THE INITIAL MASS FUNCTION IN YOUNG STAR CLUSTERS

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ABSTRACT. This review discusses both the earlier and the most recent work on the IMF in young star clusters. It is argued that the study of the stellar content of young star clusters offers the best chance of developing a theory of star formation and of the IMF.

1. INTRODUCTION

Over the last few years the Initial Mass Function (IMF) has become more and more of a hot topic mainly due to our increasing knowledge of star forming regions and galactic evolution. Yet the origin of the IMF is poorly understood despite increasing efforts to change this. It is the systematic study of young galactic star cluster, I believe, that holds the greatest promise to make major progress in developing a theory of star formation and the formation of the IMF. Here I define the IMF as the probability distribution for the formation of stars of different mass. In order to justify my claim I note that clusters are stellar aggregates coherent in space and time, while field stars represent a mixture of stars averaged over space and time; thus clusters allow a much more direct insight into star formation processes and the formation of the IMF than do the field stars (whose IMF depends on the previous rate of star formation). Moreover regarding IMF studies, young clusters have an advantage over OB-association, since clusters are gravitationally bound and therefore do not disperse as quickly as OB-associations. These advantages are also noted in a previous review on the IMF of open clusters by Scalo (1978); see also Miller & Scalo (1979, p. 536-38). Other previous reviews include those by Silk (1978) and by Burki (1980) entitled 'Fragmentation of Molecular Clouds' and 'Formation of Open Clusters', respectively.

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2. STELLAR CONTENT OF OPEN CLUSTERS: LUMINOSITY FUNCTION (LF) AND IMF

2.1 Early work on open clusters

The first papers on the observed LF of open clusters were written by Walker (1956), van den Bergh (1957), Sandage (1957) and Jaschek & Jaschek (1957) following the determination of the initial LF of field stars by Salpeter (1955). Roberts (1958) and van den Bergh & Sher (1960) investigated the faint end of the cluster LF ($6<M_V<10$) and found a lack of low-mass stars in the LF of cluster stars compared to that of field stars. This is summarized by van den Bergh (1961) who gave the mean cluster LF of eight clusters (NGC 188, 2477, 2539; M37, M67; Hyades, Pleiades, Praesepe). Because of this low-mass ($M \lesssim 1M_\odot$) discrepancy between the mean cluster LF and the field star LF, van den Bergh (1972) later postulated the ad hoc hypothesis that the LF of star formation is bimodal (see his Fig. 3) consisting of two distinct populations, one derived from the disintegration of open clusters (bound systems) and another derived from associations (unbound systems).

2.2 Effect of mass segregation

Artyukhina (1973) dealt with the intermediate portion ($0 \lesssim M_{pg} \lesssim 6.5$) of some cluster LFs (Praesepe, Pleiades, α Persei) distinguishing between an inner zone (core region) and an outer zone (halo region), a distinction which has become increasingly important in modern studies of mass segregation in young clusters such as the Pleiades or NGC 3532 (van Leeuwen 1980, Gieseking 1981) and its effect on the IMF at low-masses. (see Fig. 1).

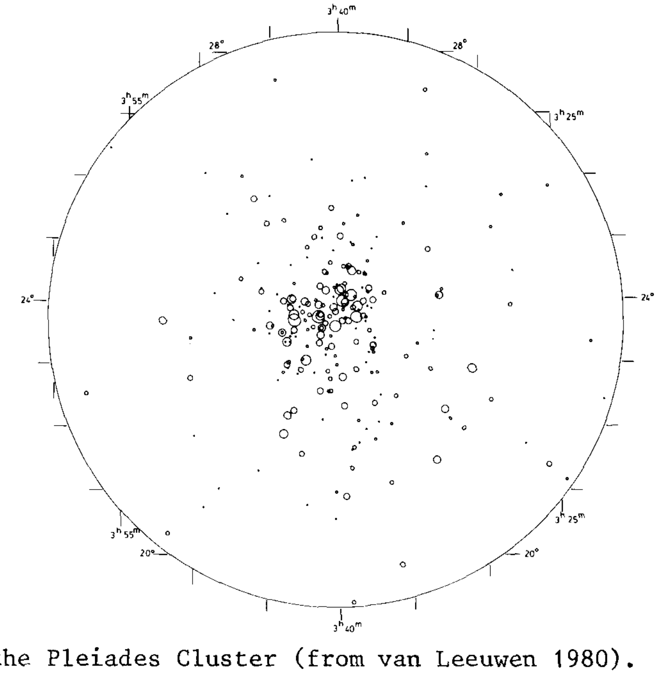

Figure 1: Map of the Pleiades Cluster (from van Leeuwen 1980). The size of the circles is measure of the brightness of the stars.

Although Artyukhina's observations seemed to show that her clusters are complex individual systems, part of the complexity may be due to mass segregation and the earliest non-equilibrium history (Agekyan & Belozerova 1979, Lada et al 1984). If most of the low-mass stars preferentially reside in the cluster halo, the observed deficiency of low-mass stars in some clusters may well be due to the difficulty of detecting them, while older clusters like M67 may have lost their low-mass stars from the halo in the course of time. This latter possibility for M67 has been disputed on the grounds of N-body calculations (Prata 1971) but the problem may be more complicated for at least two reasons:

(a) the low-mass stars can preferentially populate the halo region, because they may have initially formed in the halo region (Kholopov 1969, Larson 1982);
(b) the low-mass stars can preferentially populate the halo region because of inelastic scattering off binaries in the core region (Terlevich 1985) and stay in the halo because of the effect of the galactic tidal torque on the angular momentum of the relatively more distant light stars which prevents them from returning to the central regions (Terlevich 1980). Both, the effect of binaries and the effect of the galactic tidal field, were not taken into account in the M67 model in 1971.

2.3. Composite IMF

In a very comprehensive study, Taff (1974) determined the slope of a composite IMF of 62 open clusters mainly selected on the basis of richness (3 categories) and concentration class (4 sub-classes). He adopted an iterative procedure to correct for incompleteness at the faint end and evolutionary effects at the bright end. Taking the data of all clusters, he obtained a slope x = 1.74 ± 0.07 (well-defined over a mass range 1-10$M_\odot$) emphasising that the small range of values for x in different concentration class groupings would reflect both the universality of the IMF slope and the dominance of the medium rich clusters in each concentration class group (after most of the very rich clusters - 10 out of 13 - had to be rejected from the analysis due to the roughness of the data). Taff's overall cluster slope x = 1.74 cannot be directly compared to the original Salpeter slope x = 1.35 for field stars (originally given for the mass range 0.4-10$M_\odot$) since Taff used a different mass-luminosity relation from Salpeter. Put on the same footing, Taff rederives x = 1.05 for the Salpeter slope which demonstrates that the overall cluster IMF is considerably steeper than the field star IMF. It is also worth noting that Taff's study refers largely to the cluster cores alone (van Leeuwen, priv. comm.). Piskunov (1976) did a similar study of a composite cluster IMF (61 clusters) and obtained x = 1.3 ± 0.14. He made some critical remarks about Taff's work for using old, inadequate bolometric corrections.

2.4. The bright end from two angles

Burki (1977) investigated the bright end of the luminosity function of

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clusters within 2kpc distance of the sun (27 clusters in the range $1 > M_v > -6$ or $2.5M_\odot < M < 60M_\odot$). He claims that the slope of the IMF for large (>8pc) clusters is flatter than for small (<4pc) clusters ($x = 1.0$ as opposed to $x = 1.7$), but it is not sufficiently clear that his results are free from selection effects (clusters with large diameters tend to occur at larger galacto-centric distances, Lyngå 1982; see also Burki 1980). Burki gives a mean slope of $x = 1.2$, but Lequeux (1979) rederives $x = 1.8$ from the same data presumably using a different mass-luminosity relation.

Tarrab (1982) analysed the IMF of 58 clusters divided into 13 age groups by means of the M_v vs $(U-B)_o$ diagrams by counting stars between theoretical isomasses in these diagrams. The mass range considered was $1.25-14M_\odot$ in an attempt to avoid incompleteness at the faint end and evolutionary effects at the bright end. She derived a slope for each individual cluster as well as a mean slope for each age group. The mean slope of the best studied groups for a power-law fit to the IMF is $x = 1.7$, although the mass range is too small to be sure that a power-law fit is indeed significant (this is true for most studies discussed here). Also, the value for x can depend strongly on the lower and upper limit of the mass interval over which the IMF is fitted (e.g. in the case of the Orion cluster x will change from 1.4 to 2.0 if $M = 1.25-14M_\odot$ is narrowed down to $M = 2.5-10M_\odot$).

2.5. Comparison with associations

For comparison, I refer to the work of Claudius & Grosbøl (1980, their Table 1) who give IMF slopes fitted over the mass range 2.5 to $10M_\odot$ for 5 OB-associations ($x = 1.8$ on average) while Scalo (1985) reviewed the observational constraints on the IMF of massive stars in external galaxies (x between 1.3 and 2.3). The pioneering work for the IMF of pre-main sequence (PMS) stars in associations is that of Cohen & Kuhi (1979) yielding $x = 1.35$ for $1.0-2.5M_\odot$ in the Orion-OB1-association (averaged over the sword region of 25 pc diameter) and $x = 1.5$ for $0.35M_\odot-2.5M_\odot$ in the Taurus/Auriga T-association. Time-resolved mass spectra for each association may also be deduced from Cohen & Kuhi's data using evolutionary tracks in the HR-diagram (see Elmegreen 1985).

Since Orion is three times more distant from the Sun than Taurus/Auriga, the results for Taurus/Auriga should be more reliable than those for Orion. Therefore, one must be extremely suspicious about possible selection effects when intercomparing data from Taurus with data from Orion to interpret apparent differences. Nevertheless Larson (1982) made use of Cohen & Kuhi's data to show that the Orion IMF is deficient in very young low-mass stars (i.e. emission line stars) compared to that of Taurus. According to Larson, this difference, if real, may be related to the fact that the most recently formed stars in Taurus are widely dispersed while those in Orion belong to a single concentrated cluster. Larson's empirical results suggest some intriguing conclusions for the origin of the core halo structure of star clusters and the deficit of low mass stars in cluster cores (p.167): the mass spectrum appears to evolve with the evolution of the associated molecular complex with low mass stars forming first in an extended region of scattered gas before the gas can aggregate into a more condensed core with a higher proportion of more massive stars (cf. Elmegreen 1983, Elmegreen & Clemens 1985 and Elmegreen 1985).

2.6. Age spread and non-coeval star formation

Herbig (1962) was the first to realize that not all the stars in a young cluster appeared to have formed simultaneously. One of his arguments was the presence of hot young OB stars and cool old K-giants in the same cluster. Iben & Talbot (1966) and Williams & Cremin (1969) noted that the HR-diagram of young clusters exhibits too much scatter to be fitted by a single theoretical isochrone so they abandoned the view of the simultaneous formation of all member stars. For NGC 2264 they derived an age spread of individual stars of the order of 10 million years which was later confirmed by Warner et al (1977) and by Adams et al (1983); for another cluster see Herbst & Miller (1982). It was also found that there is a mass-age correlation in the sense that many of the low-mass stars formed long before the massive stars. This last point was recently seriously questioned by Stahler (1985) who showed that the correlation seems to be an artifact of assigning PMS contraction ages to all member stars many of which have already reached the ZAMS. Moreover, the claim of an age spread of $\sim$ 100 million years or more in the Pleiades cluster (Stauffer 1980) has not been substantiated, and has been withdrawn (Stauffer 1982).

3. RECENT PROGRESS

3.1. New observational material on the IMF

The most important recent work on the formation of the IMF in a star cluster is that by Wilking & Lada (1983) and Lada & Wilking (1984). They studied the stellar content and the luminosity function of a nearby young cluster - ρ Oph cluster - still embedded in its parent molecular cloud (distance $\sim$ 160 pc). First they mapped the $^{12}C^{18}O$-emission in the ρ Oph cloud and delineated a 1pc x 2pc ridge of gas which forms the centrally condensed core. The gas column densities in this core are extremely high and imply visual extinctions of $A_V \sim$ 50-100 mag; then, based on the distribution of the high column density gas, they selected an 0.5pc x 0.5pc box in order to probe the population of young stars embedded in the dense core. They searched the survey box for infrared sources to limiting magnitude K = 12 and brought the total number of sources up to 44 in this dense core. From the follow-up study of the infrared spectral energy distributions (1-20 μm) of the ρ Oph cluster members, they derived the luminosities of the individual stars which enabled them to assemble the first luminosity function for an embedded cluster. This luminosity function is shown in Fig. 2a for 34 cluster members with well-determined luminosities. For comparison, the luminosity function corresponding to a log-normal IMF (Miller & Scalo 1979) is also plotted and normalized to the observed low-luminosity population.

After correcting for incomplete sampling of the infrared surveys the apparent deficiency of intermediate-to-high luminosity ($L>5L_\odot$) stars in the ρ Oph cluster compared to the IMF is likely to be statistically significant (Fig. 2b). The implications of this gap for theories of star formation and the origin of the IMF have been discussed by Lada & Wilking (1984) and will not be repeated here (see also Wilking 1985).

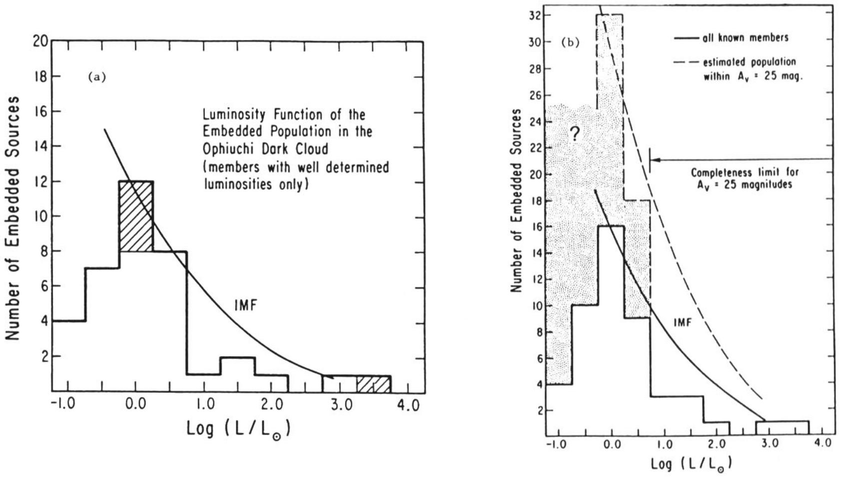

Figure 2: The luminosity function of the embedded ρ Oph cluster (from Lada & Wilking 1984).

It may be of interest that a similar gap (at $4.5M_\odot$) was noted for the cluster IMF of NGC 2264 by Eggen (1976) who, for that matter, first coined the term "bimodal star formation". Similar population gaps in cluster IMFs (at $3\text{-}4M_\odot$) are also advocated by Piskunov et al (1979). Maybe we have to take these gaps seriously.

More work on embedded clusters is in progress: Taylor & Storey 1984 on the R Corona Austrina dark cloud, Churchwell & Koornneef 1986 on the Serpens molecular cloud core, Koornneef 1985 on the Ara region and Allen 1985 on the Kleinmann-Low nebula in Orion (cf. Lonsdale et al 1982).

The embedded population of T-associations is also under investigation (deep 2 μm survey of the Chamaeleon I dark cloud by Jones et al 1985, IRAS survey of the Taurus/Auriga complex by Harris 1985). In the visible, the faint stellar content of an OB-association, i.e. the Barnard Loop region, is being investigated by Isobe (1985) and collaborators using UBV Kiso Schmidt plates and a computerized image detection system.

Another very important recent work is by Sagar et al (1985), and is on the mass and age distributions of stars in 11 young visible open clusters. The reason why this work is so highly regarded lies in the fact that it is based on a highly homogeneous set of photoelectric data (UBV) as well as on reliable cluster membership (for 9 out of the 11 clusters the sole membership criterion is proper motion). The method used to determine the IMF is star counts between isomasses in the HR-diagram, i.e., a conversion from the observed colour-magnitude plane into the theoretical log T_{eff} - log $L/L_{\odot}$ plane is involved (rather than a luminosity function and a mass-luminosity relation). As a result, Sagar et al conclude that the slope of the IMF in five young and well populated clusters is approximately the same, the average value being x =1.4 (NGC 581, 2264, 6530, 6913, 1805; the fits cover different mass ranges, but the lower limit always exceeds $1.25M_{\odot}$). In addition, the slopes of the IMFs do not vary significantly with galacto-centric distance (contrary to Burki's 1977 finding), although two inner clusters (NGC 6611, NGC 6823) have a rather flat IMF (x = 0.85 for $M>8M_{\odot}$).

Again, the above results refer only to the cores of open clusters. (It would generally be useful if authors always gave the angular diameter out to which they study a particular cluster). I mention in passing the work of Cayrel de Strobel & Delhaye (1983) who have started to re-investigate the four nearest open clusters: Ursa Major, Hyades, Coma Berenices, and the Pleiades. They have determined the new main sequences of all the four clusters which allowed them to construct empirical luminosity functions for the bright M_V range -1 to 7. The U Ma cluster seems to be different from the others. Obviously, the availability of proper motion results from automated plate measuring machines such as COSMOS would give a big boost to studies of the faint end of the main sequence luminosity function in nearby open clusters.

3.2 A little bit of IMF theory

Miller & Scalo (1979, p. 538-40) have discussed several theoretical fragmentation and fragment interaction models for the IMF which are principally applicable to star clusters rather than field stars. Since then, a few new ideas on the formation of the IMF in a cluster have emerged (see below but see also the discussion in Lada & Wilking 1984, their section IVc). It is fitting, however, to pay tribute at this point to two astrophysicists from the University of Delhi who, in 1954, devised the first theory of the IMF in an article to Nature entitled "Random Fragmentation". The authors were Auluck & Kothari, and their theory was later compared with observations of the IMF in the Hyades cluster (Kushwaha & Kothari 1961, Kushwaha also from the University of Delhi) for which good agreement was found. This is quite surprising, given that the model was just a geometrical idea without any physics in it. The model considered the case of subdividing a homogeneous parallelepiped (idealized cloud) by randomly chosen planes parallel to the faces and derived a distribution of the resulting volumes (= masses). An illustration is given in Fig. 3. In the same Figure, that model is contrasted with a sketch of hierarchical fragmentation - a physical idea that came up at nearly the same time (Hoyle 1953) but was not cast into a theory of the IMF until I did my thesis (Zinnecker 1981; see also Zinnecker 1984, Elmegreen & Mathieu 1983, and the review by Elmegreen 1985). Note that in both types of models displayed the final sub-system (star) is a fraction of a fraction (etc.) of the original system (cloud), although the efficiency of star formation is greatly different (100% versus a few %). The multiplicative nature is quite evident for the hierarchical picture, but one can visualize the factorisation in Auluck & Kothari's model as well when one tries to imagine to cut the planes

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one after the other (rather than to have them cut all simultaneously) thereby watching the splitting of a given sub-system. Thus, in both types of models star formation is a random multiplicative process involving several factors or steps (Elmegreen 1985, Zinnecker 1985). Such a multiplicative process is probably a rather general prerequisite to get a large spread in size or mass (as there is for stellar masses).

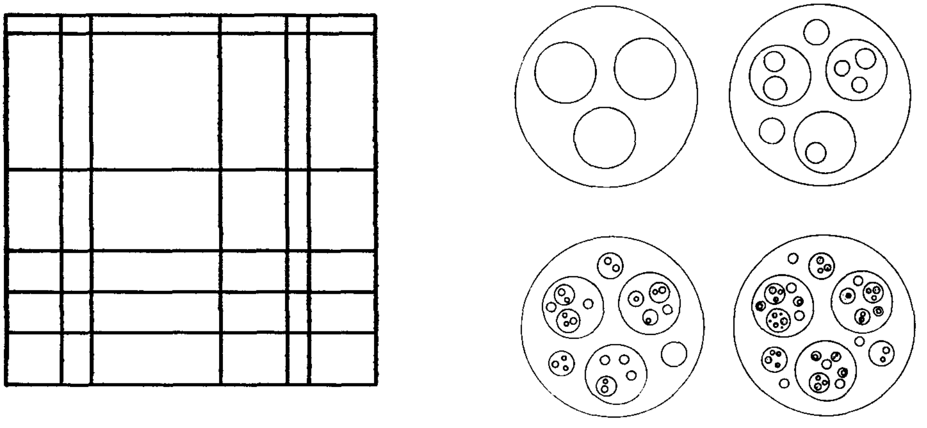

Figure 3: Illustration of random multiplicative fragmentation Auluck & Kothari (left), Elmegreen/Zinnecker (right).

If fragmentation can only proceed in a hierarchical manner as long as a cloud is able to cool (Larson 1985), a more general random multiplicative process might still prevail in the isothermal cloud phase. The random variables would then be the initial conditions entering the Jeans mass or a similar multiplicative expression (density, temperature, angular momentum, etc; Zinnecker 1985). Another conceivable pair of random variables could be the protostellar accretion rate $\dot{M}$ and, independent of the rate, the actual time Δt for accretion (which may be given by environmental events). Then the stellar mass $M_* = \dot{M}\,\Delta t$ is again a product of random variables, which may easily cover a range of a factor 100 in mass. Accretion of gas left over from star formation in a cluster is a further possibility to influence the IMF, particularly attractive to explain an IMF gap - if there is one - of intermediate mass stars (Zinnecker 1982) and a lack - if there is one - of low mass stars in some clusters (Smith 1985). More importantly, I think, one must explain the slopes of the IMF in the clusters! Which theory is able to predict slopes $x = 1.5 \pm 0.3$? I will discuss two candidate models. Coagulation theory, in which fragment-fragment collisions occur, has long been favoured, because in such a model the mass distribution converges to a self-similar power-law form independent of the initial fragment mass distribution (Silk & Takahashi 1979, Pumphrey & Scalo 1983).

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However, other authors (Yoshii & Saio 1985, Lejeune & Bastian 1985) find coagulation to be unimportant, either because the collision cross section for opacity-limited fragments is too small or because optically thin fragments collapse onto themselves too quickly before they have a chance to suffer a few collisions. Therefore, the situation seems inconclusive at present, although I feel that Pumphrey & Scalo is still the most realistic model, since their N-body simulation of fragments moving in a cluster is self-consistent.

A different kind of interaction model is the energy feedback model (Silk 1977, Yoshii & Saio 1985) in which the heat input from a previous generation of protostars affects the fragmentation process of the next generation, mainly due to the rise in temperature (see also Silk 1985). The conditions under which the feedback mechanism works are discussed in Yoshii & Saio. In this model the IMF slope is largely determined by the slope of the mass-luminosity relation L(M) for protostars, and Yoshii & Saio indeed predict $x = 1.5 \pm 0.3$ for $L(M) \propto M^{3 \pm 0.3}$ [equ. (44)]. Although this may still not be the final answer, it is the right moment to stop.

4. CONCLUSIONS

Open clusters are an ideal place to study the formation and evolution of the IMF. However, there are observational selection effects which must be eliminated. The most serious of these seems to be mass segregation, i.e., the faint stars are preferentially found in the halo of the cluster where they are difficult to detect (e.g. the Pleiades). This can lead to an apparent turn-over of the IMF at low masses ($M \lesssim 1M_\odot$). For higher masses ($M \gtrsim 1M_\odot$) the slope is rather universal ($x = 1.5 \pm 0.3$), and any differences may be mostly due to uncertainties in the mass-luminosity relation or errors in the transformation from colour-magnitude diagrams into HR-diagrams. A theory which could at the same time account for the observed slope as well as for the observed core-halo structure would probably have to combine Larson's picture of cloud evolution with feedback models of protostellar heat input. Such a scenario could also be consistent with the high overall star formation efficiency required to keep the cluster bound after the residual proto-cluster gas has been dispersed.

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