Mass segregation in diverse environments

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ABSTRACT

In this paper, using the Two Micron All Sky Survey (2MASS) photometry, we study the mass functions \( \phi(M) = dN/dM \propto M^{-\alpha} \) of a sample of nine clusters of ages varying from 4 Myr to 1.2 Gyr and Galactocentric distances from 6 to 12 kpc. We look for evidence of mass segregation in these clusters by tracing the variation in the value of \( \alpha \) in different regions of the cluster as a function of the parameter \( \tau = t_{\text{age}} / t_{\text{relax}} \) (where \( t_{\text{age}} \) is the age of the cluster and \( t_{\text{relax}} \) is the relaxation time of the cluster), Galactocentric distance, age and size of the cluster. The value of \( \alpha \) value increases with age and \( \tau \) and fits straight lines with slopes \( m \) and \( y \)-intercepts \( c \) given by \( m = 0.40 \pm 0.03, c = -1.86 \pm 0.27 \) and \( m = 0.01 \pm 0.001, c = -0.85 \pm 0.02 \), respectively, and is a clear indicator of the dynamical processes involved. The confidence level of the Pearson’s product–moment correlation of \( \alpha \) with age is 0.76 with \( p = 0.002 \) and with \( \tau \) is 0.71 with \( p = 0.007 \). The value of \( \alpha \) also increases with Galactocentric distance, indicating the presence of a larger relative number of low-mass stars in clusters at larger Galactocentric distances. We find two clusters, namely IC 1805 and NGC 1893, with evidence of primordial or early dynamical mass segregation. Implications of primordial mass segregation on the formation of massive stars and recent results supporting early dynamical mass segregation are discussed.

Key words: Hertzsprung–Russell and colour–magnitude diagrams – stars: pre-main-sequence – galaxies: star clusters: individual: NGC 6704 – galaxies: star clusters: individual: IC 1805 – galaxies: star clusters: individual: NGC 1893 – galaxies: star clusters: individual: NGC 2286.

1 INTRODUCTION

The distribution of mass amongst the stars born from a parent cloud is described by the initial mass function (IMF). It is a fundamental parameter not only in understanding the basic star formation process, but also in determining the properties and evolution of stellar systems, which are the basic building blocks of galaxies. The IMF estimated for different populations in which the stars can be observed individually show an extraordinary uniformity (Bastian, Covey & Meyer 2010). This uniformity appears to be present for stellar populations including present-day star formation in small molecular clouds, rich and dense massive star clusters forming in giant clouds and also with old and metal-poor stellar populations that may be dominated by dark matter. The universality, origin and dependence on physical conditions of the IMF is a very active research area and is very crucial to understanding the basic physics of star formation (Kroupa 2002; Bonnell, Larson & Zinnecker 2007).

The evolution of the IMF is influenced by the evolution of individual stars, the redistribution of stars of different masses and the loss of low-mass stars by evaporation. Recent studies by Goodwin & Kouwenhoven (2009) suggest that the same IMF can be derived from different modes of star formation and thus questioned if the IMF is a direct imprint of the star formation process.

Star clusters are an ideal test bed for studies of the IMF as they are a collection of coeval stars formed from the same parent cloud. Hence many uncertainties like reddening, distance, metallicity, etc., in determination of stellar masses are minimized. They are suitable for studies on star formation and the dynamics of stellar systems (Lyngå 1982; Janes & Phelps 1994; Friel 1995; Bonatto & Bica 2005a; Kharchenko et al. 2005). The term ‘ecology of star clusters’, as coined by Heggie (1992), shows the close interplay between stellar dynamics, stellar evolution, the cluster stellar content and the dynamics and properties of the host galaxy, all of which contribute to their structure and evolution.

Mass segregation is the distribution of stars according to their masses, leading to the concentration of high-mass stars near the centre and the low-mass ones away from the centre. This can take place as a result of dynamical interactions between stars in young clusters or could be primordial in nature (Bonnell & Davies 1999; Gouliermis et al. 2004; de Marchi et al. 2006; Vesperini

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2 CLUSTER SAMPLE

The images of the target clusters using the 2MASS are shown in Fig. 1. The JHK bands have been used to construct mosaics. The cluster parameters from Dias et al. (2007) are given in Table 1. In the table, RA (2000) and Dec. (2000) are the right ascension and declination for the epoch 2000, l and b are the Galactic longitude and latitude, Ang.Dia is the angular diameter, Distance is the distance from the Sun, E(B − V) is the reddening, log tage is the logarithm of the age of the cluster and RGC is the Galactocentric distance. A random sample of clusters in diverse environments was selected such that it covered a range of clusters of varying age, Galactocentric distance and size.

NGC 6704 has been studied by Delgado, Alfaro & Cabrera-Canó (1997) who found the reddening to be 0.69, with no signs of differential reddening. BVI CCD photometry of NGC 6005 was presented by Piatti et al. (1998), and the reddening was found to be 0.45 ± 0.05. NGC 6200 is a loose young open cluster in the Sagittarius Arm extension and has been studied using UBV photometry by Fitzgerald, Jackson & Moffat (1977) to find no obvious differential reddening. NGC 6604 has been studied by Forbes & DuPuy (1978), Barbon et al. (2000) and De Becker et al. (2005). Using three independent techniques, Barbon et al. (2000) found the mean reddening to the cluster to be 1.02 ± 0.01 mag with no evidence for a marked differential reddening. IC 1805 has been studied by Forato & Yu (1990), Massey, Johnson & Dugioia-Eastwood (1995)
and Sung & Lee (1995). Sagar & Yu (1990) found that there is a normal extinction law in the direction of the cluster. Proper motion studies of NGC 2286 were made by Zhao, He & Tian (1990) and Tian, Zhao & van Leeuwen (1994). The mean colour excess $E(B - V)$ was found by Pan et al. (1992) to be 0.40 ± 0.1 mag. NGC 2489, a rich open cluster in Puppis, was studied using photographic plates by Lindoff & Johansson (1968), and $UBV$ measurements were made by Ramsay & Pollaco (1992). Piatti et al. (2007) found a distance of 1800 pc to this cluster with a reddening of $E(B - V ) = 0.30 ± 0.05$ mag and an age of 500 Myr. $UBV$ photometry of NGC 1893 has been presented by Moffat & Vogt (1974) and Massey et al. (1995). Vallenari et al. (1999) did near-infrared photometry of the cluster to find an age between 4 and 6 Myr and identified candidate pre-main-sequence (MS) stars showing an inward excess. Tapia et al. (1991) estimated the age of the cluster to be 4 Myr and derived the distance modulus 13.18 ± 0.11 mag and the reddening in visual magnitudes $A_V = 1.68$ mag. Marco, Bernabeu & Negueruela (2001) did $UBVHβ$ CCD photometry of 40 very likely MS members to derive reddening $E(b-y)$ as 0.33 ± 0.03 mag and distance modulus $V_0 - M_V = 13.9 ± 0.2$ mag for NGC 1893. Lying in the Aur OB2 association towards the Galactic antecentre, NGC 1893 is associated with the H ii region IC 410 and is at a distance ≥11 kpc from the Galactic Centre. A comprehensive multiwavelength study of the star-forming region, NGC 1893, to explore the effects of massive stars on low-mass star formation has been made by Sharma et al. (2007).

### 3 MEMBERSHIP, COLOUR–MAGNITUDE AND COLOUR–COLOUR DIAGRAMS

VizieR was used to extract $JHK$ 2MASS photometry of the stars in a circular area of radius 30 arcmin from the approximate centre listed in Table 1. We plotted the apparent CMDs for a small central area of 3–5 arcmin of the cluster (with minimum field star contamination) and used a field region of the same area to decontaminate the CMD. The point-source signal-to-noise ratio ($S/N$) limit is 10 for the 2MASS data base is achieved at fainter than $J = 15.8$ mag, $H = 15.1$ mag and $K = 14.3$ mag for virtually the entire sky, and hence we have used the above magnitude limits to extract the 2MASS data from Vizier. Further, we have also added the constraint that photometric errors in each band are ≤0.2 mag. Completeness is also affected by source confusion or regions of high source density. The primary areas of confusion are (1) longitudes ±75° from the Galactic Centre and latitudes ±1° from the Galactic plane and (2) within an approximately 5° radius of the Galactic Centre. For clusters of our sample lying in these regions, the 99.9 per cent completeness limits varying with Galactic coordinates are shown in Table 2. For all these clusters, the field star contamination is also very high, and hence we do not use fainter magnitudes in our analysis.

Clusters located towards the Galactic Centre are also difficult to observe since they suffer from high interstellar absorption and/or high field star contamination, and hence such clusters are a minority in catalogues. The first four clusters in our sample, i.e. NGC 6704, 6005, 6200 and 6604, present the above difficulties and hence are of particular interest. The field star decontamination procedure similar to the one applied by Bonatto, Santos & Bica (2006), Bica et al. (2006) and Bonatto & Bica (2007) is used to study the intrinsic cluster CMDs. 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, stars equal to the number expected in the field to obtain a ‘clean’ cluster CMD. In crowded field regions, the field star density at fainter magnitudes may be larger than that of the cluster area, thus artificially truncating the MS. As this method artificially removes stars and distorts the RDPs, we used this method only to uncover the cluster CMDs and CCs. It is used to fit the isochrones to derive the reddening and distance of the cluster. To study the cluster structure, LF and MF, we use the probable members obtained by the photometric criterion (Walker 1965) lying within the area of the cluster derived from the RDPs.

The photometric method described by Walker (1965) involves plotting all the stars within the radius obtained using RDPs in the $m_{J0}V_{M_j}$ plane, where $m_{J0}$ is the apparent unreddened magnitude and $M_j$ is the absolute magnitude. A straight line representing the adopted distance modulus is drawn with boundaries of 0.75 mag which is the maximum deviation caused by an unresolved binary with equal components. Observational scatter can cause a vertical

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**Table 1. Basic cluster parameters (Dias et al. 2007).**

| Cluster   | RA (2000) (hms) | Dec. (2000) (°) | $l$ (°) | $b$ (°) | Ang. Dia (arcmin) | Distance (pc) | $E(B - V)$ (mag) | log $t_{age}$ (log yr) | $R_{GC}$ (kpc) |
|-----------|----------------|----------------|---------|---------|------------------|---------------|-----------------|---------------------|----------------|
| NGC 6704  | 18 50 45       | −05 12 18      | 28.22   | −2.22   | 5                | 2974          | 0.72            | 7.9                 | 6                |
| NGC 6005  | 15 55 48       | −57 26 12      | 325.78  | −2.99   | 5                | 2690          | 0.45            | 9.1                 | 6.5              |
| NGC 6200  | 16 44 07       | −47 27 48      | 338     | −1.07   | 14               | 2054          | 0.58            | 6.9                 | 6.6              |
| NGC 6604  | 18 18 03       | −12 14 30      | 18.25   | 1.69    | 5                | 1696          | 0.97            | 6.8                 | 6.9              |
| IC 1805   | 02 32 42       | +61 27 00      | 134.73  | 0.92    | 20               | 2344          | 0.87            | 6.1                 | 10.3             |
| NGC 2286  | 06 47 40       | −03 08 54      | 215.31  | −2.27   | 14               | 2600          | 0.66            | 8.3                 | 10.7             |
| NGC 2489  | 07 56 15       | −30 03 48      | 246.71  | −0.77   | 6                | 3957          | 0.37            | 7.3                 | 10.7             |
| NGC 2354  | 07 14 10       | −25 41 24      | 238.37  | −0.79   | 18               | 4085          | 0.31            | 8.1                 | 11.2             |
| NGC 1893  | 05 22 44       | +33 24 42      | 173.59  | −1.68   | 25               | 6000          | 0.45            | 6.5                 | 14.5             |

**Table 2. Completeness Limits.**

| Cluster   | $J$ (mag) | $H$ (mag) | $K$ (mag) |
|-----------|-----------|-----------|-----------|
| NGC 6704  | 15.8      | 15        | 14.3      |
| NGC 6005  | 15.8      | 14.8      | 14.3      |
| NGC 6200  | 15.8      | 14.5      | 14.3      |
| NGC 6604  | 15.5      | 14.5      | 14.3      |

1 http://vizier.u-strasbg.fr/cgi-bin/VizieR?-source=II/246
2 http://www.ipac.caltech.edu/2mass/releases/allsky/doc/explsup.html

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Figure 2. Apparent CMDs for the clusters, offset field and the ‘cleaned CMD’ for clusters within the solar orbit: NGC 6704; 6005; 6200 and 6604. Also plotted are the isochrones (Girardi et al. 2002) for the ‘cleaned’ CMD.

Figure 3. Apparent CMDs for the clusters, offset field and the ‘cleaned CMD’ for clusters beyond the solar orbit: IC 1805, NGC 2286, 2489, 2354 and 1893. Also plotted are the isochrones (Girardi et al. 2002) for the ‘cleaned’ CMD.

Figure 4. IC 1805. Differential reddening: values obtained by isochrone fitting for $E(B-V)$ have been indicated in the respective cells. North is up.

3.1 Radial Density Profiles

For accurate determination of the cluster parameters, it is essential to determine the radial extent of clusters. As the 2MASS data offers all sky coverage, we have the opportunity to study the outer regions of clusters. The centres of the clusters are determined using a program described in Hasan et al. (2008). A number of concentric circles with respect to the estimated centre are made in such a way that each annular region contains a 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 observed data has been corrected for interstellar reddening using the coefficients given by Dutra et al. (2002).
Using the parameters obtained for the clusters, we use the method of Walker (1965) to find photometric members. We then plot RDPs for possible photometric members as well as all the stars to get the extent of the cluster. This is often very helpful especially in the case of the clusters which lie within the solar orbit and have very high field star densities and where the cluster stars are deeply embedded in the field. The RDPs for the clusters using all stars (dotted line) and only those which satisfy the photometric criterion (solid line) are shown in the Fig. 6. As is notable from the plots, a few of the clusters like NGC 6704, 6005, 6200, 6604 and 1893 are very faint and are only notable with this method.

3.2 Colour–magnitude diagrams

The absolute CMDs for our cluster sample are shown in Fig. 7.

The unreddened CCs $(J - H)_0$ versus $(H - K)_0$ for the photometric members of the clusters are shown in Fig. 8.

Table 3 shows the values of the fundamental parameters of reddening, distance and age obtained for the clusters using isochrones (Girardi et al. 2002) and compares them to those obtained by earlier authors. We have fitted the isochrones to the ‘cleaned’ CMD of the central regions of the clusters where field star contamination is minimized and then redefined it for the entire extent of the cluster. In this work, we are only referring to the population on the MS which does not have a very large age spread, and therefore the use of single isochrone fit is justified.

In the case of NGC 6704, Forbes & DuPuy (1978) and Delgado et al. (1997) agreed on the distance, but disagreed on the age of

\[ \chi^2 \text{ minimization technique was used to fit the RDPs to the function} \]
\[ \rho(r) = \frac{\rho_0}{1 + (r/r_c)^2} \]
(King 1962) to determine $r_c$ and $\rho_0$. The cluster’s core radius $r_c$ is the radial distance at which the value of $\rho(r)$ becomes half of the central density, $\rho_0$. 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. The sky coordinates of the cluster centres for epoch 2000, core $\text{Rad}(core)$ and limiting radii $\text{Rad}(lim)$ and background and core density $\rho(bg)$, $\rho(c)$ obtained by fitting to King’s profile are given in Table 4.

To determine the membership, we use two criteria: the radial extent and the photometric criterion described by Walker (1965). The Walker method is valid only for MS stars, while other luminosity classes and groups require different methods for member identification. Hence, in this work, the results apply to the MS population of clusters under study.
the cluster basically due to the inclusion of giant stars as members. Delgado et al. (1997) included the giants and got a larger age of 200 Myr similar to the age of 250 Myr we obtained. In our case, for the cleaned CMD of the central region of the cluster, we got a large number of giant stars as probable members, and inclusion of these led to the distance and age we obtained. These giant stars appear very clearly in our ‘cleaned’ CMD and lie in the central region of the cluster and hence are difficult to reject. The distance estimate, however, agrees well with the value of 2974 pc in the Dias et al. (2007) catalogue. In the case of NGC 6005, Piatti et al. (1998) obtained reddening and ages similar to that of ours, but differing strongly in the distance estimate. Again in this case, this is because of the giant clump in the CMD, which we (and even the previous authors) have included as probable members. For NGC 6200, Fitzgerald et al. (1977) obtained the distance based on photometry of 13 probable members and spectroscopy of seven stars. Ours is based on a larger number of stars and hence can be considered an improvement on the previous value. This value, however, agrees well with the value of 2054 pc in the Dias et al. (2007) catalogue. The distances obtained for the cluster NGC 6604 by earlier authors and us perfectly agree. The distance estimates for IC 1805 are between 760 pc (Johnson 1968) and 2400 kpc (Sung & Lee 1995). As we have used the method by Walker (1965), we only identify MS members, and our estimates are based on that population. Our values are within the range of estimates obtained by different authors. The distance and age estimates obtained for NGC 2286 differ in this work and Pan et al. (1992). The distance, however, agrees well with the value of 2600 pc in the Dias et al. (2007) catalogue. In the case of NGC 2489, fitting the isochrones to the red giant members confirmed by Piatti et al. (2007), we obtained a distance of 1445 pc and an age 316 Myr compared to the values of 1800 pc and 500 Myr obtained by Piatti et al. (2007). In the case of NGC 2354, fitting the data obtained by us and the red giant members confirmed by Clarí et al. (1999), we obtained a difference in age and distance estimates. For NGC 1893, the distance obtained by Sharma et al. (2007) is 3250 pc, which is similar to the 3630 pc obtained by us.

4 LUMINOSITY AND MASS FUNCTIONS
The LFs obtained for clusters using observations have to be corrected for the following three factors: (i) fraction of cluster area studied; (ii) completeness of data and (iii) field star contamination.

Table 3. Cluster parameters.

| Cluster     | Reddening $E(B - V)$ (mag) | Distance (pc) | Age (Myr) | Reference               |
|-------------|-----------------------------|---------------|-----------|-------------------------|
| NGC 6704    | 0.71                        | 1905          | 20        | Forbes & DuPuy (1978)   |
|             | 0.69                        | 1820          | 200       | Delgado et al. (1997)   |
|             | 0.69                        | 2884          | 250       | This work               |
| NGC 6005    | 0.45                        | 2690          | 1200      | Piatti et al. (1998)    |
|             | 0.4                         | 1585          | 1258      | This work               |
| NGC 6200    | 0.63                        | 2400          | –         | Fitzgerald et al. (1977) |
|             | 0.58                        | 2050          | 6.3       | This work               |
| NGC 6604    | 1.02                        | 1700          | 5         | Barbon et al. (2000)    |
|             | 0.97                        | 1700          | 6.3       | This work               |
| IC 1805     | 0.6                         | 2400          | 0.25–1.5  | Sung & Lee (1995)       |
|             | 0.7–1.1                     | 1479          | 4         | This work               |
| NGC 2286    | 0.4                         | 1510          | 63        | Pan et al. (1992)       |
|             | 0.3                         | 2618          | 200       | This work               |
| NGC 2489    | 0.30                        | 1800          | 500       | Piatti et al. (2007)    |
|             | 0.4                         | 1445          | 316       | This work               |
| NGC 2354    | 0.15                        | 1445          | 1000      | Abumada & Lapasset (1996) |
|             | 0.13                        | 1445          | 1000      | Clarí, Mermilliod & Piatti (1999) |
|             | 0.13                        | 1148          | 630       | This work               |
| NGC 1893    | 0.4–0.6                     | 3250          | –         | Sharma et al. (2007)    |
|             | 0.45–0.65                   | 3630          | 4         | This work               |

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clusters have been calculated using the formula $t_{\text{relax}} = \frac{N}{\sigma_v^2} \times t_{\text{cross}}$, where $t_{\text{cross}} = R/\sigma_v$ is the crossing time, $N$ is the number of stars, $R$ is the radius and $\sigma_v$ is the velocity dispersion. We have used the value $\sigma_v = 3\text{ km s}^{-1}$ (Binney & Merrifield 1998).

The clusters were divided into three regions (core, inner and outer halo) so as to obtain a significant number of stars in each region (shown in Table 5).

Table 5 also shows the values of the mass estimates and $\alpha$ for different regions of the clusters which are indicative of mass segregation. The mass estimates for the clusters are the lower limits of the masses for these clusters, as a large fraction of the mass lies in low-mass stars which are embedded in the field. The number of stars $N$ in the table are given with the errors which are equal to the number of stars present in the proportionate region of the field.

Fig. 10 shows the MF for the cluster NGC 6704 where the $\alpha$ value was found to be 1.15 ± 0.33 for the overall cluster, 1.11 ± 0.77 in the core region, 1.20 ± 0.52 in halo 1 and 0.80 ± 0.41 in halo 2. The relaxation time is 26 Myr for the overall cluster. The age of the cluster based on the isochrone fit is 250 Myr, and the age based on the most massive star on the MS (3.9 $M_\odot$) is $\lesssim$330 Myr. Hence, the cluster has dynamically relaxed ($\tau \approx 9$). Some of the less massive stars have moved to the outer regions of the cluster and have been lost from halo 2, and hence halo 2 has a flatter value of $\alpha$. Halo 1 has a larger number of low-mass stars which will slowly be lost as they move to halo 2.

In the case of NGC 6005 (Fig. 11), the $\alpha$ value of the MF has been found in the core, halo 1 and halo 2 as 2.75 ± 1.54, 1.97 ± 0.48 and 2.28 ± 0.74, respectively. The cluster has an age of 1258 Myr and has an overall $\alpha$ value of 2.27 ± 0.36. The relaxation time for NGC 6005 is 15 Myr and $\tau \approx 83$. Significant mass segregation must have already taken place in the cluster, but many of the massive stars of this cluster have already moved away from the MS (as seen in the CMD). These stars have lost mass and moved to the outer regions, and the many low-mass stars have been lost due to evaporation in the presence of strong Galactic tidal forces. This is also evident from the small size of the cluster (2.8 kpc). The most massive star on the MS has a mass of 2 $M_\odot$, with a nuclear age of 1800 Myr. This cluster is a good example of a segregated cluster with high values of $\alpha$ which shows the effect of both aspects: dynamics and evolution of stars.

For the cluster NGC 6200 (Fig. 12), the relaxation times for the core and overall cluster are 0.7 and 13.8 Myr, respectively. The $\alpha$ value of the core 1.25 ± 0.43 shows that the core has relaxed since the cluster has an age of 6.3 Myr. However, halo 1 and halo 2 are in the process of relaxation and hence their $\alpha$ values are 1.15

As the 2MASS data has 99.99 per cent completeness for the magnitude range used (see Table 3) and we have extracted the complete cluster area data, 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 $J$ versus $(J - H)$ plane using colour–magnitude filters. A similar colour–magnitude filter was applied for the apparent CMDs of the field area shown in Fig. 2. Thus, we obtain the approximate number of stars which are probable non-members, but still lie within our colour–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 also found using a similar method. Fig. 9 shows the uncorrected (dotted line) and corrected (solid line) LFs for the nine clusters in the $J$, $H$ and $K$ bands.

The MFs were constructed from the LFs using the isochrones of Girardi et al. (2002) with the appropriate ages and distances and fitted them to a fourth-order polynomial to find the mass–luminosity relation. The MF, $\phi(M) = dN/dM \propto M^{-\alpha}$, is an indicator of the star formation process. The relaxation times for the core and the overall

| Cluster     | RA (2000) | Dec. (2000) | $\rho$(bg) stars arcmin$^{-2}$ | $\rho$(c) stars arcmin$^{-2}$ | Rad(core) (arcmin) | Rad(limit) (arcmin) | Rad(core) (pc) | Rad(limit) (pc) | $R_{GC}$ (kpc) |
|-------------|-----------|-------------|-------------------------------|-------------------------------|-------------------|---------------------|----------------|----------------|----------------|
| NGC 6704    | 18 50 45  | −05 12 18   | 0.95 ± 0.43                   | 8.26 ± 0.88                   | 2.15 ± 0.44       | 8                   | 1.8            | 6.7            | 6.1            |
| NGC 6005    | 15 55 48  | −57 26 12   | 6.13 ± 0.25                   | 11.42 ± 0.71                  | 1.22 ± 0.14       | 6                   | 0.8            | 2.8            | 7.2            |
| NGC 6200    | 16 44 07  | −47 27 48   | 3.17 ± 0.1                    | 1.81 ± 0.33                   | 2.03 ± 0.64       | 7                   | 1.2            | 4.2            | 6.6            |
| NGC 6604    | 18 18 03  | −12 14 30   | 2.54 ± 0.18                   | 7.33 ± 0.99                   | 0.79 ± 0.18       | 4.5                 | 0.4            | 2.2            | 6.9            |
| IC 1805     | 02 32 42  | +61 27 00   | 6.46 ± 0.08                   | 7.29 ± 0.57                   | 1.09 ± 0.13       | 9                   | 0.4            | 3.9            | 9.6            |
| NGC 2286    | 06 47 40  | −03 08 54   | 0.99 ± 0.09                   | 3.15 ± 0.33                   | 1.63 ± 0.29       | 11                  | 1.2            | 8.4            | 10.7           |
| NGC 2489    | 07 56 15  | −30 03 48   | 2.42 ± 0.31                   | 7.83 ± 0.44                   | 2.11 ± 0.25       | 10                  | 0.5            | 4.2            | 9.2            |
| NGC 2354    | 07 14 10  | −25 41 24   | 1.23 ± 0.05                   | 2.01 ± 0.18                   | 3.65 ± 0.48       | 20                  | 1.2            | 6.7            | 9.2            |
| NGC 1893    | 05 22 44  | +33 24 42   | 0.33 ± 0.56                   | 3.47 ± 0.49                   | 6.55 ± 1.51       | 12                  | 3.1            | 12.7           | 12.1           |
| Cluster       | $R$ (arcmin) | $\Delta m$ (M$_\odot$) | $\alpha$ | $N$       | Mass (M$_\odot$) | $t_{\text{relax}}$ (Myr) |
|---------------|-------------|-------------------------|----------|----------|-----------------|--------------------------|
| NGC 6704      |             |                         |          |          |                 |                          |
| Core          | 0–2.15      | 1.6–6                   | 1.11 ± 0.77 | 59 ± 31  | 19 ± 10         |                          |
| Halo 1        | 2.15–5      | 1.5–9.4                 | 1.20 ± 0.52 | 212 ± 140 | 330 ± 218       |                          |
| Halo 2        | 5–8         | 1.6–11.7                | 0.80 ± 0.41 | 325 ± 267 | 110 ± 90        |                          |
| Overall       | 0–8         | 1.5–11.7                | 1.15 ± 0.33 | 596 ± 437 | 260 ± 190       | 26                       |
| NGC 6005      |             |                         |          |          |                 |                          |
| Core          | 0–1.22      | 1.4–3.7                 | 2.75 ± 1.54 | 33 ± 11  | 12 ± 4          |                          |
| Halo 1        | 1.22–4      | 1–3.8                   | 1.97 ± 0.48 | 402 ± 252 | 348 ± 218       |                          |
| Halo 2        | 4–6         | 1–3.8                   | 2.28 ± 0.74 | 435 ± 352 | 119 ± 96        |                          |
| Overall       | 0–6         | 1–3.8                   | 2.27 ± 0.36 | 866 ± 629 | 381 ± 276       | 15                       |
| NGC 6200      |             |                         |          |          |                 |                          |
| Core          | 0–2.03      | 1.5–17.7                | 1.25 ± 0.43 | 57 ± 32  | 64 ± 36         | 0.7                      |
| Halo 1        | 2.03–4      | 1.5–17.6                | 1.15 ± 0.31 | 175 ± 131 | 288 ± 215       |                          |
| Halo 2        | 4.5–7       | 1.3–15                  | 1.18 ± 0.39 | 219 ± 153 | 326 ± 227       |                          |
| Overall       | 0–7         | 1.5–17.7                | 1.33 ± 0.23 | 479 ± 397 | 503 ± 417       | 13.8                     |
| NGC 6604      |             |                         |          |          |                 |                          |
| Core          | 0–0.79      | 1.2–17.3                | 0.53 ± 0.51 | 17 ± 3   | 34 ± 6          | 0.1                      |
| Halo 1        | 0.79–2.6    | 1.2–27                  | 0.46 ± 0.23 | 50 ± 13  | 131 ± 347       |                          |
| Halo 2        | 2.6–4.5     | 1–21                    | 0.35 ± 0.29 | 118 ± 70  | 202 ± 119       |                          |
| Overall       | 0–4.5       | 1.2–19.5                | 0.51 ± 0.17 | 200 ± 110 | 304 ± 167       | 3.58                     |
| IC 1805       |             |                         |          |          |                 |                          |
| Core          | 0–1.08      | 0.7–31                  | 0.88 ± 0.28 | 39 ± 6   | 81 ± 12         | 0.2                      |
| Halo 1        | 1.08–5      | 0.7–31                  | 1.00 ± 0.16 | 413 ± 301 | 324 ± 236       |                          |
| Halo 2        | 5–9         | 0.7–25                  | 0.75 ± 0.17 | 799 ± 702 | 196 ± 172       |                          |
| Overall       | 0–9         | 0.7–31                  | 0.93 ± 0.11 | 1256 ± 1017 | 414 ± 335       | 29                       |
| NGC 2286      |             |                         |          |          |                 |                          |
| Core          | 0–1.63      | 1.4–2.6                 | 1.37 ± 2.09 | 17 ± 5   | 6 ± 2           | 0.32                     |
| Halo 1        | 1.63–6.5    | 1–7.4                   | 2.79 ± 0.33 | 146 ± 91  | 348 ± 217       |                          |
| Halo 2        | 6.5–11      | 1.2–6.2                 | 1.91 ± 0.64 | 262 ± 235 | 38 ± 34         |                          |
| Overall       | 0–11        | 1.4–7.4                 | 2.12 ± 0.38 | 363 ± 279 | 150 ± 115       | 18                       |
| NGC 2489      |             |                         |          |          |                 |                          |
| Core          | 0–1.1       | 0.7–4.8                 | 0.89 ± 0.54 | 30 ± 5   | 26 ± 4          | 0.18                     |
| Halo 1        | 1.1–5.5     | 0.7–5.9                 | 1.27 ± 0.24 | 264 ± 123 | 442 ± 206       |                          |
| Halo 2        | 5.5–10      | 0.7–5.9                 | 1.56 ± 0.39 | 341 ± 293 | 212 ± 182       |                          |
| Overall       | 0–10        | 0.7–5.6                 | 1.11 ± 0.22 | 709 ± 532 | 264 ± 198       | 19.4                     |
| NGC 2354      |             |                         |          |          |                 |                          |
| Core          | 0–3.65      | 1–4.6                   | 1.83 ± 0.49 | 98 ± 46  | 34 ± 16         |                          |
| Halo 1        | 3.65–12     | 1–3.6                   | 1.56 ± 0.36 | 641 ± 504 | 96 ± 75         |                          |
| Halo 2        | 12–20       | 1–3.6                   | 1.63 ± 0.45 | 1077 ± 976 | 80 ± 72        |                          |
| Overall       | 0–20        | 1–3.6                   | 1.48 ± 0.24 | 1834 ± 1541 | 215 ± 181      | 70                       |
| NGC 1893      |             |                         |          |          |                 |                          |
| Core          | 0–3         | 0.8–27                  | 0.17 ± 0.24 | 80 ± 46  | 89 ± 51         | 2.4                      |
| Halo 1        | 3–7         | 0.8–33                  | 0.69 ± 0.19 | 258 ± 218 | 119 ± 100       |                          |
| Halo 2        | 7–12        | 0.8–33                  | 0.54 ± 0.18 | 525 ± 503 | 268 ± 256       |                          |
| Overall       | 0–12        | 0.8–31                  | 0.68 ± 0.11 | 827 ± 744 | 365 ± 328       | 67                       |

$\pm 0.31$ and $1.18 \pm 0.39$, respectively. The overall cluster has $\alpha = 1.33 \pm 0.23$ as the cluster has partially relaxed.

NGC 6604 has an age of 6.3 Myr which exceeds the relaxation times for the core (0.1 Myr) and cluster (3.58 Myr). Hence, the cluster has relaxed and has $\alpha$ values $0.53 \pm 0.51$, $0.46 \pm 0.23$, $0.35 \pm 0.29$ and $0.51 \pm 0.17$ for the core, halo 1, halo 2 and the overall cluster, respectively. Since the age of the cluster exceeds the relaxation time, significant relaxation/mass segregation would have taken place as is evident from the similar values of $\alpha$ for the core and the inner and outer haloes.

IC 1805 has an age of 4 Myr, and the relaxation times for the core and the overall cluster are 0.2 and 29 Myr, respectively. If we assume a Salpeter IMF ($\alpha = 2.35$), we see that the MF of the cluster seems to have changed as is evident from the $\alpha$ values of the core.
Mass segregation in star clusters

5 CONCLUSIONS

In this paper, using 2MASS data, we have studied mass segregation in nine clusters in diverse environments to understand their structure and dynamics. The RDPs of the clusters have been plotted (Fig. 6), and the parameters for the clusters such as reddening, distance and age have been determined using isochrone fits (Table 3). 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 (see Figs 9–18). Clusters have been divided into three regions: core, inner and outer halo. The α values have been determined for different regions and the overall clusters as a function of the parameter \( \tau \). We use the change in α values for

value of the core (0.89 ± 0.54). The α values of halo 1, halo 2 and the overall cluster are 1.27 ± 0.24, 1.56 ± 0.39 and 1.11 ± 0.22, respectively.

NGC 2354 has an age of 630 Myr which is large compared to the overall relaxation time of 70 Myr. The cluster core has an α value of 1.83 ± 0.49. The haloes and the overall cluster have similar α values of 1.56 ± 0.36, 1.63 ± 0.45 and 1.48 ± 0.24, respectively. As seen in the CMD, the cluster is old and most massive stars have evolved away from the MS, and hence the core has a larger number of low-mass stars.

NGC 1893 is a very young cluster of age 4 Myr which shows signs of overall mass segregation not only in the core which has a relaxation time of 2.4 Myr, but also in the overall cluster whose relaxation time is very large (67 Myr). The α values for the core, halo 1, halo 2 and overall cluster are 0.17 ± 0.24, 0.69 ± 0.19, 0.54 ± 0.18 and 0.68 ± 0.11, respectively. This cluster also shows signs of early mass segregation as the relaxation time of the cluster clearly exceeds the age of the cluster. Sharma et al. (2007) also obtained results suggesting primordial mass segregation in this cluster. This cluster is located in the Galactic anticentre region at a distance of ≈14.5 kpc from the Galactic Centre. Using Spitzer observations, Caramazza et al. (2008) found the maximum mass of stars in the cluster to be 28–46 M\(_\odot\) and infer that the cluster does not show any peculiarity regarding the ongoing star formation.

NGC 6005 has an age of 200 Myr which exceeds the core and overall relaxation times of 0.32 and 18 Myr. The α values of the core, halo 1, halo 2 and the overall cluster are 1.37 ± 0.29, 2.79 ± 0.33, 1.91 ± 0.64 and 2.12 ± 0.38, respectively, showing that the mass segregation process must have taken place, but many of the high-mass stars have moved away from the MS and have lost mass.

NGC 2489 is an old, relaxed cluster of age 316 Myr which is much larger compared to its relaxation time of the core of 19.4 Myr. This is evident from the flat α

(0.59 ± 0.17), halo 1 (0.88 ± 0.14), halo 2 (0.68 ± 0.02) and the overall cluster (0.69 ± 0.14). This indicates an excess of high-mass stars in the overall cluster and also in the core compared to the inner halo, indicative of a high degree of mass segregation. This has been earlier reported by Sagar et al. (1988).

NGC 2286 has an age of 200 Myr which exceeds the core and overall relaxation times of 0.32 and 18 Myr. The α values of the core, halo 1, halo 2 and the overall cluster are 1.37 ± 0.29, 2.79 ± 0.33, 1.91 ± 0.64 and 2.12 ± 0.38, respectively, showing that the mass segregation process must have taken place, but many of the high-mass stars have moved away from the MS and have lost mass.

NGC 489 is an old, relaxed cluster of age 316 Myr which is much larger compared to its relaxation time of the core of 19.4 Myr. This is evident from the flat α

(0.59 ± 0.17), halo 1 (0.88 ± 0.14), halo 2 (0.68 ± 0.02) and the overall cluster (0.69 ± 0.14). This indicates an excess of high-mass stars in the overall cluster and also in the core compared to the inner halo, indicative of a high degree of mass segregation. This has been earlier reported by Sagar et al. (1988).

NGC 2354 has an age of 630 Myr which is large compared to the overall relaxation time of 70 Myr. The cluster core has an α value of 1.83 ± 0.49. The haloes and the overall cluster have similar α values of 1.56 ± 0.36, 1.63 ± 0.45 and 1.48 ± 0.24, respectively. As seen in the CMD, the cluster is old and most massive stars have evolved away from the MS, and hence the core has a larger number of low-mass stars.

NGC 1893 is a very young cluster of age 4 Myr which shows signs of overall mass segregation not only in the core which has a relaxation time of 2.4 Myr, but also in the overall cluster whose relaxation time is very large (67 Myr). The α values for the core, halo 1, halo 2 and overall cluster are 0.17 ± 0.24, 0.69 ± 0.19, 0.54 ± 0.18 and 0.68 ± 0.11, respectively. This cluster also shows signs of early mass segregation as the relaxation time of the cluster clearly exceeds the age of the cluster. Sharma et al. (2007) also obtained results suggesting primordial mass segregation in this cluster. This cluster is located in the Galactic anticentre region at a distance of ≈14.5 kpc from the Galactic Centre. Using Spitzer observations, Caramazza et al. (2008) found the maximum mass of stars in the cluster to be 28–46 M\(_\odot\) and infer that the cluster does not show any peculiarity regarding the ongoing star formation.

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different regions to estimate the level of mass segregation of the clusters.

The $\alpha$ values of MFs of the clusters under study range from 0.17 to 2.79. Fig. 19 shows the dependence of $\alpha$ of clusters as a function of various parameters for 13 clusters (nine from this work and four from Hasan et al. 2008). Though our sample is small, it is homogeneous, in the sense of photometric data as well as methods of data analysis, thus making it a controlled sample. Such studies are not suitable using heterogeneous data sets where unknown biases may be present.

It is interesting to note a very high confidence level in the correlation of $\alpha$ with age and $\tau$. As clusters age, they have steeper values of $\alpha$. The $\alpha$ value increases with age and $\tau$, and fits straight lines with slopes $m$ and y-intercepts $c$ given by $m = 0.40 \pm 0.03$, $c = -1.86 \pm 0.27$ and $m = 0.01 \pm 0.001$, $c = -0.85 \pm 0.02$, respectively. The increase in the value of $\alpha$ with age and $\tau$ is a clear indicator of the dynamical processes involved where mass segregation can be explained by dynamics. The confidence level of the Pearson’s product–moment correlation of $\alpha$ with age is 0.76 with $p = 0.002$ and with $\tau$ is 0.71 with $p = 0.007$. The value of $\alpha$ increases with Galactocentric distance, indicating a larger number of low-mass stars in clusters at larger Galactocentric distances due to lesser evaporation of stars.

3 The $p$ value shows at what level of confidence the null hypothesis (correlation) can be rejected. For example, $p = 0.05$ shows a 95 per cent probability that the hypothesis of a correlation is correct.
Mass segregation in star clusters

The cluster NGC 6704 had an $\alpha$ value of $1.15 \pm 0.33$ for the overall cluster with an age exceeding nine times the relaxation time. The cluster has dynamically relaxed, many of the less massive stars have moved to the outer regions of the cluster, some have been lost due to evaporation and hence halo 2 has a flatter value of $\alpha$ compared to halo 1. NGC 6005 is an old cluster which has been mass segregated and has high values of $\alpha$ due to the effect of both dynamics and evolution of stars, in which massive stars have evolved, lost mass and moved to the outer regions of the cluster. In the case of the cluster NG 6200, the relaxation times for the core and cluster as a whole are 0.7 and 13.8 Myr, respectively, and the cluster has partially relaxed. The $\alpha$ value of the core is $1.25 \pm 0.43$, and it shows that the core has a larger number of high-mass stars due to relaxation since the cluster has an age of 6.3 Myr ($> t_{\text{relax}}$ for the core). However, the inner and outer haloes are in the process of relaxation and their $\alpha$ values are $1.15 \pm 0.31$ and $1.18 \pm 0.39$, respectively.

NGC 6604, though young, has an age of 6.3 Myr which exceeds the relaxation times for the core (0.1 Myr) and cluster (3.58 Myr). Hence, the cluster has relaxed and has $\alpha$ values $0.53 \pm 0.51$, $0.46 \pm 0.23$, $0.35 \pm 0.29$ and $0.51 \pm 0.17$ for the core, halo 1, halo 2 and the overall cluster, respectively.

IC 1805 has an age of 4 Myr, and the relaxation times for the core and the overall cluster are 0.2 and 29 Myr, respectively. It already shows mass segregation as earlier reported by Sagar et al. (1988). The $\alpha$ values of the MF of the cluster are core (0.59 $\pm$ 0.17), halo 1 (0.88 $\pm$ 0.14), halo 2 (0.68 $\pm$ 0.02) and the overall cluster (0.69 $\pm$ 0.14). NGC 2286 has an age of 200 Myr which exceeds the core and overall relaxation times of 0.32 and 18 Myr. The $\alpha$ values of the core, halo 1, halo 2 and the overall cluster are 1.37 $\pm$ 2.09, 2.79 $\pm$ 0.33, 1.91 $\pm$ 0.64 and 2.12 $\pm$ 0.38, respectively. Mass segregation process must have taken place, but many of the high-mass stars have moved away from the MS and have lost mass, and the outer halo seems to have lost low-mass stars and hence has a flatter $\alpha$.

NGC 2489 is an old relaxed cluster and many of the low-mass stars from the core have moved to the outer regions of the cluster. This is evident from the flat $\alpha$ value of the core (0.89 $\pm$ 0.54) and the larger $\alpha$ values of halo 1, halo 2 and the overall cluster (1.27 $\pm$ 0.24, 1.56 $\pm$ 0.39 and 1.11 $\pm$ 0.22, respectively).

NGC 2354 is an old cluster and most massive stars have evolved away from the MS and the haloes and the overall cluster have similar $\alpha$ values of 1.56 $\pm$ 0.36, 1.63 $\pm$ 0.45 and 1.48 $\pm$ 0.24, respectively.

NGC 1893 is a very young cluster of age 4 Myr which shows signs of overall mass segregation not only in the core which has a relaxation time of 2.4 Myr, but also in the overall cluster whose relaxation time is very large (67 Myr). The $\alpha$ values for the core, halo 1, halo 2 and the overall cluster are 0.17 $\pm$ 0.24, 0.69 $\pm$ 0.19, 0.54 $\pm$ 0.18 and 0.68 $\pm$ 0.11, respectively.

Of the nine clusters studied, two clusters (IC 1805 and NGC 1893) are too young to be dynamically relaxed, and we speculate this as evidence for primordial mass segregation. Mass segregation by birth is a natural expectation because protostars near the core. However, the inner and outer haloes are in the process of relaxation and their $\alpha$ values are $1.15 \pm 0.31$ and $1.18 \pm 0.39$, respectively.

NGC 6604, though young, has an age of 6.3 Myr which exceeds the relaxation times for the core (0.1 Myr) and cluster (3.58 Myr). Hence, the cluster has relaxed and has $\alpha$ values $0.53 \pm 0.51$, $0.46 \pm 0.23$, $0.35 \pm 0.29$ and $0.51 \pm 0.17$ for the core, halo 1, halo 2 and the overall cluster, respectively.

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density centre of the cluster have more material to accrete. The actual efficiency of this mechanism is still a matter of debate (Krumholz, McKee & Klein 2005; Krumholz & Bonnell 2009). McMillan et al. (2007) presented an alternative scenario for a dynamical origin of early mass segregation in young clusters. Even if the clumps are not initially segregated, if their internal segregation time-scale is shorter than the time needed for the clumps to merge, they will segregate through standard two-body relaxation and preserve this segregation after they have merged. The multiscale dynamical evolution of clumpy systems is, in this case, responsible for rapidly leading to mass segregation in young clusters without invoking any mechanism associated with the star formation process. Recent simulations by Allison et al. (2009, 2010) showed that early mass segregation can be due to dynamical effects even in timescales as short as a Myr, thus not requiring the need of primordial mass segregation which would violate the universality of the IMF and set constraints on the origin of the IMF. Understanding the origin of mass segregation can also help differentiate between possible models of massive star formation. Do massive stars form in the centres of clusters? Or do they migrate there over time due to gravitational interactions with other cluster members? In particular, are the masses of the most massive stars set by the mass of the core from which they form (Krumholz & Bonnell 2009) or by competitively accreting mass due to being located at a favourable position in the cluster (Bonnell & Davies 1998; Krumholz et al. 2005; Bonnell & Bate 2006)? Allison et al. (2009) showed that dynamical mass segregation can occur on a few crossing time-scales which suggests that massive stars could form in relative isolation in large cores and mass segregate later, possibly avoiding the need for competitive accretion as dominant process to form the most massive stars in the centre of a cluster. However, the simulations by Moecckel & Bonnell (2009) show that for such young systems, star formation scenarios predicting general primordial mass segregation are inconsistent with observed segregation levels. They found that a star formation scenario in which the most massive stars are primordially segregated is consistent with observations and offers a way to account for compact groups of young, massive stars.

Currently, we cannot say conclusively if mass segregation is a birth phenomenon (Gouliermis et al. 2004), or whether the more massive stars form anywhere throughout the protocluster volume. Star clusters that have already blown out their gas at ages of one to a few Myr are typically mass segregated (e.g. R136, INC). Assuming primordial mass segregation would imply that massive stars (>10M⊙) only form in rich clusters and reject the possibility they can also form in isolation (see Li, Klessen & Mac Low 2003; Parker & Goodwin 2007). A better understanding of the effects of dynamical evolution is required to clearly differentiate between present dynamically derived star cluster properties and those which were imprinted by star formation processes.

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