



The IMF of intermediate-mass stars in young star clusters

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Abstract. A large fraction of stars in a galaxy form in star clusters. Mass function of stars in the star clusters younger than about hundred million years can be considered as initial mass function as these systems are less affected by dynamical evolution. Additionally, the coeval, equidistant and similar chemical composition of the stars in a star cluster offer many advantages in estimating the stellar distribution. In this contribution, we compile and discuss some results on initial mass function derived from ground and space-based observations of young star clusters in the Milky Way and the Magellanic clouds.

Keywords : stars – luminosity function, mass function: galaxies – star clusters: Galaxy – disc: open clusters and associations – general

1. Introduction

Stars rarely form in isolation and the observations suggest that most of the stars in a galaxy form in star clusters or groups (Kroupa 2011, and references therein). The stellar initial mass function (IMF), defined as the frequency distribution of stellar masses that form in one star formation event in a given volume of space, is considered as fundamental property of any stellar population. The IMF is a key observational input to the theory of star formation as well as the evolution of star clusters and the galaxies. The IMF was first introduced and derived by Salpeter (1955) for the Galactic field stars in solar neighborhood. It was characterized in power law form¹ as $dN/dm \propto m^{-\alpha}$, where dN is the number of stars in the mass interval dm at mass m and for the mass range $0.4 - 10 M_{\odot}$, a value of $\alpha = 2.35$ was derived.

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¹Salpeter originally introduced the power law in log-log form as $dN/d \log m \propto m^{-\Gamma}$, where m is the mass of a star and dN is the number of stars in some logarithmic mass range $\log m + d \log m$. In this notation $\alpha = \Gamma + 1$. The index of IMF slope is referred as α throughout this contribution.

About a decade ago, it was recognized that the IMF was probably not a single power law over all stellar masses and it was based on a review of observational IMF of resolved stellar populations (i.e. OB associations, star clusters and young massive star clusters). Scalo (1998) suggested a three-segment power law with α index of 1.2 ± 0.3 for $100 - 10 M_{\odot}$, 2.7 ± 0.5 for $10 - 1 M_{\odot}$, and 2.3 ± 0.5 for $1 - 0.1 M_{\odot}$. Here, the quoted errors take into account the empirical uncertainties, or IMF variations or both. More recently, the IMF was parametrized by Kroupa (2008) as two-segment power law with α index of 2.3 ± 0.5 for $150 - 0.5 M_{\odot}$, and of 1.3 ± 0.3^2 for lower masses up to the hydrogen burning limit $\sim 0.08 M_{\odot}$. These findings are in contrary to the fact that the physical conditions (e.g. temperature, density and metallicity) of star forming environments vary by orders of magnitude and hence theoretically suggesting variation in index of IMF slope from 1 to 4 (Scalo 1998; Larson 1998; Elmegreen 2000). A few recent observations do cast doubts on the universality of IMF in all environments (Elmegreen 2007; Dib et al. 2010). For a recent review on stellar IMF and its variation see Scalo (1998) and Bastian, Covey & Meyer (2010).

Mass function of stars in young star clusters offer many advantages in estimating the stellar distribution as the cluster members can be considered as coeval, equidistant, and having same chemical composition. Furthermore, to estimate IMF of stars in young (< 100 Myr) star clusters, the dynamical effects can be ignored and the present day observed mass function can be considered equivalent to the IMF (see Sagar Sagar 2002). In this contribution, we compile and discuss the mass function studies carried out in the intermediate-mass range $1-20 M_{\odot}$ using photometric investigation of young stellar populations in the Milky Way and the Magellanic Clouds.

2. IMF from observations

For the study of the MF in young star clusters and associations, deep and accurate photometric colour-magnitude diagrams (CMDs) of their members are essential. Sagar (2000) has compiled reliable MFs determined until 2011 and present here the mass function slope for a sample of 56 young clusters (see Table 1). The star clusters have galactocentric distances ranging from 6 to 12 kpc and their ages are below 80 Myr. Ten clusters have double measurements, while two clusters have triple measurements and hence a total of 70 measurements are listed. Barring four, we have uncertainty measurements for all the objects, and the larger uncertainty is due to smaller number of member stars used in the determination of mass function. On the y-axis, Fig. 1 shows the frequency distribution of the MF slope (α) and the mean stellar mass. The mass range over which, the slope has been determined is shown with dotted lines. The points with mean masses less than $20 M_{\odot}$ are denoted with filled circles. For the mass range $1 - 20 M_{\odot}$ (having α range $1.69 - 3.25$), we estimate a mean value of 2.36 ± 0.30 ,

²The uncertainties in α denote 95% confidence limits and it can be accounted (see Kroupa 2001 and references therein) to the Poisson fluctuations, dynamical effects and the unresolved binaries.

for a total of 53 measurements; excluding 4 deviant points, we get 2.35 ± 0.24 . For the full mass range $1-80M_{\odot}$, we get a value of 2.32 ± 0.3 .

Reliable MF slope and cluster age for a number of young star clusters and associations located in LMCs have been determined using both ground-based telescopes and HST, see the compilation of MF slopes by Sagar (2000). We have updated this compilation and the MF slope values for a sample of 26 star clusters are listed in Table 2. The star clusters in the LMC are located in different parts of the galaxy and hence represent different conditions. Preliminary results on this sample is presented in Kumar, Sagar & Melnick (2008). Four clusters of this sample have double measurements. From 21 measurements in the mass range $1 - 20M_{\odot}$ ³ we get a value of 2.16 ± 0.13 , while for the mass range $1 - 80M_{\odot}$, a value of 2.20 ± 0.16 is obtained.

The mean values of α estimated above for MW and LMC seem close to the Salpeter value. A typical scatter in the range 0.1 to 0.3 dex is obtained in the determination of slope. It appears that the value of α is shallower in LMC, however, more data points are needed to confirm this. Variation in IMF slope is also expected to arise due to different reduction and analysis procedures used by different groups, however, this may not have significant contributions as is seen from the typical scatter quoted by other studies in the literature. For example, Piskunov (1976) analyzed the MF slopes of 61 open star clusters and found the average value of $\alpha = 2.3 \pm 0.3$ in the mass range of 1 to $25M_{\odot}$. Observations of 13 and 8 star clusters, Kjeldsen & Frandsen (1991) and Phelps & Janes (1993) derived average MF slopes of 2.3 ± 0.2 and 2.4 ± 0.3 respectively. For some more young star clusters, Subramaniam & Sagar (1999) and Sanner & Geffert (2001) determined an average value of $\alpha = 2.4 \pm 0.3$ and 2.8 ± 0.6 respectively for the MF slope above $1M_{\odot}$.

Before we derive any conclusions from these and the plots in Fig. 1, it is necessary to know the accuracy of MF determinations in young star clusters, which is discussed below.

3. Limitations in the observed IMF

The main factors which limit the precise determination of the young star cluster MF are described below.

Poisson noise: In the observed photometric CMDs, MS stars are identified and their LFs are determined. The inherently small number of stars in star clusters of our Galaxy results in large statistical uncertainties. Such errors are reduced significantly while studying the young MC star clusters as they are rich in stars. Kroupa (2001) has studied such errors using techniques of numerical simulations and found that in the MF slope determination of Galactic star cluster type objects, they introduce a scatter

³The star cluster NGC 1767, having an extreme value of α at 1.23, have been excluded from the analysis.

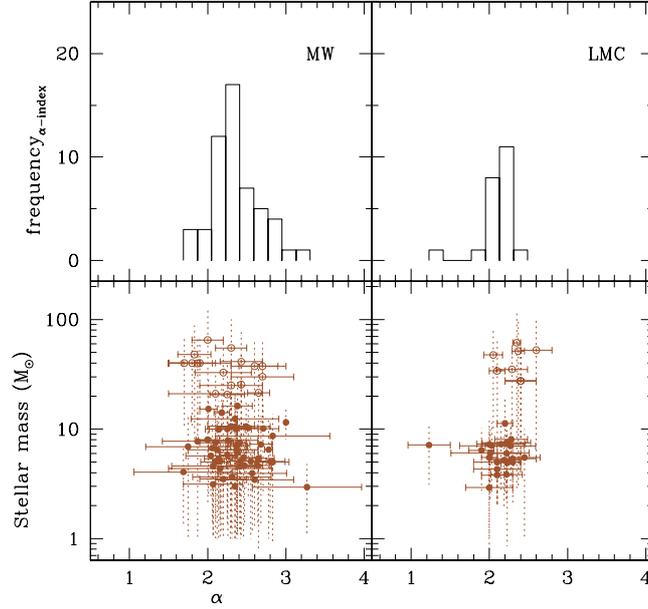


Figure 1. The distribution of α index of the IMF in young stellar populations of the MW (left panels) and LMC (right panels) are shown for a sample of 56 and 26 clusters respectively. The y-axis denote the mean stellar mass (lower) and the frequency of α index (upper). The errors in α indices denote 1σ uncertainty in the determination of IMF slope, while the vertical dotted bars in mass denote the range of stellar mass over which IMF is determined. The samples with mean stellar mass lying in the intermediate mass-range ($1 - 20M_{\odot}$) are shown in filled circles.

of $\sigma_{\alpha} \sim 1$ dex above $1M_{\odot}$. A similar study carried out by Sagar & Richtler (1991) for MC star clusters indicates a comparatively smaller value of $\sigma_{\alpha} \sim 0.4$ dex. The later is consistent with the typical scatter in MF slope found using a large sample of star clusters in MW and LMCs (see §2).

Cluster parameters and MS mass-luminosity relation : The accuracy of distance estimates is $\sim 15\%$ while that of age determination is about 20% in young star clusters. The effects of uncertainty in metallicity (z) and of the MS mass-luminosity relations derived from the different theoretical stellar evolutionary models have been investigated by Sagar & Richtler (1991). It is observed that the MF slope becomes flatter with decreasing value of z . The change in α is ~ 0.1 and ~ 0.3 dex when z varies from 0.02 to 0.004 and from 0.004 to 0.001 respectively. The $z=0.02$ stellar evolutionary models with convective core overshooting and without it can change the value of α by ~ 0.2 dex which can be considered as error introduced due to uncertainty in mass-luminosity relation.

Data incompleteness and field star contamination: In determining the MS cluster LF from the observed photometric CMDs, field star contamination and data incom-

pleteness 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 by Mateo (1988); Sagar & Richtler (1991); Sagar & Griffiths (1998); Banks, Dodd & Sullivan (1995). These authors have also discussed the effects of improper correction of these parameters on the determination of the cluster MF slope. For example, it becomes flatter if correction for data incompleteness is not applied, while the lack 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. The change in MF slope can be significant, if the corrections are large.

Dependence of MF slope on the mass loss rate: In extremely young star clusters, mass loss occurs in massive ($> 20M_{\odot}$) stars. The rate of mass loss can vary from one cluster to another. An analysis carried out by Sagar et al. (1986) for extremely young star clusters indicates that the value of α will decrease with the increase in rate of mass loss and it is found that by neglecting the effects of mass loss on MF determination, one can introduce a maximum error of $\sim 15\%$ where mass loss is important (i.e., in stars with masses $> 20M_{\odot}$).

4. Discussion and conclusions

The inherent uncertainties discussed above clearly indicate that the observational determination of the MF slope of young stellar populations and hence the IMF based on them, can never be determined more accurately than the scatter seen in Fig. 1. The variation in MF slope, if any, is less than the uncertainties discussed in §3.

The young star clusters discussed here are situated in different parts of the MCs while the open star clusters discussed are located in different regions of the Galactic disk. Even then, they seem to have MF slopes similar to the Salpeter value as the mean of α as 2.35 ± 0.24 , and 2.16 ± 0.13 estimated from a sample of 49 measurements of Milky Way, and 21 measurements of Large MC. The mean values of α derived for half a dozen young star clusters in SMC and M33 is 2.33 ± 0.04 and

Table 1. The catalog of stellar mass function slopes for young stellar populations of Milky Way. The complete table is available in electronic form only.

#	Cluster	l ($^{\circ}$)	b ($^{\circ}$)	D_{hel} (kpc)	Age (Myr)	α index	Mass range (M_{\odot})	Ref.
1	NGC 6530	6.1	-1.3	1.3	7	2.49 ± 0.31	2.9 – 18.2	1
2	NGC 6531	7.7	-0.4	1.2	11	2.29 ± 0.17	1.0 – 20.0	2
...
56	NGC 6231	343.5	1.2	1.2	6	2.20 ± 0.36	2.5 – 63.1	28

Table 2. The catalog of stellar mass function slopes for young stellar populations of Large Magellanic Clouds. The complete table is available in electronic form only.

#	Cluster	α_{J2000} (h m s)	δ_{J2000} ($^{\circ}$ ' ")	D_{gal} (deg)	Age (Myr)	α index	Mass range (M_{\odot})	Ref.
1	NGC 1711	4 50 36	-69 59 08	2.672	32	2.3 ± 0.3	2.6 - 8.1	1
2	NGC 1767	4 56 27	-69 24 12	2.149	23	1.23 ± 0.27	3.1 - 11.2	2
...
26	NGC 2214	6 12 58	-68 15 33	4.829	63	2.1 ± 0.3	2.1 - 6.5	1

2.34 ± 0.1 respectively (Sagar 2002). The MF slopes of OB association NGC 206 in M31 determined from HST observations indicate a value of 2.4 ± 0.5 in the mass range 7-14 M_{\odot} (Hunter et al. 1996). The IMF appear to have similar slopes in OB associations of the Milky Way, the LMC and the SMC, with a Salpeter-like slope 2.35 (cf. Massey et al. 1995). Sakhibov & Smirnov (2000) have studied the IMF in star formation complexes in 3 spirals, one irregular and one peculiar galaxy and conclude that the values of α , ranging from 2.06 to 2.57, are close to the Salpeter value. Meyer et al. (2000) 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. Using deep infrared surveys, Muench, Lada & Lada (2000) derived the LF of two extremely young stellar clusters, IC 348 and NGC 2362, in the mass range 10-0.01 M_{\odot} and found that the underlying stellar MFs of these two star clusters are quite similar despite the differences in their apparent star formation rates and massive stellar contents.

All these findings demonstrate that whatever it is that controls the star formation processes; there is no distinct difference between resulting MF slopes despite the difference of a factor of 10 in metallicity of these systems and supports the idea of some universal IMF as a consequence of star formation process in star clusters and associations. We, therefore conclude that the IMF does not vary wildly from region to region having different natal environments, metallicities, etc. though more subtle differences may exist. The inherent uncertainty in the observational determination of MF slope of young star clusters is found to be ~ 0.2 dex.

References

- Banks T., Dodd R. J., Sullivan D. J., 1995, MNRAS, 274, 1225
 Bastian N., Covey K. R., Meyer M. R., 2010, ARA&A, 48, 339
 Elmegreen B., 2000, ESASP, 445, 265
 Hunter D. A., Baum W. A., O'Neil E. J., Jr., Lynds R., 1996, ApJ, 468, 633
 Kjellden H., Frandsen S., 1991, A&AS, 87, 119
 Kroupa P., 2001, MNRAS, 322, 231
 Kroupa P., 2008, ASPC, 390, 3

- Kroupa P., 2011, *Sca..Conf.* 17
Kumar B., Sagar R., Melnick J., 2008, *MNRAS*, 386, 1380
Larson R. B., 1998, *MNRAS*, 301, 569
Mateo M., 1988, *ApJ*, 331, 261
Massey P., Lang C. C., Degioia-Eastwood K., Garmany C. D., 1995, *ApJ*, 438, 188
Meyer M. R., Adams F. C., Hillenbrand L. A., Carpenter J. M., Larson R. B., 2000, *prpl.conf*, 121
Muench A. A., Lada E. A., Lada C. J., 2000, *ESASP*, 445, 301
Phelps R. L., Janes K. A., 1993, *AJ*, 106, 1870
Piskunov V. G., 1976, *SvApM*, 12, 1124
Sagar R., Piskunov A. E., Miakutin V. I., Joshi U. C., 1986, *MNRAS*, 220, 383
Sagar R., Griffiths W. K., 1998, *MNRAS*, 299, 777
Sagar R., Richtler T., 1991, *A&A*, 250, 324
Sagar R., 2000, *BASI*, 28, 55
Sagar R., 2002, *IAUS*, 207, 515
Sakhibov F., Smirnov M., 2000, *A&A*, 354, 802
Salpeter E. E., 1955, *ApJ*, 121, 161
Sanner J., Geffert M., 2001, *A&A*, 370, 87
Scalo J., 1998, *ASPC*, 142, 201
Scalo J., 2005, *ASSL*, 327, 23
Subramaniam A., Sagar R., 1999, *AJ*, 117, 937