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Effect of mass segregation on mass function of young open clusters

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Abstract. The effect of mass segregation on cluster mass function has been studied and it is found that the slope of the mass function is steeper in the outer part of the open clusters. Since derived dynamical relaxation time is always larger than the age of the cluster, it is inferred that the observed mass segregation might have taken place at the time of cluster formation.

Key words : mass function—star clusters—mass segregation

1. Introduction

In a few open clusters, there is clear evidence that the mean stellar mass is a decreasing function of radial distance (Sagar *et al.* 1988 and references therein). Recently Subramaniam *et al.* (1992) have also found an evidence of mass segregation, in the sense that massive stars tend to lie near the cluster centre, in one young Large Magellanic Cloud star clusters. On the other hand, Burki (1978) has found the opposite effect in six very young clusters. He found that massive stars ($M > 20\ M_\odot$) are formed with lesser degree of central concentration than less massive stars ($20 > M/M_\odot > 4$). The knowledge of spatial variation of mass function in open clusters has an important bearing on their dynamical evolution. In the present work an effort has been made to study the spatial variation of mass function within a cluster, using reliable cluster members of a few young open clusters. In this work we have included five clusters which had also been used by Burki (1978). The spatial variation of mass function has been obtained and discussed in light of contrary results of Burki.

2. Observational data

In the present work we have included 11 open clusters. The effect of mass segregation in a few of these clusters has been observed by Sagar *et al.* (1988). The observational data for nine clusters NGC 581, 654, 2264, 6530, 6611, 6823, 6913, Tr 1 and IC 1805 have been taken from the catalogue of Myakutin *et al.* (1984) while for the other two clusters, NGC 869 and 884, have been taken from the catalogue of Muminov (1983). In the catalogue of Myakutin *et al.* (1984) membership of cluster stars are based on only proper motion studies, while both proper motion and photometric criteria have been used by Muminov (1983).

The mass of cluster members is estimated from stellar position in the HR diagram and the theoretical evolutionary tracks based on the models considering the effect of mass loss in evolution of massive stars ($M > 15\ M_\odot$). The details of the method used for the mass estimation of cluster members are given by Sagar *et al.* (1986).

3. Spatial variation of the mass function

The point of maximum stellar density has been considered as the cluster centre which has been estimated with an accuracy of ~ 1 arc sec (*cf.* Sagar *et al.* 1988). The cluster region is then divided into two, three or four concentric regions, depending upon the total number of stars in the cluster so that each region has generally more than 20 stars. The boundaries of concentric regions and number of stars in each region are given in table 1.

The cumulative mass function has been constructed for each cluster by counting the number of stars, N, having masses within the limit of the interval, M, and using the relations

$$\log N = -X \log M + \text{const.},$$

where, X is the slope of the cumulative mass function. The limit of the mass intervals and total number of stars up to that interval are given in table 2. Using the least squares linear regression, the values of slope as well as their standard errors and correlation coefficients have been obtained and these are given in table 3. Assuming normal error

Table 1. Boundaries of the concentric regions and number of stars N in each region.

Cluster	Region I		Region II		Region III		Region IV	
	limit (arc min)	N	limit (arc min)	N	limit (arc min)	N	limit (arc min)	N
NGC 581	2.1	37	3.5	36	—	—	—	—
NGC 654	3.5	28	20.0	30	—	—	—	—
NGC 869	4.9	123	7.5	131	10.8	127	14.2	83
NGC 884	6.0	144	9.1	113	13.1	117	—	—
NGC 2264	10.0	46	15.0	46	21.0	44	—	—
NGC 6530	9.0	45	24.0	41	—	—	—	—
NGC 6611	4.0	23	16.0	26	—	—	—	—
NGC 6823	5.7	20	16.0	19	—	—	—	—
NGC 6913	10.0	54	17.2	43	—	—	—	—
IC 1805	9.0	46	18.0	47	26.0	46	—	—
Tr 1	1.0	18	2.3	19	—	—	—	—

Table 2a. Mass distribution of stars

NGC 581			NGC 654			NGC 6530			NGC 6611			NGC 6823			NGC 6913			Tr 1		
limit	I	II	limit	I	II	limit	I	II	limit	I	II	limit	I	II	limit	I	II	limit	I	II
7.0	7	3	6.0	16	13	10.0	6	0	20.0	10	6	30.0	2	3	10.0	7	1	5.0	8	1
5.0	13	3	5.0	20	15	7.5	14	1	15.0	12	8	20.0	7.	5	7.0	9	4	4.0	10	1
4.0	19	6	4.5	23	20	5.0	24	4	11.0	15	10	15.0	12	8	6.0	9	5	3.0	13	9
3.5	23	10	4.0	25	23	3.5	36	13	9.0	20	12	11.0	15	10	5.0	12	7	2.7	15	14
2.9	26	19	3.5	26	26	3.0	41	22	8.0	23	26	9.0	16	11	4.0	24	18	2.5	16	17
2.2	37	36	3.0	28	30	2.5	45	41	—	—	—	7.5	20	19	3.0	54	43	2.3	18	19

Limit represents the limit of the mass interval.
I, II represent number of stars in the region.

Table 2b. Mass distribution of stars

NGC 869					NGC 884				NGC 2264				IC 1805			
limit	I	II	III	IV	limit	I	II	III	limit	I	II	III	limit	I	II	III
20.0	14	2	3	1	20.0	10	4	6	10.0	2	1	0	40.0	2	1	0
15.0	20	7	9	5	15.0	16	9	7	5.0	3	6	1	20.0	8	2	1
10.0	28	12	15	11	10.0	27	20	12	4.0	5	6	1	10.0	19	11	6
7.0	40	20	22	14	7.0	40	27	25	3.0	8	11	2	8.0	26	14	12
4.0	82	60	59	43	4.0	84	64	62	2.0	13	18	11	6.0	33	22	20
2.8	123	131	127	83	2.8	144	113	117	1.0	46	46	44	4.0	46	47	46

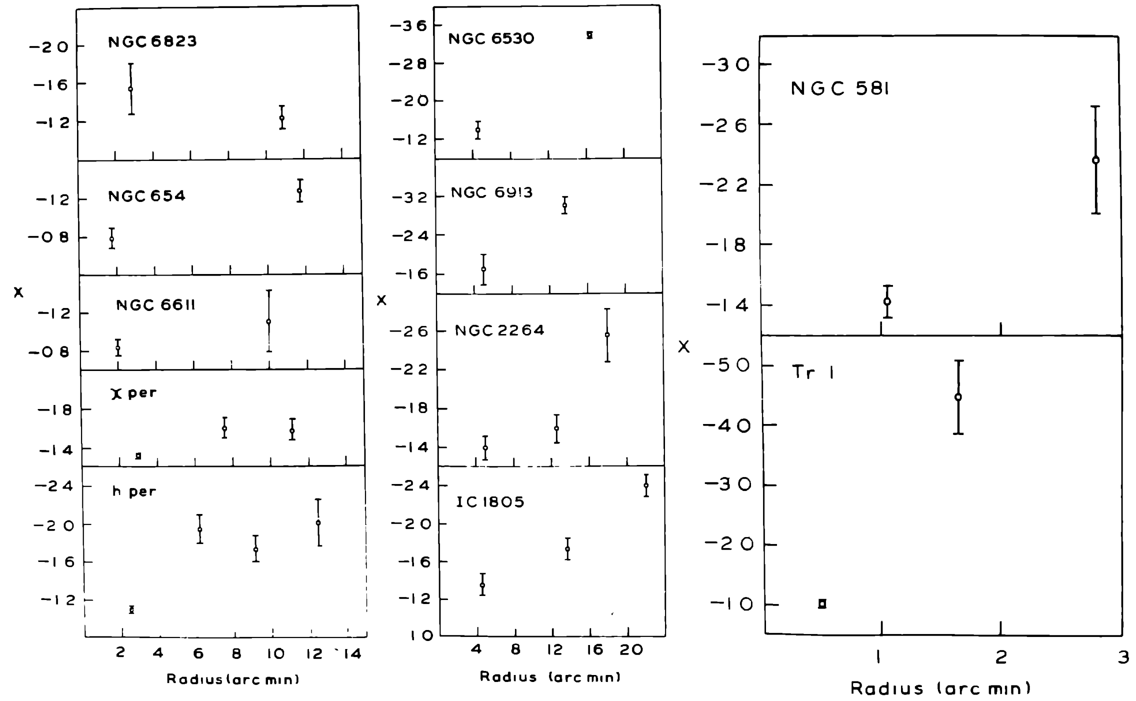
Limit represents the limit of the mass interval.
I, II, III, IV represent the number of stars in the region.

Table 3. Mass function in different regions of the clusters

Cluster	Region I		Region II		Region III		Region IV		Confidence
	$X \pm$ s.e.	$\lvert r \rvert$	$X \pm$ s.e.	$\lvert r \rvert$	$X \pm$ s.e.	$\lvert r \rvert$	$X \pm$ s.e.	$\lvert r \rvert$	level (%)
NGC 581	−1.42 ± 0.11	0.99	−2.36 ± 0.36	0.96	—	—	—	—	98.7
NGC 654	−0.79 ± 0.11	0.96	−1.27 ± 0.12	0.98	—	—	—	—	99.7
NGC 869	−0.10 ± 0.04	1.00	−1.95 ± 0.15	0.99	−1.74 ± 0.14	0.99	−2.01 ± 0.25	0.97	99.9
NGC 884	−1.32 ± 0.03	1.00	−1.61 ± 0.11	0.99	−1.57 ± 0.09	0.99	—	—	98.7
NGC 2264	−1.40 ± 0.13	0.98	−1.60 ± 0.15	0.98	−2.56 ± 0.28	0.98	—	—	98.0*
NGC 6530	−1.39 ± 0.17	0.97	−3.37 ± 0.01	1.00	—	—	—	—	99.9
NGC 6611	−0.84 ± 0.08	0.98	−1.11 ± 0.32	0.87	—	—	—	—	58.0
NGC 6823	−1.54 ± 0.27	0.94	−1.22 ± 0.11	0.98	—	—	—	—	77.0
NGC 6913	−1.70 ± 0.33	0.93	−3.04 ± 0.18	0.99	—	—	—	—	99.9
IC 1805	−1.36 ± 0.12	0.99	−1.74 ± 0.11	0.99	−2.40 ± 0.12	1.00	—	—	98.0
Tr 1	−1.03 ± 0.03	1.00	−4.48 ± 0.63	0.96	—	—	—	—	99.9

* for regions I and III.

distribution, statistical significance level (in percent) for difference in the values of X for regions I and II are also given in table 3. Except for NGC 6611 and 6823, the statistical confidence level is above 98% in all other cases. The variation of mass function slope with the radial distance is shown in figure 1.



(a) (b) (c)

Figure 1a, b and c. The spatial variation of mass function in young open clusters.

4. Effect of mass segregations on the mass function

Figure 1 manifests that the slope of the mass function is steeper in the outer parts of the open clusters except NGC 6823, which suggests a preferential concentration of massive stars towards the centre than the outer region of the cluster. Two clusters, NGC 6611 and 6823 do not show statistically significant difference in the slope of mass functions for the inner and outer regions. A possible reason for this could be the completeness limit of the present data (~ $8M_\odot$) in both the clusters. Sagar *et al.* (1988) also could not study the effect of mass segregation in NGC 6611 and 6823 because of the completeness limit. We could make more than two concentric regions in four clusters NGC 869, 884, 2264 and IC805 only. The slope of the mass function in NGC 2264 and IC 1805 increases systematically with the radial distance, while for h and χ Per it changes from region I to II but remains practically constant in the outer regions. Such results are expected if low mass stars have escaped from the outer parts of the cluster because of dynamical evolution. Therefore, in the ensuing section we have tried to find out the dynamical stages of the clusters used in the present study.

It is interesting to note that Burki (1978) has reported that massive stars ($M > 20\ M_\odot$) are formed with lesser degree of central concentration than the less massive stars ($20 > M/M_\odot > 4$) and it is also concluded that the slope of the mass spectrum is steeper in the central regions than in the outer regions of the newly formed clusters. Five common clusters, *i.e.* NGC 654, 869, 884, 6823 and IC 1805, which are included in the present study have been discussed, in light of the contrary results of Burki (1978).

NGC 654 and IC 1805 : The findings of Burki (1978) are based on smaller cluster regions as compared to those used in the present study. In both clusters the linear radius of the cluster, r_{cl}, used by Burki (1978) is nearly equal to region I of the present study. Our results which have been derived from a larger region of the clusters, are expected to give a better picture of the spatial variation of the mass function.

NGC 6823 : In case of NGC 6823 the value r_{cl} used by Burki (1978), is less than the boundary of the region I of the present study. In the present study a steeper mass function is observed in the central region than the outer region, however, the errors are quite large.

NGC 869 and 884 : The values of r_{cl} used by Burki (1978) are comparable to the boundary of the outer regions used in the present study. The result, that the massive stars show a higher degree of central concentration than the less massive stars, obtained by Burki (1978) for these two clusters is in agreement with the result obtained in the present study.

Thus, we can infer from the above mentioned discussions that the results obtained by Burki (1978) do not represent the true spatial variation of mass function in open clusters, especially in case of NGC 654 and IC 1805. Scalo (1986) has suggested that one should view individual cluster IMFs with some caution unless a relatively large area is surveyed.

5. Dynamical stage of the clusters

Dynamical relaxation may be one of the possible reasons for the variation in the slope of the mass function, X. Since due to dynamical relaxation, low mass stars in a cluster may possess the largest random velocities, consequently these will try to occupy a large volume than the high mass stars (*cf.* Mathieu & Latham 1986; McNamara & Sekiguchi 1986; Mathieu 1985).

Clusters used in the present study, have already been studied by Sagar *et al.* (1988) and they have concluded that except Tr 1, the other clusters are not dynamically relaxed, therefore, the observed variation in the value of X in these clusters might be a result of star formation process. However, Sagar *et al.* (1988) have not taken into account the incompleteness of the observational data in estimation of dynamical relaxation time, T_{E}, of the clusters, which has been estimated using the relation

$$T_{\mathrm{E}} = 8.9 \times 10^5 \, (NR^3_{\mathrm{h}}/\bar{m}\,)^{1/2}/\log\,(0.4\,N);$$

where, N is the number of cluster members, R_h the radius containing half of the cluster mass and $\bar{m}$ the average mass of cluster stars (Spitzer & Hart 1971). The N, R_h, $\bar{m}$ cannot be estimated directly from existing observations due to lack of information about faint cluster members. Several studies support the presence of coronal region around nucleus of open cluster which contains generally faint members (*cf.* Kholopov 1969; Danilov *et al.* 1985;

Stone 1980; Stone 1988; Pandey *et al.* 1990). Recently Pandey *et al.* (1990) have obtained the limiting redius for a few young open clusters and concluded that these radii, in case of bound open clusters, are dynamically stable in the tidal forces of the Galaxy. The contribution of unobserved faint cluster members in estimation of the values of N, R_h, $\bar{m}$ can be included if we assume that the mean slope of the mass function is same upto the lowest mass stars formed in the cluster and extrapolating the values to the lowest assumed mass. However, the slope of the mass function at the fainter end is still a controversial issue (*cf.* Scalo 1986) but for the sake of simplicity we have made this assumption.

The distribution of stars in a cluster can be represented by the following power law,

$$N \propto \int_{M_L}^{M^U} M^{\alpha}\, dM \qquad \ldots (1)$$

where, N is the number of stars in a cluster, $\alpha = X - 1$ and X is the slope of the cumulative mass function. The total stellar mass of the cluster can be obtained from the following relation

$$M_{\text{cluster}} = C \int_{M_L}^{M^U} M^{\alpha} M\, dM, \qquad \ldots (2)$$

where, M_U and M_L are the upper and lower limits for stellar masses in the cluster. Larson (1985) has concluded that fragmentation becomes less likely for masses below about $0.3M_{\odot}$, therefore, we have assumed a lower mass limit of $M = 0.3M_{\odot}$. Total number of stars and total mass of the cluster have been obtained using relations 1 and 2 respectively and these are given in table 4. The average mass can be obtained from the relation $\bar{m} = M_{\text{cluster}}/N$.

The limiting radius of a bound cluster can be determined from the relation given by King (1968)

$$r = R_{\text{p}}\, (M_{\text{cluster}}/3.5\ M_{\text{G}})^{1/3}$$

where, R_p is the perigalactic distance of the cluster, M_G is the mass of the Galaxy. Sagar *et al.* (1988) have found that the surface density in open clusters can be represented by a power law on the form $D\ \alpha\ r^{-b}$. Using the data of Sagar *et al.* (1988) we have obtained a mean value of $b \approx 1.4$. Using the above relation and assuming that the clusters are moving in circular orbits having radius $R = 10$ kpc and the mass of the Galaxy $M_G \simeq 2 \times 10^{11} M_{\odot}$, half mass radii obtained are given in table 4. Using the values of N, R_h and $\bar{m}$ we have finally estimated the dynamical relaxation time and these values are given in table 4. A comparison of these values with those given by Sagar *et al.* (1988) manifests that the latter values are always smaller than the former. This is expected because lack of information about faint cluster members will reduce the value of N and increase the value of $\bar{m}$ and consequently the value of T_E will decrease. The ages given in table 4 are taken from the catalogue of Lynga (1987). A comparison of cluster age with its relaxation time indicates that the relaxation time is larger than the age of the clusters. Thus we can infer that these clusters are not dynamically relaxed.

Table 4. Estimated mass, total number of stars, R_h and T_E

Cluster	Mean slope of the mass function	Total number of stars, N	Total estimated mass of the cluster ($M_\odot$)	R_h (PC)	log T_E	Log age
NGC 581	-1.75 ± 0.05	2376	1576	4.2	8.2	7.60
NGC 654	-1.02 ± 0.10	622	688	3.2	7.7	7.18
NGC 869	-1.51 ± 0.08	12786	10470	7.9	8.8	6.75
NGC 884	-1.46 ± 0.02	9585	8187	7.3	8.7	6.50
NGC 2264	-1.65 ± 0.04	964	703	3.2	7.9	7.30
NGC 6530	-1.82 ± 0.12	4277	2740	5.1	8.4	6.30
NGC 6611	-0.96 ± 0.18	883	1524	4.2	7.8	6.74
NGC 6823	-1.37 ± 0.16	3362	3275	5.4	8.4	6.70
NGC 6913	-2.07 ± 0.28	8770	5032	6.2	8.7	7.00
IC 1805	-1.67 ± 0.05	11477	8370	7.3	8.8	6.12
Tr 1	-1.97 ± 0.14	2058	1210	3.8	8.1	7.41

6. Discussion and conclusions

In the present work we have studied the effect of mass segregation on the mass function. We have found that the slope of the mass function is steeper in the outer parts of open clusters NGC 581, 654, 869, 884, 2264, 6530, 6913, IC 1805 and Tr 1. In case of NGC 581, 869, 884, 6530, 6913, Tr 1 and IC 1805 Sagar *et al.* (1988) have also found evidence for the presence of mass segregation. Therefore, one may conclude that mass segregation produces spatial variation in the mass function of a cluster. Since the derived dynamical relaxation time is always larger than the age of the cluster, it is inferred that the observed mass segregation might have taken place at the time of cluster formation. This conclusion is in agreement with the finding of Larson (1982) and Sagar *et al.* (1988). Kholopov (1969) have concluded that a cluster from the time of its formation occupies the volume that is determined by the boundaries of its corona. The corona, which generally contains low mass stars, is inherent in the cluster from the time of its formation and it is not generated by the nucleus but arises simultaneously with the nucleus through the process in which a diffuse cloud is transformed into a star cluster.

The development of mass segregation in the early stages of a cluster's evolution has been theoretically studied by Lada *et al.* (1984) using N body calculations. Their model incorporates a realistic mass function and dissipation of cloud out of which the cluster is formed. The model indicates that as a result of two-body interactions some mass segregations may occur after a time (> 3×10^6 years) substantially longer than that is necessary for gas removal. This time is more than the ages of NGC 6530 and IC 1805 (see table 4). Moreover presence of variable interstellar extinction in these cluster regions (*cf.* Sagar 1987; Pandey *et al.* 1990) suggests that the gaseous matter is still present in these clusters. Therefore, we can conclude that the observed variation in the mass function of young open clusters bears the imprint of star formation process. On the basis of above discussion we conclude that the assumption of no initial mass segregation and of a uniform mass function in an open cluster may not be justified in theoretical studies of dynamical evolution of open clusters.

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