and halo3 (8′ - 12′). Due to the central obscuring nebula, we have no stars in the core region, and hence we excluded the same. In the case of NGC 637, we divided the cluster into three regions: core (0′ - 0.4′), halo1 (0.4 - 3) and halo2 (3′ - 6′). As there were no stars in the core of NGC 189 and the cluster is very small, we divided the cluster into only two regions: halo1 (0 - 2.5′) and halo2 (2.5′ - 5′).

The values of \( \chi \) for different regions of the clusters are also indicative of mass segregation and are shown in Table 4 with the mass estimates for each region. The mass estimates for the clusters King 16, NGC 1931, NGC 637 and
Fig. 11.— NGC 189: Mass function

NGC 189 are $1382 \pm 44 M_\odot$, $848 \pm 14 M_\odot$, $583 \pm 6 M_\odot$ and $94 \pm 3 M_\odot$ respectively using the observed mass ranges. These are the lower limits of the masses for these clusters.

As observed in the Fig 8, for the cluster King 16, the $\chi$ value was found to be $0.96 \pm 0.11$ for the overall cluster, $-0.44 \pm 0.10$ in the core region, $0.95 \pm 0.14$ in halo1 and $0.89 \pm 0.18$ in halo2. (Errors in $\chi$ values in this section are asymptotic standard errors.) The relaxation time is 2 Myr for the core and 10.5 Myr for the overall cluster. The age of the cluster based on the isochrone fit is 6 Myr. The mass of the most massive star is $17 \pm 1 M_\odot$, which has a nuclear age, $t_{nuc} = 10^{10} \times \left( \frac{1}{M/M_\odot} \right)^{2.5} = 7.9$ Myr, which is the upper limit to the age. Since the age of the cluster is much larger than the relaxation time of the core, the core has dynamically relaxed. However, the halo of the cluster has not yet relaxed, hence we see no change in the $\chi$ values of the inner and outer halos.

In the case of NGC 1931, as seen in Fig 9, the MF has been found in three concentric rings each at a radius increasing by $4'$. The regions have the mass functions $0.02 \pm 0.13$, $1.22 \pm 0.18$ and $1.32 \pm 0.19$ respectively. This indicates a rearrangement of stars as a function of distance and a certain degree of mass segregation. The relaxation time for NGC 1931 is 20 Myr and the upper limit of its age based on the most massive star on the main sequence is 3.5 Myr and its age based on isochrone fits is 4 Myr. The overall cluster has a mass function of $\chi = 1.1 \pm 0.18$. We conclude that the innermost halo1 ($0-4'$) has relaxed, while the rest of the cluster is in the process of relaxation.

In NGC 637, as in Fig 10, the $\chi$ values were $0.66 \pm 0.14$, -1.0, $0.39 \pm 0.13$
Table 4: Dynamical Parameters estimated for King 16, NGC 1931, NGC 637 and NGC 189

| Cluster      | R (arc min) | χ          | N   | mass($M_\odot$) |
|--------------|-------------|------------|-----|-----------------|
| King 16      |             | 1.4–17.44 $M_\odot$ |     |                 |
| core         | 0–0.89      | -0.44 ±0.10 | 10  | 16 ± 1          |
| halo1        | 0.89–3      | 0.95 ± 0.14 | 129 | 811 ± 26        |
| halo2        | 3–7         | 0.89 ± 0.18 | 193 | 811 ± 26        |
| overall      |             | 0.96 ± 0.11 | 1382| 129 ± 44        |
| NGC 1931     |             | 2.39–14.44 $M_\odot$ |     |                 |
| halo1        | 0–4         | 0.029 ±0.13 | 39  | 105 ± 4         |
| halo2        | 4–8         | 1.22 ± 0.18 | 100 | 265 ± 12        |
| halo3        | 8–12        | 1.32 ±0.19  | 184 | 516 ± 24        |
| overall      |             | 1.159 ±0.18 | 848 | 848 ± 14        |
| NGC 637      |             | 1.6–17.14 $M_\odot$ |     |                 |
| core         | 0–0.4       | -1.00       | 7   | 35 ± 1          |
| halo1        | 0.4–3       | 0.39 ±0.13  | 101 | 328 ± 24        |
| halo2        | 3–6         | 1.18 ± 0.13 | 123 | 217 ± 44        |
| overall      |             | 0.55 ±0.14  | 583 | 583 ± 6         |
| NGC 189      |             | 0.86–4.75 $M_\odot$ |     |                 |
| halo1        | 0–2.5       | 0.68 ±0.22  | 33  | 61 ± 3          |
| halo2        | 2.5–5       | 0.087 ±0.02 | 14  | 36 ± 1          |
| overall      |             | 0.66 ±0.31  | 94  | 94 ± 3          |
and $1.18 \pm 0.13$ for the overall, core, halo1 and halo2 of the cluster respectively. The cluster age by isochrone fits has been found to be 4 Myr and based on the most massive star ($15 \pm 1 \text{ M}_\odot$) of the cluster is 11.5 Myr. The relaxation times for the core and the overall cluster are 0.039 Myr and 7.6 Myr respectively. Hence the core has relaxed and the overall cluster has also partially relaxed as is indicative by the value of $\tau$.

For the cluster NGC 189, as seen in Fig. 11, the age of the cluster is around 10 Myr, which is larger than the $t_{\text{relax}}$ of 3.59 years. Hence, we see the overall cluster MF is flatter $\chi = 0.66 \pm 0.31$, while the halo1 and halo2 have $\chi$ values $0.68 \pm 0.22$ and $0.09 \pm 0.02$ respectively. Halo2 appears flatter since probably it has already started losing low mass stars to its outer environment.

5. Conclusions

In this paper we have studied four young clusters of comparable ages to understand their structure and dynamics. The RDPs of the clusters have been plotted and the parameters for the clusters such as reddening, distance and age have been determined using isochrone fits.

We have also plotted the LFs in the $J$, $H$ and $K$ bands and used the derived mass–luminosity relation to find the MFs using all three bands independently. The $\chi$ values have been determined for different regions and the overall clusters as a function of the parameter $\tau$. We use the difference in $\chi$ values to estimate the level of mass segregation of the clusters and their cores.

In the case of King 16, where $\tau = 3$ for the core, the core is clearly relaxed as in indicated by its flat $\chi = -0.44$, while for the outer regions where $\tau = 0.57$,
the cluster has begun to relax. In the case of NGC 1931, the core is relaxed and the outer region seems to have begun relaxation. In the case of NGC 637, the core is relaxed \((\tau = 4/0.039)\), and there appears to be a redistribution of stars in the cluster, indicated by a progressive increase in \(\chi\) from 0.39 to 1.15. The outer halo has a larger value of \(\chi\) compared to the overall cluster (0.55) as, it appears that the inner halo has thrown away a large number of low mass stars to the outer halo, thus causing an excess in low mass stars and a steeper \(\chi\). In the case of NGC 189, where \(\tau = 2.79\), the cluster has already relaxed, as is indicative of the flat \(\chi\) of the core. The outer core has a flatter \(\chi\), probably because low mass stars which were thrown out of the inner halo during relaxation, have been lost and hence the outer halo has a deficit of low mass stars.

As, seen from our analysis, mass segregation is observable in the cores of the clusters King 16, NGC 1931 and NGC 637 where the cluster ages are comparable to the relaxation times. In the case of NGC 189, where the relaxation time is lesser than the age of the cluster, we notice a flatter mass function. This implies that the observed mass segmentation in these clusters is a dynamical effect. However, larger samples will improve the statistics and give us a better insight in the physical processes leading to the structure and dynamical evolution of clusters.

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