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SOME PROCESSES INFLUENCING THE STELLAR INITIAL MASS FUNCTION

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ABSTRACT. Current evidence suggests that the stellar initial mass function has the same basic form everywhere, and that its fundamental features are (1) the existence of a characteristic stellar mass of order one solar mass, and (2) the existence of an apparently universal power-law form for the mass spectrum of the more massive stars. The characteristic stellar mass may be determined in part by the typical mass scale for the fragmentation of star forming clouds, which is predicted to be of the order of one solar mass. The power-law extension of the mass spectrum toward higher masses may result from the continuing accretional growth of some stars to much larger masses; the fact that the most massive stars appear to form preferentially in cluster cores suggests that such continuing accretion may be particularly important at the centers of clusters. Numerical simulations suggest that forming systems of stars may tend to develop a hierarchical structure, possibly self-similar in nature. If most stars form in such hierarchically structured systems, and if the mass of the most massive star that forms in each subcluster increases as a power of the mass of the subcluster, then a mass spectrum of power-law form is predicted. Some possible physical effects that could lead to such a relation are briefly discussed, and some observational tests of the ideas discussed here are proposed.

1. Introduction

A major goal of studies of star formation is to understand the spectrum of masses with which stars are formed, since this is of fundamental importance in many areas of astronomy. It has, however, become increasingly clear that the initial mass function (IMF) of stars depends on many complex and still poorly understood processes, and it may even be that processes not yet recognized will turn out to be important. Therefore it is not yet possible to enumerate or discuss with any confidence all of the processes that may play a role in determining the IMF. Many theories have of course been proposed; these have been reviewed a number of times, for example by Miller and Scalo (1979), Elmegreen (1985), Larson (1986b, 1989), and Zinnecker (1987, 1989), and for the most part they will not be reviewed again here. Instead, I shall first summarize what seem to be the essential features of the IMF that need to be understood, and then I shall briefly mention some possible approaches to understanding these properties, with emphasis on the relevant evidence and on further observations that may help to clarify the processes involved.

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2. Some Basic Properties of the IMF

The observational evidence on the stellar IMF has been summarized in extensive reviews by Miller and Scalo (1979) and by Scalo (1986), and further reviews of some of the evidence have been given by Larson (1986b), Rana (1987), Scalo (1987, 1990), and Zinnecker (1987). The most familiar and well-established property of the IMF is that, at least for stars more massive than about one solar mass, it can be approximated by a power law; within the uncertainties, the slope of this power law appears to be much the same everywhere, and it is similar to but probably somewhat steeper than the slope originally found by Salpeter (1955). If we define the IMF as the number of stars formed per unit logarithmic mass interval, and if for masses above one solar mass we approximate this function by

$$dN/d \log m \propto m^{-x}$$

where m is the stellar mass, then the value of the exponent x, according to Scalo (1986), is 1.7 ± 0.5. This is somewhat larger than Salpeter's value of 1.35, although the uncertainties remain large and Salpeter's slope is not yet excluded. All of the systems for which extensive direct star counts exist, including the solar neighborhood (Scalo 1986), nearby galaxies (Freedman 1985), and star clusters in our Galaxy and the Magellanic Clouds (Mateo 1988, 1990), show a very similar form for the upper IMF, and there is at present no convincing evidence for any variability in its slope.

A second basic and apparently general feature of the IMF is that it does not keep rising indefinitely with the same slope toward smaller masses, but instead falls well below an extrapolation of the above power law at masses less than about 0.5 solar masses. According to Miller and Scalo (1979), the IMF for solar neighborhood field stars becomes approximately flat ($x \sim 0$) at the smallest masses, while according to Scalo (1986), it has a peak at a mass near 0.25 solar masses and drops steeply toward lower masses. Although the IMF for the least massive stars remains particularly uncertain because of the poorly determined mass-luminosity relation for faint stars, and although some continuing increase of the IMF toward smaller masses is possible (Zinnecker 1987, 1989), it nevertheless appears that the IMF does not rise much, if at all, in the region from several tenths of a solar mass down to the hydrogen-burning limit at 0.08 solar masses. Unless it turns sharply upward again at yet lower masses, for which significant data do not yet exist, there cannot be much mass in stars of very small mass or “brown dwarfs”. In fact, no evidence has yet been found for the existence of large numbers of brown dwarfs, despite extensive searches. If there is indeed very little mass in such objects, this would have the important implication that the typical mass with which stars form is not much smaller than one solar mass.

The upper and lower parts of the IMF for solar neighborhood field stars can be properly matched together only if an assumption is made about the past history of the star formation rate. It has been conventional to assume a constant star formation rate, but models of galactic evolution have also been proposed in which the star formation rate decreases strongly with time; in the latter case, the inferred IMF does not decline monotonically with mass near one solar mass but has a second peak just above one solar mass. Models of this type with a double-peaked or “bimodal” IMF might account for the unseen mass that has been thought to exist in the solar neighborhood, since they predict a substantial amount of mass to be in the form of stellar remnants (Quirk and Tinsley 1973; Larson 1986a). However, recent data and analyses imply a smaller surface density of mass in the local Galactic disk than had been found in earlier studies, and together with increased estimates of the amount of mass in visible stars and gas, these results no longer leave much room for any unseen mass (Kuijken and Gilmore 1989; Gould 1990). This is a very important finding, if correct, since it implies that neither brown dwarfs nor stellar remnants can constitute a large fraction of the mass in the local Galactic disk, and consequently that neither the lower nor the upper end of the IMF can ever have been greatly enhanced above the standard form discussed above. Any bimodality of the IMF is therefore strongly constrained by these results, and in particular the model of Larson (1986a) now seems excluded by them; instead, the current data seem consistent with a relatively simple and conventional model of galactic evolution in which there has been only a modest decline of the star formation rate with time (Larson 1990b).

It is worth noting that similar constraints are also placed on the IMF in other stellar systems by recent studies of their dynamics, which have generally yielded relatively small mass-to-light ratios. For example, studies of the mass distributions in the disks of other spiral galaxies have found mass-to-light ratios of the order of 2.5 or less which are similar to that of the local Galactic disk, and which again leave little room for unseen mass (Kent 1986,1987; Athanassoula, Bosma, and Papaioannou 1987). Also, the best-studied globular clusters have mass-to-light ratios that are very similar to each other and that mostly lie between 1.0 and 1.5, consistent with the directly observed stellar content of these clusters and arguing against any large variations in at least the upper part of the IMF, which would influence the mass-to-light ratio through a varying content of stellar remnants (Pryor *et al.* 1989). Thus, the current evidence supports a considerable degree of universality in the basic form of the IMF, and it also demonstrates that the processes that determine this apparently universal form operate even on the scale of individual star clusters.

It remains possible that there is some variability in the lower part of the IMF, even if at a more modest level than in the various "bimodal star formation" hypotheses that have been considered. For example, there is some evidence for differences in the mass spectra of the T Tauri stars in different regions of star formation, as was discussed by Larson (1982); in the Taurus clouds the median mass of the known T Tauri stars is about 0.6 solar masses, while in the Orion cloud it is about 1.1 solar masses (Larson 1986b). A possibly related difference between these two regions is that in the Taurus clouds the young stars are distributed in scattered small groups, whereas in the Orion cloud they are more concentrated into a single large cluster. Additional evidence for differences in the mass spectra of T Tauri stars in different regions of star formation and for possible correlations with cloud properties has been presented at this meeting by P. C. Myers. There may be a correlation between the typical masses of newly formed stars and the typical masses of the clumps in the associated molecular clouds, and the typical clump mass may in turn correlate with cloud mass; this is suggested by the fact that the Orion cloud, which is by far the most massive nearby star forming cloud, contains the most massive clumps and also seems to be forming stars with the largest typical mass. It is not yet entirely clear whether the apparent deficiency of low mass stars in the Orion cloud compared with other regions is real or is just due to incomplete sampling of the least massive stars, owing to the relatively large distance and high opacity of the Orion cloud; in any case, a real turndown in the mass function at the smallest masses is suggested by the steep drop at faint magnitudes in the K-band luminosity function of the Trapezium cluster (McCaughrean et al. 1990; H. Zinnecker, private communication). A similar deficiency of faint stars may also be present in the young cluster NGC 2023 in the Orion B cloud (DePoy *et al.* 1990).

Another difference in the observed mass spectra of young stars in different star forming regions is that the mass of the most massive star in each cloud or complex increases systematically with the mass of the cloud, varying approximately as the 0.43 power of cloud mass (Larson 1982). This result is consistent with, and in fact adds support to, the existence of a universal power-law form for the upper part of the IMF; however, it also implies that the most massive stars do not form in random locations but only in the most massive aggregates of gas and young stars. The most massive stars also appear to form preferentially in the dense core regions of these massive star forming complexes; the Trapezium stars in Orion provide a well-known example. These properties of star forming regions suggest that the upper part of the IMF is built up systematically in a way that depends on the total amount of matter present as well as on the spatial structure of the system (see Section 4).

Summarizing the evidence that has been discussed, I conclude that there are two principal facts to be explained about the IMF: (1) There is a characteristic mass scale for star formation that is of the order of one solar mass; defined as the mass such that half of the matter condensing into stars goes into less massive stars and half into more massive ones, this characteristic mass is within a factor of 2 of one solar mass. (2) The IMF has an extended tail toward larger masses that is approximately of power-law form, with an apparently universal slope of $x = 1.7 \pm 0.5$. Both the characteristic stellar mass and the slope of the power law may vary to some extent with location, but such variations appear not to be large. In the following sections, I shall review briefly some possible ways of trying to understand these basic properties of the IMF, and also some relevant types of observations that could help to clarify the physical processes involved.

3. The Mass Scale for Star Formation

A classical and well-known mass scale that is presumably relevant to star formation is the Jeans mass, which is the minimum mass that a cloud fragment must have in order for its gravity to dominate over thermal pressure at a given temperature and density. The validity of the Jeans criterion as originally derived has always been somewhat questionable, since the Jeans analysis is inconsistent in neglecting the collapse of the postulated initially nearly uniform medium as density fluctuations begin to grow in it. A more rigorous and probably more relevant stability analysis which predicts a similar critical mass can be made if it is assumed that the initial state of a fragmenting cloud is, instead of a uniform medium, an equilibrium sheet, disk, or filament (Larson 1985). These latter configurations all have qualitatively similar dispersion relations, which imply in each case a well-defined characteristic length and mass scale for fragmentation; this is true even in the presence of rotation and magnetic fields, which act primarily to reduce the growth rate but do not change the basic length or mass scales involved. The predicted fragmentation scale depends on two readily measurable parameters, namely the temperature and the surface density of the fragmenting cloud, so it is easy to calculate a characteristic mass scale for fragmentation in star forming clouds, provided that these clouds are not far from being in hydrostatic equilibrium locally.

A variety of numerical simulations of the fragmentation of collapsing clouds have yielded results that are in general agreement with the above predictions. The relatively crude simulations by Larson (1978) of the fragmentation of rotating collapsing clouds showed that the number of objects formed was comparable to the number of Jeans masses in the initial cloud; however, fragmentation did not actually become pronounced in these simulations until the cloud had flattened to a disk, and the results were also roughly consistent with the predictions for the fragmentation of disks (Larson 1985). More detailed simulations of the fragmentation of rotating collapsing clouds by Miyama, Hayashi, and Narita (1984) again showed marked fragmentation following the collapse of the cloud to a disk, and in this case a larger number of fragments was found for similar initial conditions, in better agreement with the theory. Analytic and numerical studies of the fragmentation of non-rotating sheets and filaments by Miyama, Narita, and Hayashi (1987a,b) suggest that fragmenting sheets may first tend to break up into filaments, such as are often seen in star forming clouds, and that the filaments may then fragment into clumps. The most recent simulations of the fragmentation of rotating collapsing clouds by Monaghan and Lattanzio (1990) include a proper treatment of gas cooling, and they show the formation of a network of filaments and voids reminiscent of those obtained in cosmological simulations; they also show the formation of dense knots at the intersections of the filaments. Lattanzio, Keto, and Monaghan (1990) suggest that these results may be able to explain the ring-like distribution of massive young stars seen in W49A. In all of these numerical investigations, there appears to be a fairly well-defined characteristic mass scale for fragmentation, a result which is in at least qualitative agreement with the theoretical expectations.

Nevertheless, it may still be questioned, given the obvious complexity in the structure and dynamics of molecular clouds, whether stability analyses and collapse simulations such as those discussed above really provide an accurate description of how star formation is initiated and how a characteristic stellar mass comes about. A more general approach to estimating a mass scale for clump formation, which again leads to essentially equivalent results, is to suppose that clumps form, whether dynamically or quasi-statically, in approximate pressure balance with the ambient molecular cloud; if the internal pressure in the clumps is predominantly thermal, the minimum mass that a clump must have in order for gravity to dominate over pressure is then

$$M_{\mathrm{crit}} \sim c^4 / G^{3/2} P^{1/2},$$

where c is the sound speed and P is the ambient pressure. Here the relevant ambient pressure is the total pressure acting to support the molecular cloud against gravity, and in general it includes thermal, turbulent, and magnetic contributions; on large scales, turbulent and magnetic pressures dominate, while on the smallest scales thermal pressure is dominant (Larson 1981; Myers 1983). The scaling relations that appear to hold between the sizes, densities, and internal turbulent velocities of molecular clouds imply that the supporting pressure is of similar magnitude in different clouds and in different parts of clouds, possibly reflecting a tendency toward general pressure balance; for example, if the supporting pressure is largely magnetic, then the data imply a nearly constant magnetic field strength (Myers and Goodman 1988). If the associated typical pressure in molecular clouds is substituted into the above relation along with a typical sound speed of 0.2 km/s, the minimum mass predicted for bound clumps is about one solar mass. The fact that this predicted mass scale for clump formation is essentially the same (within perhaps a factor of 3) as the observed characteristic stellar mass suggests that stellar masses may be determined, at least in part, by the mass scale for clump formation in molecular clouds.

A different view has been advocated by Shu and Terebey (1984), Shu, Adams, and Lizano (1987), and Shu et al. (1988). These authors argue that since the clumps or cloud cores in which stars form are not sharply bounded but merge smoothly with their surroundings, a forming star would continue to accrete matter and grow almost indefinitely in mass if the accretion process were not somehow shut off, for example by a stellar wind; they suggest, moreover, that the typical stellar mass is determined by the effect of winds in stopping accretion, and not by any property of star forming clouds. In this view, the onset of a stellar wind is assumed to be associated with the beginning of deuterium burning in a forming star, although it is not clear that deuterium burning is actually responsible for initiating winds, or even that a wind will necessarily stop accretion (Stahler 1988; Zinnecker 1989). Stellar winds probably do play a role in limiting the accretional growth of embryonic stars, but other effects may also act to prevent the accretion of the outer part of a cloud core by a forming star. Outside the thermally supported inner region of the core, which has the mass discussed above, magnetic fields and turbulence dominate the dynamics and may tend to inhibit further infall (e.g. Mouschovias 1987); tidal forces may also limit the amount of mass that can be accreted (Zinnecker 1989), and it even seems possible that in some star forming regions the outer parts of cloud cores may be ablated away by large-scale gas flows. Clearly, it is difficult to predict exactly how much of the core mass will end up in a star, since this depends on various intricacies of the dynamics of the accreting gas that are not yet well understood.

In any case, the question of whether stellar masses depend on cloud properties can be addressed observationally, given sufficiently good data. If typical stellar masses depend on the properties of star forming clouds, the lower part of the IMF might be expected to vary between different regions of star formation. For example, if the typical stellar mass depends on the mass scale for fragmentation, and if this in turn depends most importantly on cloud temperature, as suggested by Larson (1985), then warmer clouds might be expected to form stars with higher typical masses. Such a difference may exist between the Orion cloud and other nearby star forming clouds, as was noted in Section 2, although more data are needed to confirm this possibility. Continuing studies of the stellar content of star forming regions, particularly at infrared wavelengths, will help to provide better answers to such questions.

4. The Origin of the Power-Law Upper IMF

Unlike the lower part of the IMF, the upper part shows no evidence for any preferred mass. Instead, for the larger stellar masses there is approximately a constant *ratio* between the numbers of stars formed in adjacent logarithmic mass intervals: for example, the number of stars formed per unit logarithmic mass interval decreases by about a factor of three for each factor of two increase in stellar mass. This suggests that the upper part of the IMF may be generated by processes that operate similarly on different mass scales. Many ideas have been proposed about how to account for a scale-free upper IMF of the observed form, and a few of the possibilities are mentioned below.

Recent observations of the clump mass spectrum in several large molecular clouds have yielded results that are fairly similar and are approximately of power-law form; for example, in the M17 cloud the clump mass spectrum is approximately a power law with $x \sim 0.7$, which is similar to the form predicted by coagulation theories of clump growth (Stutzki and Güsten 1990). If each clump forms one star, and if there is a relation between clump mass and stellar mass such that the efficiency of star formation decreases with increasing clump mass, then the clump mass spectrum may translate directly into a stellar mass spectrum of the observed form (Zinnecker 1989). However, it is not clear that there is such a direct relation between the clump mass spectrum and the stellar mass spectrum, since it has not yet been shown that there is a one-to-one correspondence between clumps and stars, or that there is a relation of the required form between clump mass and stellar mass. In fact, reality is almost certainly more complicated than such a simple picture, since we have seen evidence that at least the most massive clumps may form not just single stars but entire groups or clusters of stars, and it is possible that most stars actually form in such groups or clusters. If this is the case, then in order to understand the upper IMF, it is necessary to understand the processes that control the way in which matter is apportioned among the stars in a forming system of stars.

A possible way to generate a scale-free upper IMF in a forming system of stars is via the continuing growth in mass of the stars by gas accretion at a rate varying as a power of the stellar mass. Accretion was found to play an important role in building up the masses of the most massive objects obtained in the fragmentation simulations of Larson (1978), and circumstantial evidence that accretion is important for the formation of massive stars is provided by the fact that these stars appear to form preferentially in dense cluster cores, where conditions for continuing accretion are likely to be especially favorable (Larson 1982). If the accretion rate is proportional to a power of the stellar mass greater than unity, then an extended power-law tail is built up on any initially peaked mass distribution. For example, if the accretion rate is proportional to the square of the stellar mass, as in classical accretion theory, then a power-law upper IMF with a slope of $x = 1$ is generated (Zinnecker 1982); this is similar to, but not quite as steep as, the observed upper IMF. A steeper IMF would result if the accretion rate were proportional to a higher power of the stellar mass. Since the accretion rate increases with increasing gas density and with decreasing relative velocity between the accreting object and the ambient gas, a stronger dependence of the accretion rate on stellar mass would result if the more massive objects were preferentially located in denser regions or were moving more slowly with respect to the ambient gas. Correlations of this sort between the masses of newly formed stars and their locations and motions in young clusters are in fact suggested by the observational evidence, and they are also to be expected theoretically as a consequence of gravitational drag effects, as discussed below.

Considerable evidence, much of it obtained only recently with infrared array cameras, suggests that many and perhaps most stars, even of low mass, actually form in compact groups or clusters deeply embedded in dense molecular cloud cores. Some of this evidence has been presented and discussed at this meeting by E. A. Lada and by K.-W. Hodapp, and a review of some of the early results obtained with infrared arrays has been given by Gatley, DePoy, and Fowler (1988). Some well-known examples of compact young clusters that are still partly embedded in molecular cloud cores are the Trapezium cluster in the Orion A cloud (Herbig and Terndrup 1986) and the ρ Ophiuchi cluster (Wilking, Lada, and Young 1989). An infrared photograph of the Trapezium cluster obtained by McCaughrean (1989) shows clearly the extremely high central density of this cluster and also its symmetrical and centrally concentrated structure, which is less apparent at visible wavelengths where part of the cluster is not seen. Particularly striking is the presence of the Trapezium multiple system itself right at the center of this cluster, since it contains several of the most massive stars and also the single most massive star in the entire Orion region of star formation. A central location for the most massive stars is not unique to the Trapezium cluster, since other examples are provided by the massive young clusters in NGC 3603 and the 30 Doradus nebula (Moffat, Seggewiss, and Shara 1985), each of which has at its center a multiple system containing some of the most massive stars in the cluster (Baier, Ladebeck, and Weigelt 1985; Weigelt and Baier 1985). Most, but not all, of the compact clusters in the Orion B cloud studied by E. A. Lada (1990) and described at this conference also appear to have their most luminous stars located near the center. This evidence suggests that accretion processes occurring at the centers of dense clusters may play an important role in the formation of the most massive stars.

An additional effect that might be important in organizing the way in which matter is accreted by the objects in a forming system of stars is a tendency toward the development of hierarchical clustering in the system. Some of the simulations of cloud fragmentation of Larson (1978) yielded hierarchical multiple systems containing subsystems similar to, but scaled down from, the larger system; some of these groupings of objects also contained a dominant centrally located object (see, for example, Fig. 6(a) of that paper). It was suggested in that paper that forming systems of stars might tend to develop a self-similar or fractal hierarchical structure, and it was noted that if the most massive star in each subsystem acquires a mass that is a constant fraction of the mass of the subsystem, this would lead to a power-law IMF. Hierarchical clustering may be of quite general importance in cosmogony, since it has been found or suggested to occur in other contexts as well; for example, the simulations by West and Richstone (1988) of the formation of clusters of galaxies show a similar phenomenon, even though the physics is simpler and involves only stellar dynamics. Hierarchical clustering may also be important for the formation of individual galaxies (Larson 1990c). In the simulations of West and Richstone (1988), many small subclusters initially form, and they subsequently merge into progressively larger ones; at each stage, the most massive objects tend to be centrally located in these subclusters. This tendency of the most massive objects to be centrally located is a result of the action of dynamical friction, which is most important for the most massive objects and causes them to sink rapidly toward the centers of local mass concentrations (Binney and Tremaine 1987; Richstone 1990). Similar gravitational drag effects will be even more important in young clusters of stars that still contain a significant amount of gas, since the gas produces a drag on all of the stars and not just the most massive ones; again, however, the effect is most important for the most massive stars, so the result is likely to be the formation of very dense clusters dominated by central subgroups of very massive stars (Larson 1990a), similar to the observed young clusters mentioned above.

If the most massive stars in a forming cluster or subcluster quickly settle to the center and then remain nearly at rest there because of gravitational drag effects, this will favor their continuing rapid growth by accretion. Because of this positive feedback effect, the amount of matter accreted by a star may be a strong function of its mass, just as would be required to generate an extended upper IMF of the observed form. If systems of stars are built up hierarchically from smaller systems, as suggested above, then a central most massive star may form in each subsystem, and central stars of progressively larger mass may form as larger and more centrally concentrated systems of stars are built up. In this way, a correlation may be introduced between the mass of the most massive star that can form in each system and the mass of the system. Negative feedback effects may also tend to introduce a coupling between the masses of accreting stars and the distribution of matter in their surroundings by limiting or regulating the accretion; for example, radiation pressure is a very important effect for luminous stars, and it may inhibit or prevent the formation of massive stars by conventional spherical accretion processes (Wolfire and Cassinelli 1987). The net result of such effects may be that the most massive stars can form only at the centers of exceptionally massive and condensed aggregates of gas and young stars, where the deep potential well produced by the surrounding matter, as well as possible interactions with neighboring objects (Larson 1982, 1990a), may allow accretion to continue even onto very luminous stars. Thus, there may be several reasons for the mass of the most massive star that can form in a cluster to depend on overall properties of the system such as its total mass and central density.

The mass of the most massive star that forms might then be expected to depend on at least two basic mass scales, the minimum fragment mass or Jeans mass and the total cluster mass. On very general grounds, the Jeans mass might be expected to be relevant because it determines the typical size of the clumps in which the matter is distributed, while the cluster mass should be relevant because the mass of the most massive object that can form should increase with the total mass available. In many problems in physics where two fundamental scales are involved, the scale of the phenomenon of interest is the geometric mean of these two fundamental scales; if we were to guess that similar behavior holds in the present problem, the maximum stellar mass might then be something like the geometric mean of the Jeans mass and the cluster mass. Such a simple guess would not obviously conflict with the observational evidence; for example, the maximum stellar mass in the Trapezium cluster is about 42 solar masses (Larson 1982), not far from the geometric mean of the Jeans mass and the cluster mass, which are of the order of one solar mass and a thousand solar masses, respectively.

More generally, one might consider the hypothesis that the mass of the most massive star that can form in a cluster or subcluster is related to the mass of the associated system by a scaling relation of the power-law form

$$M_{\rm star,max} \propto M_{\rm cluster}{}^{n} .$$

The existence of such a relation is already suggested by the fact that the mass of the most massive young star in each region of star formation is found to vary approximately with the 0.43 power of the mass of the associated molecular cloud (Larson 1982). It was noted by Larson (1982) that this dependence of maximum stellar mass on cloud mass can be understood if the IMF has a universal power-law form with a slope of $x = 1/0.43 = 2.3$, and if all clouds form stars with the same efficiency. Here, I note that the inverse can also be argued: if the processes of star formation result in a general power-law relation between the mass of the most massive star and the mass of the associated stellar system, and if stellar systems are built up from subsystems in all of which the same relation holds, then an IMF of power-law form is predicted. For example, if the maximum stellar mass is proportional to the square root of the cluster mass, as in the simple example of the previous paragraph, and if each system of stars contains or is built from two subsystems whose most massive objects are less massive by a factor of $2^{1/2}$ on the average, then the number of stars per unit logarithmic mass interval increases by a factor of 2 with each decrease by a factor of $2^{1/2}$ in stellar mass, which corresponds to a power-law IMF with a slope of $x = 2$. More generally, if the maximum stellar mass is proportional to a power n of the cluster mass, then the slope of the resulting IMF is $x = 1/n$. For example, the observed IMF slope of $x = 1.7 \pm 0.5$ would be reproduced if n were equal to 0.6 ± 0.2, close to the simple square-root dependence suggested above.

The above scaling law is suggested here only as a possibly useful working hypothesis to be tested observationally, without necessarily being based on any very specific theory or model. A variety of possible theoretical explanations for such a relation might of course be proposed, and some have already been suggested in the literature (for example, a possible explanation based on feedback effects was suggested by Larson 1989). However, it is likely that many complex processes are actually involved in determining the form of the upper IMF, and it is not yet clear which ones are most important, or even that all of the important ones have yet been recognized. Therefore any attempted theoretical explanation for such a scaling relation would at best be incomplete. Like the other scaling relations that have been discussed at some length at this meeting, a scaling law such as that suggested above might serve as a useful description of empirical trends even though it does not have a well-understood theoretical basis; nevertheless, all such scaling relations should be treated with some caution, because the processes that occur in star forming clouds are clearly so complex that any regularities that might exist are bound to show many exceptions and a wide dispersion about any mean trend.

5. Some Questions for Observers

All of the effects that have been discussed in this review, as well as others that have not been discussed, probably play a role in determining the form of the stellar IMF, so a complete understanding of the subject is still a distant goal. Therefore, I conclude not with any answers but with a list of questions for further observational research suggested by some of the issues that have been discussed. Much progress in this subject can be expected on the observational front, given the large amount of relevant data now being produced by various new techniques, but it may be useful to propose some specific questions or tests that can be addressed with these data. Some of these questions were already anticipated by P. C. Myers in his review at this meeting, in which some important first efforts at correlating and organizing the large amount of relevant information were presented. My suggested questions are:

(1) What is the relation between the clumpy structure of molecular clouds and newly formed stars? Do all dense clumps form stars? If not, which ones actually form stars?

(2) In the clumps that form stars, is there a simple relation between clump mass and stellar mass? Can the clump mass spectrum, as a result, be translated directly into a stellar mass spectrum?

(3) Do some clumps, for example the larger ones, form not just single stars but entire compact groups or clusters of stars?

(4) What fraction of all stars is formed in such compact groups and clusters?

(5) In clumps or cloud cores that form clusters of stars, is there a relation between the clump mass and the mass of the cluster?

(6) Is there a relation between the maximum mass of a star that can form in a group or cluster and the total mass or other properties of the cluster?

(7) What is the spatial structure of forming systems of stars? In particular, is any tendency toward hierarchical clustering observed?

(8) What is the spatial distribution of stars in forming clusters as a function of mass? Are the most massive stars centrally located, and are stars progressively more widely dispersed with decreasing mass?

(9) What are the properties of the residual gas in forming clusters? Is it concentrated around the stars, for example in disks? Can any evidence be found for accretion or gravitational drag effects?

Better answers to these and similar questions will lead to a better observational understanding of how the stellar IMF is built up, and will also provide a stimulus for further theoretical efforts to understand the physical processes involved.

REFERENCES

Athanassoula, E., Bosma, A., and Papaioannou, S. (1987) 'Halo parameters of spiral galaxies', *Astron. Astrophys.* **179**, 23-40.

Baier, G., Ladebeck, R., and Weigelt, G. (1985) 'Speckle interferometry of the central object in the giant HII region NGC 3603', *Astron. Astrophys.* **151**, 61-63.

Binney, J. and Tremaine, S. (1987) *Galactic Dynamics*, Princeton University Press, Princeton.

DePoy, D. L., Lada, E. A., Gatley, I., and Probst, R. (1990) 'The luminosity function in NGC 2023', *Astrophys. J. (Letters)* **356**, L55-L58.

Elmegreen, B. G. (1985) 'The initial mass function and implications for cluster formation', in R. Lucas, A. Omont, and R. Stora (eds.), *Birth and Infancy of Stars*, North-Holland, Amsterdam, pp. 257-277.

Freedman, W. L. (1985) 'The upper end of the stellar luminosity function for a sample of nearby resolved late-type galaxies', *Astrophys. J.* **299**, 74-84.

Gatley, I., DePoy, D. L., and Fowler, A. M. (1988) 'Astronomical imaging with infrared array cameras', *Science* **242**, 1264-1270 and cover photograph.

Gould, A. (1990) 'Galactic disc column density by maximum likelihood', *Mon. Not. Roy. Astron. Soc.* **244**, 25-28.

Herbig, G. H., and Terndrup, D. M. (1986) 'The Trapezium cluster of the Orion Nebula', *Astrophys. J.* **307**, 609-618.

Kent, S. M. (1986) 'Dark matter in spiral galaxies. I. Galaxies with optical rotation curves', *Astron. J.* **91**, 1301-1327.

Kent, S. M. (1987) 'Dark matter in spiral galaxies. II. Galaxies with HI rotation curves', *Astron. J.* **93**, 816-832.

Kuijken, K., and Gilmore, G. (1989) 'The mass distribution in the galactic disc - II. Determination of the surface mass density of the galactic disc near the Sun', *Mon. Not. Roy. Astron. Soc.* **239**, 605-649.

Lada, E. A. (1990) 'Global star formation in the L1630 molecular clouds', this volume; Ph.D. thesis, University of Texas.

Larson, R. B. (1978) 'Calculations of three-dimensional collapse and fragmentation', *Mon. Not. Roy. Astron. Soc.* **184**, 69-85.

Larson, R. B. (1981) 'Turbulence and star formation in molecular clouds', *Mon. Not. Roy. Astron. Soc.* **194**, 809-826.

Larson, R. B. (1982) 'Mass spectra of young stars', *Mon. Not. Roy. Astron. Soc.* **200**, 159-174.

Larson, R. B. (1985) 'Cloud fragmentation and stellar masses', *Mon. Not. Roy. Astron. Soc.* **214**, 379-398.

Larson, R. B. (1986a) 'Bimodal star formation and remnant-dominated galactic models', *Mon. Not. Roy. Astron. Soc.* **218**, 409-428.

Larson, R. B. (1986b) 'The initial mass function', in C. A. Norman, A. Renzini, and M. Tosi (eds.), *Stellar Populations*, Cambridge University Press, Cambridge, pp. 101-123.

Larson, R. B. (1989) 'Fragmentation and the initial mass function', in G. Tenorio-Tagle, M. Moles, and J. Melnick (eds.), *Structure and Dynamics of the Interstellar Medium*, IAU Colloquium No. 120, Springer-Verlag, Berlin, pp. 44-54.

Larson, R. B. (1990a) 'Formation of star clusters', in R. Capuzzo-Dolcetta, C. Chiosi, and A. Di Fazio (eds.), *Physical Processes in Fragmentation and Star Formation*, Kluwer Academic Publishers, Dordrecht, pp. 389-400.

Larson, R. B. (1990b) 'Galactic evolution', in D. L. Lambert (ed.), *Frontiers of Stellar Evolution*, Astronomical Society of the Pacific Conference Series, San Francisco, in press.

Larson, R. B. (1990c) 'Galaxy building', *Publ. Astron. Soc. Pacific* **102**, 709-722.

Lattanzio, J. C., Keto, E. R., and Monaghan, J. J. (1990) 'Hydrodynamical models of the W49A star-forming region', poster presented at this conference.

Mateo, M. (1988) 'Main-sequence luminosity and initial mass functions of six Magellanic Cloud star clusters ranging in age from 10 megayears to 2.5 gigayears', *Astrophys. J.* **331**, 261-293.

Mateo, M. (1990) 'The initial mass functions of Magellanic Cloud star clusters', in R. Capuzzo-Dolcetta, C. Chiosi, and A. Di Fazio (eds.), *Physical Processes in*

Fragmentation and Star Formation, Kluwer Academic Publishers, Dordrecht, pp. 401-414.

McCaughrean, M. J. (1989) 'Multicolour near infrared imaging of the Orion Nebula and Trapezium cluster', *Bull. Amer. Astron. Soc.* **21**, 712; photograph published in *Sky and Telescope* **77**, 352 (1989).

McCaughrean, M., Zinnecker, H., Aspin, C., and McLean, I. (1990) 'Low mass pre-main sequence clusters in regions of massive Galactic star formation', in R. Elston and C. A. Pilachowski (eds.), *Astrophysics with Infrared Arrays*, Astronomical Society of the Pacific Conference Series, San Francisco, in press.

Miller, G. E. and Scalo, J. M. (1979) 'The initial mass function and stellar birthrate in the solar neighborhood', *Astrophys. J. Suppl.* **41**, 513-547.

Miyama, S. M., Hayashi, C., and Narita, S. (1984) 'Criteria for collapse and fragmentation of rotating, isothermal clouds', *Astrophys. J.* **279**, 621-632.

Miyama, S. M., Narita, S., and Hayashi, C. (1987a) 'Fragmentation of isothermal sheet-like clouds. I. Solutions of linear and second-order perturbation equations', *Prog. Theor. Phys.* **78**, 1051-1064.

Miyama, S. M., Narita, S., and Hayashi, C. (1987b) 'Fragmentation of isothermal sheet-like clouds. II. Full nonlinear numerical simulations', *Prog. Theor. Phys.* **78**, 1273-1287.

Moffat, A. F. J., Seggewiss, W., and Shara, M. M. (1985) 'Probing the luminous stellar cores of the giant HII regions 30 Dor in the LMC and NGC 3603 in the Galaxy', *Astrophys. J.* **295**, 109-133.

Monaghan, J. J. and Lattanzio, J. C. (1990) 'A simulation of the collapse and fragmentation of cooling molecular clouds', *Astrophys. J.*, in press; poster presented at this conference.

Mouschovias, T. Ch. (1987) 'Star formation in magnetic interstellar clouds: I. Interplay between theory and observations', in G. E. Morfill and M. Scholer (eds.), *Physical Processes in Interstellar Clouds*, D. Reidel Publishing Company, Dordrecht, pp. 453-489.

Myers, P. C. (1983) 'Dense cores in dark clouds. III. Subsonic turbulence', *Astrophys. J.* **270**, 105-118.

Myers, P. C. and Goodman, A. A. (1988) 'Magnetic molecular clouds: Indirect evidence for magnetic support and ambipolar diffusion', *Astrophys. J.* **329**, 392-405.

Pryor, C., McClure, R. D., Fletcher, J. M., and Hesser, J. E. (1989) 'Mass-to-light ratios for globular clusters. I. The centrally concentrated clusters NGC 6624, M28 (NGC 6626), and M70 (NGC 6681)', *Astron. J.* **98**, 596-610.

Quirk, W. J. and Tinsley, B. M. (1973) 'Star formation and evolution in spiral galaxies', *Astrophys. J.* **179**, 69-83.

Rana, N. C. (1987) 'Mass function of stars in the solar neighbourhood', *Astron. Astrophys.* **184**, 104-118.

Richstone, D. (1990) 'Dynamical evolution of clusters of galaxies', in W. R. Oegerle, M. J. Fitchett, and L. Danly (eds.), *Clusters of Galaxies*, Cambridge University Press, Cambridge, PP. 231-255.

Salpeter, E. E. (1955) 'The luminosity function and stellar evolution', *Astrophys. J.* **121**, 161-167.

Scalo, J. M. (1986) 'The stellar initial mass function', *Fundam. Cosmic Phys.* **11**, 1-278.

Scalo, J. M. (1987) 'The initial mass function, starbursts, and the milky way', in T. X. Thuan, T. Montmerle, and J. Tran Thanh Van (eds.), *Starbursts and Galaxy Evolution,* Editions Frontières, Gif sur Yvette, pp. 445-465.

Scalo, J. M. (1990) 'Top-heavy IMFs in starburst galaxies', in G. Fabbiano, J. S. Gallagher, and A. Renzini (eds.), *Windows on Galaxies*, Kluwer Academic Publishers, Dordrecht, pp.125-140.

Shu, F. H., and Terebey, S. (1984) 'The formation of cool stars from cloud cores', in S. L. Baliunas and L. Hartmann (eds.), *Cool Stars, Stellar Systems, and the Sun*, Springer-Verlag, Berlin, pp. 78-89.

Shu, F. H., Adams, F. C., and Lizano, S. (1987) 'Star formation in molecular clouds: observation and theory', *Ann. Rev. Astron. Astrophys.* **25**, 23-81.

Shu, F. H., Lizano, S., Adams, F. C., and Ruden, S. P. (1988) 'Beginning and end of a low-mass protostar', in A. K. Dupree and M. T. V. T. Lago (eds.), *Formation and Evolution of Low Mass Stars*, Kluwer Academic Publishers, Dordrecht, pp. 123-137.

Stahler, S. W. (1988) 'Deuterium and the stellar birthline', *Astrophys. J.* **332**, 804-825.

Stutzki, J. and Güsten, R. (1990) 'High spatial resolution isotopic CO and CS observations of M17 SW: The clumpy structure of the molecular cloud core', *Astrophys. J.* **356**, 513-533.

Weigelt, G. and Baier, G. (1985) 'R136a in the 30 Doradus nebula resolved by holographic speckle interferometry', *Astron. Astrophys.* **150**, L18-L20.

West, M. J. and Richstone, D. O. (1988) 'The formation of clusters of galaxies containing dark matter', *Astrophys. J.* **335**, 532-541.

Wilking, B. A., Lada, C. J., and Young, E. T. (1989) 'IRAS observations of the ρ Ophiuchi infrared cluster: Spectral energy distributions and luminosity function', *Astrophys. J.* **340**, 823-852.

Wolfire, M. G. and Cassinelli, J. P. (1987) 'Conditions for the formation of massive stars', *Astrophys. J.* **319**, 850-867.

Zinnecker, H. (1982) 'Prediction of the protostellar mass spectrum in the Orion near-infrared cluster', in A. E. Glassgold, P. J. Huggins, and E. L. Schucking (eds.), *Symposium on the Orion Nebula to Honor Henry Draper*, *Ann. New York Acad. Sci.* **395**, 226-235.

Zinnecker, H. (1987) 'A review of the IMF', in J. Palous (ed.), *Evolution of Galaxies*, Proceedings of the 10th European Regional Meeting of the IAU, Vol. **4**, Czechoslovak Academy of Sciences, Prague, pp. 77-85.

Zinnecker, H. (1989) 'Towards a theory of star formation', in J. E. Beckman and B. E. J. Pagel (eds.), *Evolutionary Phenomena in Galaxies*, Cambridge University Press, Cambridge, pp. 113-127.