Bull. Astr. Soc. India (2000) **28**, 55-62

Distribution of stellar mass in young star clusters of our Galaxy and nearby galaxies

Ram Sagar

Uttar Pradesh State Observatory, Manora Peak, Nainital 263129, India

Abstract. Stellar mass distribution in young star clusters of our Galaxy, the Magellanic Clouds and the nearby local groups of galaxies has been used to investigate the universality of initial mass function and presence of mass segregation in these systems. There is no obvious dependence of the MF slope on either galactocentric distance or age of the galactic open star clusters. A comparison of initial mass function slopes that have been measured in star clusters and associations of our and nearby galaxies indicates that the slope is independent of the spatial concentration of the star formed, galactic characteristics including metallicity, and at least down to 0.85 $M_{\odot}$, the stellar mass range. Effects of mass segregation have been observed in good number of young stellar groups of our Galaxy and Magellanic Clouds. As their ages are much smaller than their dynamical evolution times, star formation processes seems to be responsible for the observed mass segregation in them.

Key words : Mass functions - star clusters - Galactic disk - Magellanic Clouds - mass segregation

1. Introduction

It is a happy occasion to address the astronomical community during the 19th meeting of the Astronomical Society of India being held at the Raman Research Institute, Bangalore as part of its golden jubilee celebrations. On this occasion, I would like to highlight some of the recent ground based and the Hubble Space Telescope (HST) results related to the studies of spatial distribution of stellar mass in young star clusters and associations of our Galaxy, Magellanic Clouds (MCs) and nearby galaxies.

Star clusters are groups of dynamically associated stars presumably created from the same molecular cloud at about the same time. All the cluster members are therefore located at the same distance, have almost same primordial chemical composition and move together through the star fields of their galaxy. With time, stellar and dynamical evolution take place in the cluster members. Even though the majority of stars probably do form in clusters, their formation

---

e-mail : sagar@upso.ernet.in

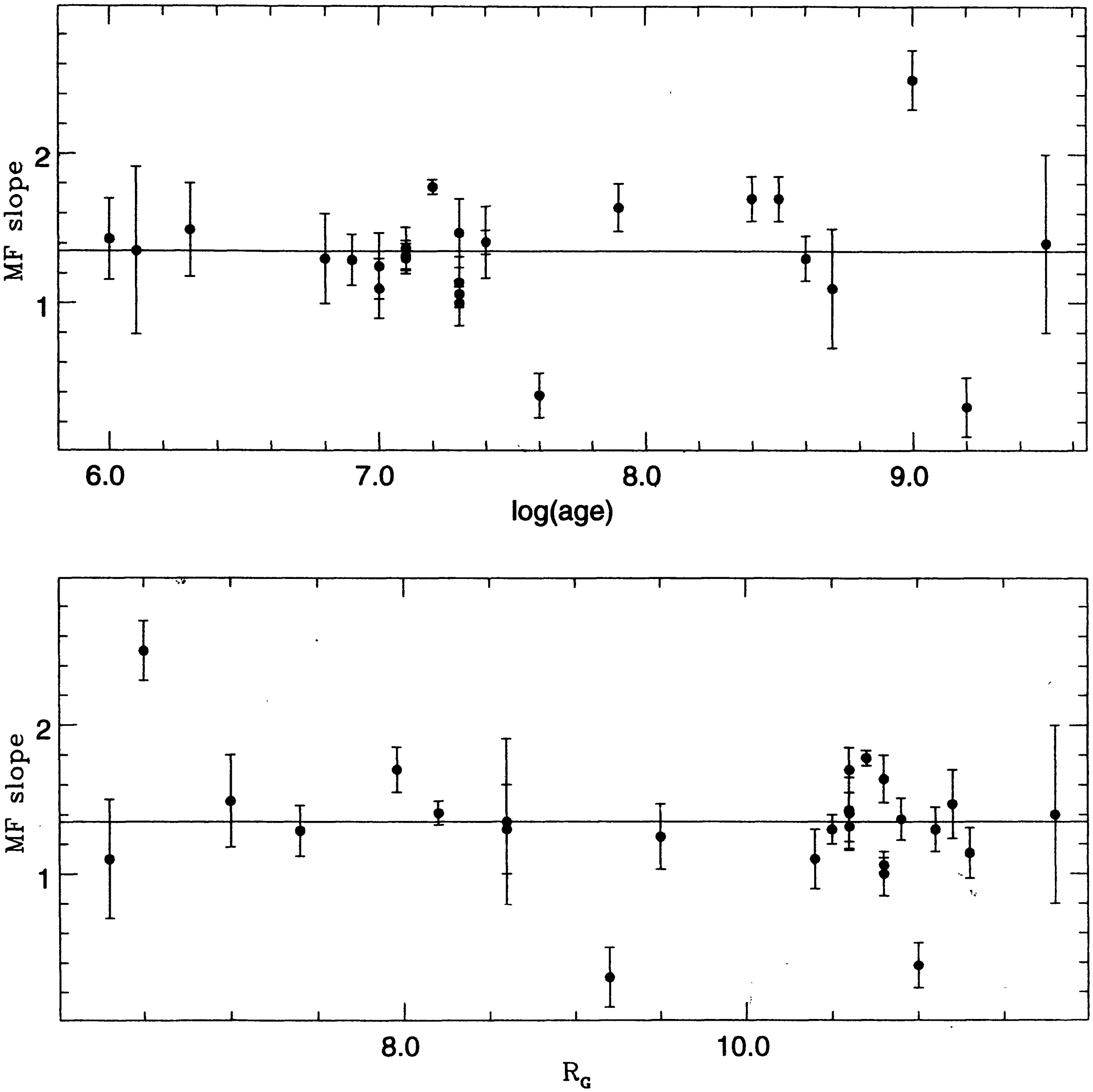
is still poorly understood. For this, a knowledge of distribution of stellar mass in young ($\leq$ 100 Myr) star clusters is desired as they are a fossil records of very complex process of star formation and present the first stage in the evolution of young stellar complexes embedded in dense gas and dust clouds. Due to their small ages in comparison to their dynamical evolution times, the stellar mass distribution in these clusters can provide answers to some crucial questions concerning the universality and shape of the Initial Mass Function (IMF) which is defined as the distribution of stellar mass at birth. Its behaviour as a function of cluster radius helps in understanding the star formation process. Detailed knowledge of the IMF in different environments is crucial for studies that attempt to describe the spectral, photometric, and chemical evolution of integrated stellar systems because mass is one of the primary parameters which dictate the evolution of stars. Knowledge of IMF also provides an important link between the easily observable population of luminous stars in a stellar system and the fainter, but dynamically more important low-mass stars. The IMF is one of the fundamental properties that must be explained by any complete theory of the star formation process (cf. Scalo 1998; Richtler 1994; Larson 1998 and references therein). Knowledge of the spatial variation of MF in young star clusters has an important bearing on their dynamical evolution.

As the evolutionary history of the Magellenic Clouds (MCs) and nearby galaxies has been very different from that of our Galaxy, young stars clusters of these galaxies are not only formed in different environments but also have wide range in metallicity and total mass of the system. A study of stellar mass distribution in these objects can therefore provide the much needed clue for understanding the star formation process. In such studies one would like to know whether all star-forming events give rise to the same distribution of stellar masses or not. How sensitively does the distribution of stellar masses depend on the initial conditions in the natal environment? If the star formation is essentially a self-regulating process, then one might expect the IMF to be strictly universal. Alternatively, if stellar masses are determined only by the physical structure of the interstellar medium (e.g. fragmentation), then one may expect differences in the IMF which depend on local conditions such as cloud temperature etc.

There are, however, observational limitations in defining stellar mass distribution of all mass products of star formation events in young star clusters as star formation is still going on there. As such, the observed mass distribution is only a **snap-shot** of the IMF for the star-forming event, and may not represent the integrated final product of the cloud core. Most of the IMFs discussed here are therefore for mass $\geq 1\ M_\odot$. The observations and procedures used to derive stellar mass distribution are described in the next section, while studies related to its behaviour with environment etc. have been described in the sections to follow.

2. Photometric Observations and determination of stellar mass distribution

For the study of stellar mass distribution in young star clusters and associations, deep and accurate photometric colour-magnitude diagram(CMDs) of their members are essential. Such work could not be done till recently, because most of the earlier observations were, in general, not only restricted to bright stars but also limited in accuracy. The launch of HST in combination with modern CCD detectors and software for doing accurate photometry in crowded regions have made such work possible. In producing the vastly improved CMDs of the crowded regions of star clusters, the software technique used for CCD data reduction shares at least equal responsibility with the linearity, dynamic range and sensitivity of the detectors. Due to superior angular resolution (about 10 times better than ground based observations) capability, CCD observations taken with the HST have been able to resolve stars in extremely crowded regions like central regions of the MCs star clusters and outer regions of young stellar systems located in nearby galaxies M 31 and M 33. The CMDs of such stellar regions have become available to astronomers only recently. This provides a rare opportunity for the study of stellar mass distribution in young star clusters and associations of the Local Group of galaxies.



Figrue 1. Dependence of MF slope on the galactocentric distance, R_G and age of the star cluster of our Galaxy.

In the observed photometric CMDs, main-sequence (MS) stars are identified and their luminosity function (LF) is determined. In determining the true MS cluster LF, field star contamination and data incompleteness should be properly accounted for. Field star contamination increases with decreasing stellar brightness while data incompleteness increases with both increasing stellar crowding and decreasing stellar brightness. The procedures used for their corrections are described in detail earlier by Mateo (1998) and Sagar & Richtler (1991) and recently by Bank et al. (1995) and Sagar & Griffiths (1998). These authors have also discussed the effects of improper correction of these parameters on the true LF of a cluster MS. In order to convert the true LF into the mass function (MF) of a cluster, information about cluster reddening, metallicity and age alongwith the appropriate theoretical stellar evolutionary models are needed. Uncertainties in these parameters as well as in data incompleteness and field star contamination corrections affect determination of the cluster MF slope. For example, it becomes flatter if correction for data incompleteness is not applied, while an ignorance of correction for field star contamination makes the MF steeper. Thus one can say that although both the corrections increase with decreasing stellar brightness, they affect the MF slope in exactly the opposite way.

Despite the difficulties mentioned above, reliable MFs of the young star clusters and associations of our Galaxy, MCs, M 31 and M 33 have been determined recently. In our Galaxy, they are determined for some young star clusters by Sagar et al. (1986), Sagar et al. (1988), Phelps & Janes (1993), Deeg & Ninkov (1996), Forbes (1996), Moitinho et al. (1997), Sagar & Griffiths (1998) and Subramaniam & Sagar (1999). Fig. 1 shows the plot of the MF slope versus galactocentric distance, R_G and age of the clusters. The MF slope, distance and age of the clusters have been taken from their respective photometric studies. In converting distance from geocentric to galactocentric in our Galaxy, distance between the Sun and the galactic centre is taken as 8.8 kpc. The range in R_G is from 6 to 12 kpc, while the ages of the clusters range from 1 to 3200 Myr. The value of the Salpeter (1955) slope is shown as straight line in Fig. 1. The values of MF slopes seem to have no dependence on either R_G or cluster age and all are close to the Salpeter value. A few open clusters, however, seem to deviate significantly for which dynamical evolution rather than intrinsic difference in the IMF of these clusters seems to be responsible, as most of them are older than 100 Myrs. However, more observations and information about the structural and kinematical parameters of the clusters are needed to confirm these findings and also to understand the effects of dynamical evolution on the IMF slope.

Reliable MF slope and cluster age for a number of young star clusters and associations located in MCs, M 31 and M 33 have also been determined recently using both ground based telescopes and HST. These are given in Table 1. The star clusters listed in the table are situated in the different parts of the MCs while the open clusters discussed in the above paragraph are located in the different regions of the galactic disk. Even then, they seem to have MF slopes similar to Salpeter. The MF slopes of young stellar groups determined in nearby galaxies from HST observations indicate that the value of MF slope is 1.4±0.5 in the mass range 7–14 $M_\odot$ for M 31 and 1.6±0.7 in the mass range 8–16 $M_\odot$ for M 33. The IMFs appear to have similar slopes in OB associations of the Milky Way, the LMC and the SMC, with a Salpeter-like slope 1.35 (cf. Massey, 1995a, b). All these demonstrate that whatever it is that controls the star formation processes; there is no distinct difference between resulting MF slopes despite the

Table 1. Mass function slopes of young star clusters and associations determined recently in Magallenic Clouds, M 31 and M 33. Mass range is in solar mass unit while age is in million years.

Object (s)	Mass range	Age	MF slope	Source
	Ground based observations in SMC			
NGC 330		10 – 25	1.35 ± 0.1	Chiosi et al. (1995)
NGC 346		2 – 4	1.3 ± 0.1	Massey et al. (1995a)
	Ground based observations in LMC			
LH 9		1 – 5	1.4 ± 0.2	Massey et al. (1995a)
LH 10		0 – 3	1.1 ± 0.1	Parker et al. (1992)
LH 47	2.0 – 8.0	5 – 6	1.3 ± 0.1	Wills et al. (1998)
LH 58		2 – 4	1.4 ± 0.2	Massey et al. (1995a)
LH 101		2 – 6	1.05 ± 0.12	Testor & Niemela (1998)
LH 104		2 – 6	1.29 ± 0.20	Testor & Niemela (1998)
LH 117/118		1 – 3	1.6 ± 0.2	Massey et al. (1995a)
NGC 1711	2.6 – 8.1	32	1.3 ± 0.3	Sagar & Richtler (1991)
NGC 1818	2.0 – 8.0	40	1.1 ± 0.3	Wills et al. (1995a)
NGC 1962-65-66-70 Ass	1.6 – 20.0	4 – 9	1.06 ± 0.1	Wills et al. (1995b)
NGC 1962-65-66-70 Ass	2.5 – 20.0		1.21± 0.1	Wills et al. (1995b)
NGC 2004	2.6 – 11.9	16	1.0 ± 0.1	Sagar & Richtler (1991)
NGC 2006		23	1.27 ± 0.32	Dieball & Grebel (1998)
NGC 2070	3 – 100	5	1.37 ± 0.08	Selman et al. (1999)
NGC 2164	1.9 – 5.7	63	1.1 ± 0.2	Sagar & Richtler (1991)
NGC 2214	2.1 – 6.5	63	1.1 ± 0.3	Sagar & Richtler (1991)
SL 538		18	1.22 ± 0.31	Dieball & Grebel (1998)
	HST observations in LMC			
NGC 1818	0.85 – 9	20	1.23 ± 0.08	Hunter et al. (1997)
NGC 2004	1 – 10	15	1.0 ± 0.1	Richtler et al. (1999)
NGC 2031	1 – 10	140	1.45 ± 0.2	Richtler et al. (1999)
NGC 2157	0.75 – 5.1	100	1.0 ± 0.3	Fischer et al. (1998)
R 136 in 30 Dor	2.8 – 120	4 – 5	1.35 ± 0.05	Massey & Hunter (1998)
	HST observations in M 31			
OB ass NGC 206	6 – 5	6	1.4 ± 0.5	Hunter et al. (1996a)
	HST observations in M 33			
OB ass NGC 604	6.5 – 18	3 – 5	1.6 ± 0.7	Hunter et al (1996b)

difference of a factor of 10 in metallicity of these systems. Recently Meyer et al.(1999) have discussed the IMF in very young, partially-embedded stellar clusters. They find that the mass distribution of young stars just emerging from different star forming molecular clouds are almost similar and are consistent with having been drawn from the Salpeter IMF. An agreement between the MFs of these various stellar systems supports the idea of some universal IMF as a consequence of star formation process in star clusters and associations.

3. Mass Segregation in young star clusters

Recent ground based as well as HST photometric studies of star clusters of our Galaxy and MCs indicate that massive stars in star clusters tend to form near the cluster centre (Sagar et al. 1988; Pandey et al. 1992; Subramanian et al. 1993; Zinnecker et al. 1993; Fisher et al. 1998; Hillenbrand & Hartmann 1998; Richtler et al. 1998; Sagar & Griffiths 1998; Bonnell & Davis 1998 and references therein). Central concentration of binaries has also been observed in a few star clusters of our Galaxy and MCs (cf. Raboud & Mermilliod 1998; Elson et al. 1998 and references therein). The infrared images of star clusters still embedded in the natal dust/molecular clouds which makes them opaque in visible light show that mass segregation could already be present at the very beginning of the cluster life(Lada & Lada 1991). If these evidences of mass segregation are a reality, then it is important to know whether it is an imprint of the star formation processes itself or it is due to dynamical evolution of the cluster. At the time of formation, if the cluster had a uniform spatial stellar mass distribution, then as the cluster evolves dynamically which leads to equipartition of kinetic energy in cluster members, the spatial stellar mass distribution changes and we would find the massive stars concentrated towards the centre of the cluster, as the low-mass stars attained high velocity and moved away from the cluster centre. The dynamical relaxation time, T_e, is the time in which the individual stars exchange energies and their velocity distribution approaches a Maxwellian equilibrium. A comparison of cluster age with its T_e can therefore indicate whether the location of stars in the cluster is representative of primordial or not. This question may be better answered by studying young star clusters, as their ages are smaller in comparison to their dynamical evolution time. In some such star clusters of our Galaxy as well as in the MCs, effects of mass segregation have been observed recently using ground based and HST photometric observations (Pandey et al. 1992; Subramaniam et al. 1993; Hillenbrand & Hartmann 1998; Fisher et al. 1998; Kontizas et al. 1998; Richtler et al. 1998 and references therein). It has been noticed that effects of mass segregation are not present in all young clusters and the number of galactic clusters showing mass segregation effects are relatively larger in comparison to MC stars clusters. It is presently unknown whether differences in gravitational potentials between the two galaxies are responsible for this or not.

Numerical simulations of the early dynamical evolution of clusters containing a few hundred to a thousand stars indicate that dynamical mass segregation occurs on approximately the cluster relaxation time (see Bonnell & Davies 1998 and references therein). For young star clusters, close gravitational encounters are more important than long-range gravitational relaxation. Numerical simulations that treat close gravitational encounters and binary formation indicate that dynamical evolution is more rapid (by an order of magnitude) than what T_e indicates, and presence of mass spectrum further accelerates the relaxation. In addition, the relaxation time depends upon the location in the cluster and varies with a significant radial gradient through the cluster (for a review see Meylan & Heggie 1997 and references therein). How this affects the cluster structure and hence the dynamical process is not well understood. However, the simulations show that significant mass segregation among the heaviest stars in the core occurs in the local relaxation time but affecting a large fraction of the mass of the cluster requires a time comparable to the average relaxation time averaged over the inner half of the mass. The spatial distribution of members in young clusters (age $<< T_e$) therefore cannot be due to dynamical mass segregation and instead, represent the primordial distribution. Such findings indicate that the assumption of no initial mass segregation used in most of the numerical simulations may not be justified, as they could lead to revision of the effects of timescale of the dynamical evolution.

4. Conclusions

Recent studies of spatial distribution of stellar mass in most star clusters and associations younger than their dynamical evolution time indicate that :

1. The IMF does not vary wildly from region to region having different natal environments, metallicities, etc. though more subtle differences could still exist.

2. In some young star clusters observed mass segregation seems to be the imprint of star formation processes in the clusters. Its absence in some such objects needs further investigations.

3. More observations are desired to ascertain the differences noticed in frequency of young star clusters having mass segregation in our Galaxy and the Magellanic Clouds.

Acknowledgements

Thanks to Drs. T. Richtler and A. K. Pandey for useful discussions and also for reading the manuscript carefully.

References

Banks T., Dood R. J., Sullivan D. J., 1995, MNRAS 274, 1225

Bonnell I. A., Davies M. B. 1998, MNRAS 295, 691

Chiosi C., Vallenari A., Bressan A., Deng L., Ortolani S. 1995, A&A 293, 710

Deeg H. J., Ninkov Z., 1996, A&AS 119, 221

Dieball A., Grebel E. K., 1998, A&A 339, 773

Elson R. A. W., Singurdsson S., Davies M., Hurley J., Gilmore G., 1998, MNRAS 300, 857

Fisher P., Pryor C., Murray S., Mateo M., Richtler T., 1998, AJ 115, 592

Forbes D., 1996, AJ 112, 1073

Hillenbrand L. A., Hartmann L. W., 1998, ApJ 492, 540

Hunter D. A., Baum W. A., O'Neil E. J., Lynds R., 1996a, ApJ 468, 633

Hunder D. A., Baum W. A., O'Neil E. J., Lynds R., 1996b, ApJ 456, 174

Hunter D. A., Light R. M., Holtzman J. A., Lynds R., O'Neil E. J., Grillmair C. J., 1997, ApJ 478, 124

Kontizas M., Hatzidimitriou D., Bellas - Velidis I., Gouliermis D., Kontizas E., Cannor R. D., A&A 336, 503

Lada C. J., Lada E. I.A., 1991, ASP Conf. Ser. 13, 3

Larson R. B., 1998, MNRAS 301, 569

Massey P., Lang C. C., DeGioia-Eastwood K., Garmany C. D., 1995a, ApJ 438, 188

Massey P., Johnson K. E., DeGioia-Eastwood K., 1995b, ApJ 454, 151

Massey P., Hunter D. A., 1998, ApJ 493, 180

Mateo M., 1988, ApJ 331, 261

Meyer M. R., Adams F. C., Hillenbrand L. A., Carpenter J. M., Larson R. B. 1999, in Protostars and planets IV, eds V. Mannings, A. Boss, S. Russell, (Tucson : The University of Arizona Press) (in press) (Astro-ph/9902198)

Meylon G., Heggie D. C., 1997, A&AR 8, 1

Moitinho A., Alfaro E. J., Yun J. L., Phelps R. L., 1997, AJ 113, 1359

Pandey A. K., Mahra H. S., Sagar R., 1991, BASI 20, 287

Parker J. W., Garmany C. D., Massey P., Walbron N. R., 1992, AJ 103, 1205

Phelps R. L., Janes K. A., 1993, AJ 106, 1870

Raboud D., Mermilliod J. C., 1998, A&A 333, 897

Richtler T., 1994, A&A 287, 517

Richtler T., Fisher P., Mateo M., Pryor C., Murray S., 1998, in The Magellanic Clouds and Other Dwarf Galaxies, eds T. Richtler & J. M. Braun, Shaker Verlag p. 285

Richtler T., Fisher P., Mateo M., Pryor C., Murray S., 1999, Preprint

Sagar R., Griffiths W.K., 1991, MNRAS 250, 683

Sagar R., Griffiths W. K., 1998, MNRAS 299, 777

Sagar R., Piskunov A. E., Myakutin V. I., Joshi U. C., 1986, MNRAS 220, 383

Sagar R., Myakutin V. I., Piskunov A. E., Dluzhnevskaya O. B., 1998, MNRAS, 234, 831

Salpeter E. E., 1955, ApJ 121, 161

Scalo J., 1998, ASP Conf. Ser. 142, 201.

Selman F., Melnick J., Bosch C., Terlevich R., 1999, Preprint

Subramaniam A., Sagar R., Bhatt H. C., 1993, A&A 273, 100

Subramaniam A., Sagar R., 1999, AJ 117, 937

Testor G., Niemela V., 1998, A&AS 130, 527

Will J. M., Bomans D. J., de Boer K. S., 1995a, A&A 295, 54

Will J. M., Vāzquez R. A., Feinstein A., Seggewiss W., 1995b, A&A 301, 396

Will J. M., Bomans D. J., Dieball A., 1998, A&AS 123, 455

Zinnecker H., McCaughrean M. J., Wilking B. A., 1993, in Protostars and Planets III. eds. E.Lery & J. Lumine, Univ. Arizona Press p. 429