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The Stellar Initial Mass Function and Beyond

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Abstract.
A brief review is given of the basic observed features of the stellar IMF, and also of some of the theoretical ideas and simulations that may help to explain these features. The characteristic stellar mass of order one solar mass may derive from the typical masses of the observed star-forming clumps in molecular clouds, and the typical clump mass may in turn be determined mainly by the Jeans mass, as is true in many numerical simulations of cloud collapse and fragmentation. The Salpeter power law that approximates the IMF at higher masses is less well understood, but it may result from the effects of continuing gas accretion by the more massive forming stars together with the effects of interactions and mergers in dense forming stellar systems. The mass of the most massive star that forms in a cluster is observed to increase systematically with the mass of the cluster, and the most massive clusters may form stars that are massive enough to collapse completely to black holes.

1. Introduction

It is almost 50 years since Salpeter (1955) published the first and still most famous paper on the stellar Initial Mass Function, or distribution of masses with which stars are formed, and showed that for masses between 0.4 and 10 solar masses it can be approximated by a declining power law. Since then, this 'Salpeter law,' or variants or extensions of it, have been used in countless efforts to model the properties and evolution of stellar systems. Recently, for example, it has been used to model the evolution of galaxies at high redshifts. Because of its importance in many areas of astronomy, the stellar IMF has been a subject of intense study for almost five decades, and much effort has been invested in trying to determine how valid and how universal the Salpeter law or other approximations to the IMF might be, and also whether the IMF is variable, depending perhaps on parameters such as metallicity or location.

The most important result of all this work can be stated simply: Salpeter was basically right, and the power-law approximation that he proposed to the IMF between 0.4 and 10 solar masses has yet to be conclusively falsified or superseded. However, we have also learned that this power law does not apply at all masses: the IMF may not continue to follow the Salpeter law at the very largest masses, and it definitely falls below this law at the smallest masses, becoming nearly flat (in number of stars per unit log mass) below about 0.5 solar masses. This flattening of the IMF at low masses implies that most of the mass in the IMF is contained in stars whose masses are within an order of magnitude of one solar mass. Variability of the IMF has frequently been suggested, and it probably does occur at some level, but it has yet to be conclusively established. Extensive reviews of the literature on the stellar IMF have been presented by Miller & Scalo (1979), Scalo (1986, 1998), and Kroupa (2001, 2002); a briefer review has been given by Larson (1999), and a review with emphasis on young clusters has been given by Meyer et al. (2000).

2. Summary of The Evidence

Evidence concerning the IMF of the field stars in the solar vicinity has been collected and reviewed by Scalo (1986, 1998) and Kroupa (2001, 2002). Several proposed approximations to the IMF are all consistent with the data for masses between about 0.5 and 10 solar masses, including the original Salpeter law and the lognormal approximation of Miller & Scalo (1979). However, for masses above $10\,\mathrm{M}_\odot$, the lognormal approximation now seems excluded because it falls off too steeply; although some results suggest a high-mass slope that is steeper than the Salpeter law (Scalo 1986, 1998), other results remain consistent with it (Kroupa 2001, 2002), and the Salpeter law therefore continues to be widely used as an approximation to the IMF at all masses above a solar mass. Below about 0.5 solar masses, however, the field IMF becomes almost flat in logarithmic units, and it may even decline in the brown dwarf regime. If we define the slope x of the IMF by $dN/d\log m \propto m^{-x}$, the Salpeter slope is $x = 1.35$ (where the second decimal place has never been significant and the uncertainty is at least ± 0.3), while the slope at masses below about $0.5\,\mathrm{M}_\odot$ is approximately $x \sim 0$. Kroupa (2002) suggests an approximation to the field IMF consisting of three power laws: $x = 1.3$ (essentially the Salpeter law) for $m > 0.5\,\mathrm{M}_\odot$, $x = 0.3$ (a nearly flat IMF) for $0.08 < m < 0.5\,\mathrm{M}_\odot$, and $x = -0.7$ (an IMF declining toward small masses) for $m < 0.08\,\mathrm{M}_\odot$. Many often inconsistent definitions and notations have been used for the IMF slope, but some alternative notations that have been widely used are the parameter $\Gamma = -x$ defined by Scalo and the parameter $\alpha = 1 + x$ used by Kroupa.

Scalo (1986) noted a possible tendency for the IMFs of star clusters to be flatter than the field IMF and more similar to the Salpeter law for masses above a solar mass, although the data show a large scatter. The scatter in the IMF slopes of clusters was illustrated graphically by Scalo (1998), who concluded that either there are real variations in the IMF or the measurements have very large uncertainties. Since the slopes found at masses above $1\,\mathrm{M}_\odot$ scatter roughly equally above and below the Salpeter value, most researchers have preferred the conservative interpretation that the data are consistent, within the large uncertainties, with a universal Salpeter-like IMF for masses above $1\,\mathrm{M}_\odot$. However the cluster IMFs, like the field IMF, clearly flatten at smaller masses, and Kroupa's (2002) plot of IMF slope versus average stellar mass suggests that the slope varies continuously below $1\,\mathrm{M}_\odot$, and that the IMF eventually even declines in the brown dwarf regime. Recent studies of young clusters have generally yielded results consistent with a universal IMF (e.g., Meyer et al. 2000; Luhman et al. 2000; Muench et al. 2002), but some studies continue to suggest variability of the IMF; for example, the Taurus region may have a deficiency of brown dwarfs (Briceño et al. 2002), while the massive young clusters in the Galactic Center region may have a relatively flat upper IMF (Figer et al. 1999; Figer 2001; Stolte et al. 2003). Some studies of field populations have also suggested that some old populations like the Galactic Thick Disk may have a relatively flat IMF (Reylé & Robin 2001; Robin & Reylé 2003). However, many past claims of variability have not withstood the test of time, and therefore the default assumption of a universal IMF is still widely adopted.

The observed IMF is of interest also because of what it may tell us about the physics of star formation. The implications of the IMF for star formation processes are best illustrated by considering the amount of mass that goes into stars per unit logarithmic mass interval. This function is flatter by one power of mass than the number of stars per unit log mass discussed above, and it is broadly peaked around one solar mass, with a slow decline toward larger masses and a much faster decline below $0.1\,\mathrm{M}_{\odot}$. This implies that the processes of star formation turn most of the star-forming gas into stars whose masses are within an order of magnitude of one solar mass; although significant mass also goes into the more massive stars, very little goes into low-mass stars or brown dwarfs. Therefore, in terms of where most of the mass goes, there are two main features of the IMF that need to be understood: (1) there is a characteristic stellar mass of the order of one solar mass, and (2) at larger masses the IMF has a power-law tail similar to the original Salpeter law that also contains significant mass.

3. The Origin of the Characteristic Mass

What processes might account for a characteristic stellar mass of the order of one solar mass? Two basic types of hypotheses have been proposed to explain this characteristic mass: (1) One possibility is that stars form from small molecular gas clumps whose masses are similar to those of the stars that from them; the stars then derive their typical masses from those of the clumps, whose properties are presumably determined by cloud fragmentation processes (Larson 1985, 1996, 1999). (2) Another possibility is that forming stars may continue to accrete mass indefinitely from an extended medium, and they may 'determine their own masses' by producing outflows that terminate the accretion process at some stage (Shu, Adams, & Lizano 1987; Adams & Fatuzzo 1996). Neither of these possibilities can yet be definitely excluded, and both may well play some role in determining stellar masses. However, the hypothesis that typical stellar masses are determined by cloud fragmentation processes is more amenable to direct observational test, and it appears to receive support from some recent observations.

Motte, André, & Neri (1998) have made high-resolution millimeter continuum maps of the rho Ophiuchus star-forming cloud that show many small, dense, apparently pre-stellar clumps with masses extending down to well below a solar mass (see also André et al. 1999; André, Ward-Thompson, & Barsony 2000). They found that the mass spectrum of these clumps closely resembles the stellar IMF, and they suggested on this basis that the clumps are direct stellar progenitors. Luhman & Rieke (1999) and Motte & André (2001) have noted in addition that the mass spectrum of these clumps resembles not only the standard stellar IMF described above, but also the IMF of the young stars in the ρ Oph cloud itself. It may be premature to claim that there is quantitative agreement between the clump mass spectrum and the stellar IMF, since a similar study of the ρ Oph clumps by Johnstone et al. (2000) finds somewhat larger clump masses and questions whether the smallest clumps found by Motte et al. (1998) are gravitationally bound. Studies of the dense clumps in the Orion clouds by Motte & André (2001) and Johnstone et al. (2001) have also yielded somewhat larger typical clump masses. However, the results of all of these studies are qualitatively very similar, and they all imply the existence of a typical clump mass of the order of one solar mass. Thus they all appear to be consistent with the view that typical stellar masses derive from the masses of small pre-stellar clumps created by cloud fragmentation processes. These results may pose a problem for the hypothesis that forming stars continue to accrete mass indefinitely from an extended medium until the accretion is shut off by outflows, since the observed clump masses are not much larger than those of the stars that form from them; however, it cannot be ruled out that outflows still play a significant role in limiting the efficiency with which stars can form in these clumps.

If the small apparently pre-stellar clumps observed in molecular clouds are created by cloud fragmentation processes, and if they are gravitationally bound, then some version of the Jeans criterion, which balances gravity against thermal pressure, almost certainly plays some role in determining their typical sizes and masses. The original Jeans (1929) analysis of the stability of an infinite uniform medium predicted a minimum mass for a collapsing clump that depends on the temperature and density of the medium, but the relevance of this analysis has often been questioned because it was not mathematically self-consistent, neglecting the overall collapse of the fragmenting medium (Spitzer 1978). However, rigorous analyses of the stability of equilibrium configurations that do not undergo overall collapse, such as sheets, filaments, and disks, yield results that are dimensionally equivalent to the original Jeans criterion (Larson 1985). Another type of rigorous analysis considers the stability of an equilibrium isothermal sphere with a given temperature and boundary pressure, and derives the size and mass of a marginally stable or 'Bonnor-Ebert' isothermal sphere (Spitzer 1968). The result is again dimensionally equivalent to the Jeans criterion, so this type of criterion seems likely to be of quite general relevance, at least in an approximate dimensional sense.

If star-forming clumps are produced by turbulent compression in clouds that have supersonic internal turbulent motions, as suggested by Larson (1981), then the clumps may initially have boundary pressures that are comparable to the typical turbulent ram pressure in these clouds. Assuming a temperature of 10 K and a typical turbulent cloud pressure of 3×10^5 cm^{-3} K, the mass and radius of a marginally stable 'Bonnor-Ebert' sphere are predicted to be about $0.7\,\mathrm{M}_\odot$ and 0.03 pc, similar to the typical masses and sizes of the pre-stellar clumps actually observed in star-forming clouds (Larson 1996, 1998, 1999). Simulations of supersonic turbulence provide at least qualitative support for the idea that star-forming clumps are created by turbulent compression, perhaps typically in clumpy filaments such as are found quite generally in many types of simulations (e.g., Ostriker, Gammie, & Stone 1999; Vázquez-Semadeni et al. 2000; Klessen

2001), regardless of the possible role of magnetic fields, but much more work is needed to clarify the quantitative details of this process and the initial properties of the collapsing clumps.

In any case, many simulations of cloud collapse and fragmentation, both with and without turbulence, have demonstrated the formation of bound clumps whose masses are typically comparable to the initial Jeans mass, and in some cases the distribution of clump masses around this value resembles qualitatively the lower stellar IMF (Larson 1978; Klessen 2001; Bate, Bonnell, & Bromm 2002a,b, 2003). For example, the bound clumps that appear in Klessen's (2001) simulations of the collapse and fragmentation of turbulent clouds have a mass spectrum that is roughly centered on the Jeans mass and that declines at larger masses but is flatter at lower masses, as observed; similar results have also been found in the higher-resolution simulations of Bate et al. (2002a,b, 2003). In the latter simulations, significant numbers of objects are formed with masses all the way down to the opacity limit for fragmentation, which is about 0.01 solar masses; these very low-mass objects or 'proto-brown dwarfs' are formed by the fragmentation of the thin dense spiral filaments that appear frequently in these simulations. Thus ordinary gravitational or Jeans fragmentation, when simulated with sufficiently high spatial resolution, can yield a considerable range of masses and may be able to account for the basic observed features of the lower IMF, including the observed numbers of brown dwarfs.

Evidence for the existence of a preferred size and mass scale in the cloud fragmentation process also comes from studies of the clustering of newly formed stars (Gomez et al. 1993; Larson 1995; Simon 1997), and from studies of the scaling properties of the kinematics (Goodman et al. 1998) and the spatial structure (Williams, Blitz, & McKee 2000) of the gas in star-forming molecular clouds. As discussed by Goodman et al. (1998), all of this evidence is consistent with a picture in which star-forming clouds are dominated on large scales by turbulence and chaotic dynamics, possibly self-similar, while on scales smaller than about 0.1 parsecs the motions become more orderly, and 'coherent cores' can form and collapse to form individual stars or binary systems. These 'coherent cores' are observed to have sizes comparable to the Jeans length, as might be expected if they form on scales that are small enough for turbulence to have become unimportant but large enough that the Jeans criterion is still satisfied. While many of the details remain to be clarified, such a picture appears to offer at least a framework for understanding many features of the formation of low-mass stars, including the origin of the characteristic stellar mass.

4. The Origin of the Power-Law Upper IMF

The most important effects of star formation on the environment are produced by the most massive stars, so it is important also to understand the origin of the power-law upper IMF, which may have a universal Salpeter-like slope. The fact that a significant amount of mass goes into this power law means that the processes that form massive stars must be fairly efficient, and the possible universality of the Salpeter slope also suggests that these processes may be universal in nature and not dependent on local conditions. Numerous efforts have been made over the years to explain the Salpeter law, and some of the types of models that might naturally produce such a power law IMF have been reviewed by Larson (1991, 1999). These include (1) clump coagulation models, which tend under a variety of assumptions to produce a power-law clump mass spectrum; (2) models involving the continuing accretional growth of forming stars, which in simple cases can build up a power-law tail on the IMF; and (3) models postulating self-similar clustering or cloud structure, which may also naturally produce a power-law mass spectrum.

The older literature on the subject contains many models of clump coagulation that can explain the relatively flat mass spectrum ($x \sim 0.7$) of the CO clumps in molecular clouds, but they do not directly explain the steeper Salpeter slope ($x \sim 1.35$) without additional assumptions. These models do not now seem very relevant to the stellar IMF, because the CO clumps whose mass spectra they explain are of relatively low density and are not closely associated with star formation, unlike the smaller and denser continuum clumps discussed above. On the other hand, models postulating the continuing accretional growth of the most massive forming stars, such as the model suggested by Zinnecker (1982), now seem more promising when implemented in the context of realistic simulations of cluster formation. Zinnecker (1982) noted that if accreting protostars moving at a typical speed V through a medium of density ρ gain mass at the Bondi-Hoyle rate $dM/dt \sim G\rho M^2/V^3$, then an initially peaked mass function gets stretched out toward larger masses and develops a power-law tail with a slope $x = 1$ that is not greatly different from the Salpeter slope $x = 1.35$. A steeper slope would result if the accretion rate were more strongly dependent on stellar mass, and this might in fact be expected since the more massive stars tend to form preferentially in the central regions of clusters where the ambient density ρ is higher (Larson 1982; Zinnecker, McCaughrean, & Wilking 1993; Hillenbrand & Hartmann 1998; Bonnell & Davies 1998). The simulations by Bonnell et al. (1997, 2001; see also Bonnell 2000) of the accretional growth of stars in a forming cluster confirm this expectation and predict the development of a power-law tail on the IMF that has a slope similar to the Salpeter slope. Thus, continuing accretional growth of the more massive stars in a forming cluster seems likely to play an important role in the development of the upper IMF.

The tendency of stars to form in a hierarchy of groupings, and the tendency of the more massive stars to form in the larger groupings (Larson 1982; Zinnecker et al. 1993; Elmegreen et al. 2000), must also play some role in the origin of the upper IMF. A power-law IMF could result if, for example, stars form in a self-similar clustering hierarchy, and if the mass of the most massive star that forms in each subgroup of the hierarchy increases as some power n of the mass of the subgroup; then a power-law IMF results whose slope is $x = 1/n$ (Larson 1991). An example of this type of model would be the formation of stars in a cloud with a fractal mass distribution, such as a cloud consisting of a fractal network of filaments; for example, if stars form by the accumulation of matter at the nodes of such a network, and if they acquire masses proportional to the lengths of the filaments intersecting there, then the resulting IMF is a power law whose slope x is equal to the fractal dimension D of the network (Larson 1992). If this dimension were similar to the fractal dimension $D \sim 1.4$ characterizing the clustering of the T Tauri stars in the Taurus-Auriga clouds (Larson 1995), then an IMF with a slope $x \sim 1.4$ would be predicted by this model. Other types of fractal models to explain the Salpeter law, based on different assumptions, have been developed by Elmegreen (1997, 1999, 2000a).

A model based only on geometrical concepts is, however, likely to be too simple since it neglects the effects of the dynamical interactions that occur in systems of forming stars. For example, if star formation involves the accumulation of matter at the nodes of a filamentary network, then stars as well as gas will accumulate at these nodes and will interact strongly there. Interactions among the forming stars can play an important role in the star formation process itself by helping to redistribute angular momentum and enabling continuing accretion to occur (Larson 1990, 2002). Interactions may play an even more important role in the formation of massive stars than they do for low-mass stars because more interactions are likely to be involved (Larson 2002). An example of a simple model whereby a sequence of accretion events in a hierarchy of interacting protostars can lead to a Salpeter-like IMF was suggested by Larson (1999). However, the ease with which it is possible to devise explanations of the Salpeter law shows that this power law does not by itself place strong constraints on the physics of massive star formation; numerous theories have been shown to be equally capable of explaining the Salpeter law.

Important progress has recently come from high-resolution numerical simulations of cloud collapse and star formation that include the effects of continuing gas accretion as well as the effects of interactions and mergers in dense forming systems of stars (Bonnell 2002; Bonnell & Bate 2002). In the detailed simulation of cluster formation by Bonnell & Bate (2002), all of these processes occur and play important roles in the development of the upper stellar IMF. A striking result is the occurrence of a runaway increase in the density of a central core region containing some of the most massive forming stars, similar to what had been suggested by Larson (1990); this is accompanied by a runaway growth in the masses of these stars that is due to continuing gas accretion and mergers, as had been suggested by Bonnell, Bate, & Zinnecker (1998). The collapsing cluster-forming cloud also develops a filamentary structure, and groups of stars form at the nodes of the resulting network of filaments, similar to what happens in simulations of galaxy formation in cosmological models; these results may thus reflect quite general features of the evolution of systems of gas and stars under the influence of gravity and dissipation.

Like the earlier simulations of cluster formation by Bonnell et al. (1997, 2001), the more detailed simulation by Bonnell & Bate (2002) yields a power-law upper IMF that is very similar to the Salpeter law. Because many processes occur in this simulation and the dynamics becomes highly complex and chaotic, the reason for this result is not immediately apparent, but almost certainly a combination of processes is involved, including all of those discussed above and perhaps others as well. It is nevertheless worth noting, as these authors point out, that the basic physics included in this simulation is very simple – only isothermal gas dynamics, Newtonian gravity, and the merging of protostars at close distances, but magnetic fields are not included, and neither are any effects of stellar evolution or radiative feedback. Because isothermal gas dynamics and gravity introduce no new mass scale larger than the Jeans mass, the dynamics of the system becomes nearly scale-free on large scales, so it is not surprising that a power-law upper IMF should result. However, it is not obvious why the slope should be very similar to the Salpeter law, and more work will again be needed to clarify the processes involved.

5. The Most Massive Objects

Clearly, it is particularly important to understand better how the most massive stars are formed. It is also relevant at a meeting on “Star Formation Across the Stellar Mass Spectrum” to ask how far the stellar mass spectrum extends, and whether there is an upper limit on stellar masses. If a Salpeter IMF were to extend indefinitely to very large masses, this would imply that there is no mass limit and that stars of larger and larger mass form in systems of larger and larger size. However, the Salpeter law cannot continue indefinitely, because this would imply the existence of some stars in our Galaxy with masses of 1000 solar masses or more, which are not observed (Elmegreen 2000b). The formation of massive stars remains, unfortunately, a very poorly understood subject because massive stars form in very complex environments that are difficult to study observationally and model theoretically (Evans 1999; Garay & Lizano 1999; Stahler, Palla, & Ho 2000). Thus it may be of interest to see what can be learned just from the phenomenology of massive star formation, and from observed trends such as the dependence of maximum stellar mass on system mass.

The most massive stars form near the centers of the densest and most massive clusters (Zinnecker et al. 1993; Hillenbrand & Hartmann 1998; Elmegreen et al. 2000; Clarke, Bonnell, & Hillenbrand 2000), and the mass of the most massive star present also tends to increase systematically with the mass of the cluster (Larson 1982; Testi, Palla, & Natta 1999; Testi 2003). This is illustrated by comparing the ρ Oph cluster, which has a mass of about $100\,\mathrm{M}_\odot$ and whose most massive star has a mass of about $8\,\mathrm{M}_\odot$ (Wilking, Lada, & Young 1989), with the Orion Nebula cluster, which has a mass of about $2000\,\mathrm{M}_\odot$ and whose most massive star, located in the Trapezium at its center, has a mass of about $40\,\mathrm{M}_\odot$ (Hillenbrand & Hartmann 1998). Even the Orion Nebula cluster is only a modest example of massive star formation, however; for example, the Arches and Quintuplet clusters near the Galactic Center have masses of at least 10^4 solar masses and contain stars with masses well over $100\,\mathrm{M}_\odot$ (Figer et al. 1999). The most luminous and massive star known may be the ‘Pistol star’ in the Quintuplet cluster; the mass of this star is estimated to be at least $150\,\mathrm{M}_\odot$, and the mass of the associated cluster is about $2 \times 10^4\,\mathrm{M}_\odot$ (Figer et al. 1998, 1999; Figer & Kim 2002). A similarly luminous star, LBV 1860-20, has been found in a similarly massive cluster that is not near the Galactic Center (Eikenberry et al. 2001). The R136 cluster in the Large Magellanic Cloud, which has a mass of about $5 \times 10^4\,\mathrm{M}_\odot$, also contains stars with masses up to about $150\,\mathrm{M}_\odot$ (Hunter et al. 1995; Massey & Hunter 1998).

The examples mentioned above, namely the ρ Oph cluster, the Orion Nebula cluster, and the Quintuplet and R136 clusters, together with a number of other young systems for which data were collected by Larson (1982), define a rough power-law correlation between the mass of the most massive star and the mass of the associated cluster which is approximately $M_{\mathrm{star,\,max}} \sim 1.2\,M_{\mathrm{cluster}}^{0.45}$. From these very limited data it is not clear that any limiting stellar mass has yet been reached, since the mass of the most massive star increases more or less continually with cluster mass up to the most massive young clusters known in our Galaxy and the LMC. However, the dependence of maximum stellar mass on cluster mass found here is not consistent with a simple extension of the Salpeter law to very large masses, since this would predict that the maximum stellar mass should vary as $M_{\rm cluster}^{0.74}$, rather than only as $M_{\rm cluster}^{0.45}$. If the data used here are reliable and representative, they suggest that the upper IMF eventually becomes steeper than the Salpeter law and approaches a slope that is closer to $x = 1/0.45 = 2.2$ at very large masses. Thus the IMF may not be truly self-similar for the most massive stars but may have a slope that increases with mass, possibly reflecting an increasing difficulty in forming progressively more massive stars that is due to the effects of radiation pressure and winds.

Do stars with even larger masses form in more massive clusters, such as young globular clusters? It has long been suspected that the massive centrally condensed globular cluster M15 has a central black hole with a mass of the order of 1000 $M_\odot$, and this possibility is supported by recent radial velocity measurements of stars only a few tenths of an arcsecond from the center (Gebhardt et al. 2000; Gerssen et al. 2001). According to Gebhardt et al. (2000), this evidence is consistent with a black hole with a mass of $\sim$ 2000 $M_\odot$, although other interpretations are not excluded, and the STIS measurements of Gerssen et al. (2001) provide further support for an increase in stellar velocity dispersion toward the center. If M15 does indeed contain such a central black hole, one explanation could be that a similarly massive star formed at the center of this cluster and then collapsed to a black hole. Stars with masses larger than 250 $M_\odot$ are predicted to collapse completely to black holes at the end of their lifetimes, provided that they do not first lose most of their mass in winds (Fryer, Woosley, & Heger 2001), and it may be relevant in this case that mass loss is expected to be relatively unimportant for metal-poor stars (Baraffe, Heger, & Woosley 2001) and that M15, with [Fe/H] = −2.0, is one of the most metal-poor clusters known. M15 might thus have provided a particularly favorable environment for the formation of a very massive star that could have collapsed to a massive black hole.

Other centrally condensed systems are also known that contain central black holes: supermassive black holes are found at the centers of most, if not all, galaxy bulges, and the masses of these nuclear black holes increase systematically with the mass of the bulge (Kormendy & Richstone 1995; Kormendy & Gebhardt 2001). If M15 contains a black hole of mass $\sim$ 2000 $M_\odot$, it falls on the same relation between black hole mass and system mass that was found by Kormendy & Richstone (1995) for galaxy bulges, since these authors found that the mass of the central black hole is typically about 0.002 times the mass of the system, which is also approximately true for M15. The updated reviews of Kormendy & Gebhardt (2001) and McLure & Dunlop (2002) find, for a much larger sample of galaxies, a very similar relation between black hole mass and bulge mass, with a slightly smaller value of 0.0013 for the typical ratio of black hole mass to bulge mass.

Could there be a connection between the formation of massive stars at the centers of clusters and the formation of supermassive black holes at the centers of galaxies? In both cases, the mass of the central object increases systematically with the mass of the system, and this suggests that similar processes may be involved in building up the central object (Larson 2002). For example, runaway accretion and coalescence processes like those discussed above could play a role not only in forming massive stars in clusters but in building supermassive black holes in galactic nuclei. The relation between central object mass and system mass is not identical in the two cases, however, since the mass of the most massive star in a cluster increases with system mass only as $1.2\,M_{\rm system}^{0.45}$, while the mass of the central black hole in a galaxy bulge increases more nearly linearly with system mass and is approximately equal to $0.0015\,M_{\rm system}$. These two relations intersect at a system mass of about $2 \times 10^5\,{\rm M}_\odot$ and a central object mass of about $300\,{\rm M}_\odot$, suggesting that a transition may occur at about this point from a regime of normal massive star formation in systems of smaller mass to a regime of black hole formation and growth in systems of larger mass. It is consistent with this possibility that the transition appears to occur at a maximum object mass of around $300\,{\rm M}_\odot$, since this is approximately the same as the mass of $250\,{\rm M}_\odot$ above which stars are predicted to collapse completely to black holes; this suggests that systems more massive than a few times $10^5\,{\rm M}_\odot$ may sometimes make stars massive enough to collapse completely to black holes.

Once a massive black hole has formed, the possibilities for the further growth in mass of this object are increased because such a black hole, unlike a massive star, is a permanent feature of the system that can only grow in mass by any continuing interaction with its surroundings. For example, a central black hole might continue to accrete matter from neighboring massive stars in a central subcluster whose members might otherwise have merged. Such processes might have contributed to the mass of the possible black hole in M15, since the maximum stellar mass predicted by the above relation for a cluster with the mass of M15 is only about $600\,{\rm M}_\odot$, and this suggests that some further growth in mass might have been required. In the case of galaxy bulges, which are built up at least partly by mergers of smaller systems, the mergers may lead to the continuing growth of the nuclear black holes through the accretion of gas, stars, or other black holes that become concentrated at the center during each merger, and such processes might account for the existence of a relation between black hole mass and bulge mass (Cattaneo, Haehnelt, & Rees 1999; Kauffmann & Haehnelt 2000; Larson 2000).

Even without gas dynamics, runaway stellar mergers can occur in massive and dense young star clusters when they experience a stellar dynamical 'core collapse', and this can lead to the building up of very massive stars and black holes at their centers. Portegies Zwart et al. (1999, 2002) and Figer & Kim (2002) suggest that stellar mergers might account for the existence of such very massive stars as the Pistol star, and Ebisuzaki et al. (2001) and Portegies Zwart & McMillan (2002) suggest that black holes with masses of hundreds to thousands of solar masses may be built up by similar processes at the centers of massive young clusters. X-ray observations provide evidence that such 'intermediate mass black holes' exist in some very luminous young clusters in starburst galaxies (Ebisuzaki et al. 2001; Portegies Zwart & McMillan 2002), and this evidence supports the possibility that massive black holes can indeed form at the centers of massive young clusters. Portegies Zwart & McMillan (2002) speculate further that the accumulation of such clusters at the centers of galaxies, accompanied by the merging of their black holes, could lead to the building up of supermassive black holes in galactic nuclei, and they argue that central objects with masses of the order of 0.1 percent of the system mass should result quite generally from such processes.

6. Summary

Much evidence indicates that there are two basic general features of the stellar IMF that need to be understood: there is a characteristic stellar mass of the order of one solar mass, and the IMF also has a power-law tail toward larger masses that is similar to the original Salpeter law. Variability of the IMF has often been suggested, but has not been conclusively established. The characteristic mass may derive from the typical masses of the small, dense, apparently pre-stellar clumps that have been observed in a number of star-forming clouds. In many simulations of cloud collapse and fragmentation, the typical masses of the clumps formed are similar to the Jeans mass, regardless of whether turbulence plays an important role; magnetic fields also do not appear to make a major difference. Gravitational fragmentation produces in addition significant numbers of proto-brown dwarfs by the fragmentation of thin dense spiral filaments, and it may thus be able to account for the basic observed features of the lower stellar IMF. The Salpeter power-law that approximates the IMF at higher masses is less well understood, but it probably results from a combination of processes including the effects of continuing gas accretion by the more massive forming stars and the effects of interactions and mergers in dense forming systems of stars. Simulations of the formation of star clusters show that the dynamics of these accretional growth processes becomes almost scale-free at large masses, and that these processes can produce a power-law upper IMF that is very similar to the Salpeter law.

Observations also indicate that the mass of the most massive star that forms in a cluster increases systematically with the mass of the cluster, although not as rapidly as is predicted by the Salpeter law, and there is no clear indication of an upper stellar mass limit. Some of the most massive known clusters, including the globular cluster M15 and some luminous young clusters in starburst galaxies, may contain massive black holes that originated from the collapse of very massive stars that formed near the centers of these systems. The observed dependence of maximum object mass on system mass suggests that stellar systems more massive than a few times 10^5 solar masses may sometimes make stars massive enough to collapse completely to black holes.

References

Adams, F. C., & Fatuzzo, M. 1996, ApJ, 464, 256

André, P., Motte, F., Bacmann, A., & Belloche, A. 1999, in Star Formation 1999, ed. T. Nakamoto (Nobeyama Radio Observatory, Nobeyama), p. 145

André, P., Ward-Thompson, D., & Barsony, M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Univ. of Arizona Press, Tucson), p. 59

Baraffe, I., Heger, A., & Woosley, S. E. 2001, ApJ, 550, 890

Bate, M. R., Bonnell, I. A., & Bromm, V. 2002a, MNRAS, 332, L65

Bate, M. R., Bonnell, I. A., & Bromm, V. 2002b, in The Origins of Stars and Planets: The VLT View, ed. J. F. Alves & M. J. McCaughrean (Springer-Verlag, Berlin), p. 139

Bate, M. R., Bonnell, I. A., & Bromm, V. 2003, in Galactic Star Formation Across the Stellar Mass Spectrum, ASP Conf. Ser. Vol. 287, ed. J. M. De Buizer & N. S. van der Bliek (ASP, San Francisco), p. 427 (this volume)

Bonnell, I. A. 2000, in Star Formation from the Small to the Large Scale, 33rd ESLAB Symposium, ed. F. Favata, A. A. Kaas, & A. Wilson (ESA SP-445, ESA, Noordwijk), p. 273

Bonnell, I. A. 2002, in Hot Star Workshop III: The Earliest Stages of Massive Star Birth, ASP Conf. Ser. Vol. 267, ed. P. A. Crowther (ASP, San Francisco), p. 163

Bonnell, I. A., & Bate, M. R. 2002, MNRAS, 336, 659

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

Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 1997, MNRAS, 285, 201

Bonnell, I. A., Bate, M. R., & Zinnecker, H. 1998, MNRAS, 298, 93

Bonnell, I. A., Clarke, C. J., Bate, M. R., & Pringle, J. E. 2001, MNRAS, 324, 573

Briceño, C., Luhman, K. L., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, ApJ, 580, 317

Cattaneo, A., Haehnelt, M. G., & Rees, M. J. 1999, MNRAS, 308, 77

Clarke, C. J., Bonnell, I. A., & Hillenbrand, L. A. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Univ. of Arizona Press, Tucson), p. 151

Ebisuzaki, T., Makino, J., Tsuru, T., Funato, Y., Portegies Zwart, S., Hut, P., McMillan, S., Matsushita, S., Matsumoto, H., & Kawabe, R. 2001, ApJ, 562, L19

Eikenberry, S. S., Matthews, K., Garske, M. A., Hu, D., Jackson, M. A., Patel, S. G., Barry, D. J., Colonno, M. R., Houck, J. R., & Wilson, J. C. 2001, BAAS, 33, 1448

Elmegreen, B. G. 1997, ApJ, 486, 944

Elmegreen, B. G. 1999, ApJ, 515. 323

Elmegreen, B. G. 2000a, MNRAS, 311, L5

Elmegreen, B. G. 2000b, ApJ, 539, 342

Elmegreen, B. G., Efremov, Y., Pudritz, R. E., & Zinnecker, H. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Univ. of Arizona Press, Tucson), p. 179

Evans, N. J. 1999, ARA&A, 37, 311

Figer, D. F. 2001, in Starburst Galaxies: Near and Far, ed. L. Tacconi & D. Lutz (Springer-Verlag, Berlin), p. 13

Figer, D. F., & Kim, S. S. 2002, in Stellar Collisions, Mergers, and Their Consequences, ASP Conf. Ser. Vol. 263, ed. M. M. Shara (ASP, San Francisco), p. 287

Figer, D. F., Najarro, F., Morris, M., McLean, I. S., Geballe, T. R., Ghez, A. M., & Langer, N. 1998, ApJ, 506, 384

Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., & McLean, I. S. 1999, ApJ, 525, 750

Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372

Garay, G., & Lizano, S. 1999, PASP, 111, 1049

Gebhardt, K., Pryor, C., O'Connell, R. D., Williams, T. B., & Hesser, J. E. 2000, AJ, 119, 1268

Gerssen, J., van der Marel, R. P., Dubath, P., Gebhardt, K., Guhathakurta, P., Peterson, R., & Pryor, C. 2001, BAAS, 33, 1385

Gomez, M., Hartmann, L., Kenyon, S. J., & Hewett, R. 1993, AJ, 105, 1927

Goodman, A. A., Barranco, J. A., Wilner, D. J., & Heyer, M. H. 1998, ApJ, 504, 223

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

Hunter, D. A., Shaya, E. J., Holtzman, J. A., Light, R. M., O'Neil, E. J., & Lynds, R. 1995, ApJ, 448, 179

Jeans, J. H. 1929, Astronomy and Cosmogony (Cambridge Univ. Press, Cambridge; reprinted by Dover, New York, 1961)

Johnstone, D., Wilson, C. D., Moriarty-Schieven, G., Joncas, G., Smith, G., Gregersen, E., & Fich, M. 2000, ApJ, 545, 327

Johnstone, D., Fich, M., Mitchell, G. F., & Moriarty-Schieven, G. 2001, ApJ, 559, 307

Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576

Klessen, R. S. 2001b, ApJ, 556, 837

Kormendy, J., & Gebhardt, K. 2001, in The 20th Texas Symposium on Relativistic Astrophysics, ed. J. C. Wheeler & H. Martel (AIP Conference Proceedings Vol. 586, AIP Press, New York), p. 363

Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581

Kroupa, P. 2001, MNRAS, 322, 231

Kroupa, P. 2002, Science, 295, 82

Larson, R. B. 1978, MNRAS, 184, 69

Larson, R. B. 1981, MNRAS, 194, 809

Larson, R. B. 1982, MNRAS, 200, 159

Larson, R. B. 1985, MNRAS, 214, 379

Larson, R. B. 1990, in Physical Processes in Fragmentation and Star Formation, ed. R. Capuzzo-Dolcetta, C. Chiosi, & A. Di Fazio (Kluwer, Dordrecht), p. 389

Larson, R. B. 1991, in Fragmentation of Molecular Clouds and Star Formation, IAU Symposium No. 147, ed. E. Falgarone, F. Boulanger & G. Duvert (Kluwer, Dordrecht), p. 261

Larson, R. B. 1992, MNRAS, 256, 641

Larson, R. B. 1995, MNRAS, 272, 213

Larson, R. B. 1996, in The Interplay Between Massive Star Formation, the ISM and Galaxy Evolution, ed. D. Kunth, B. Guiderdoni, M. Heydari-Malayeri, & T. X. Thuan (Editions Frontières, Gif sur Yvette), p. 3

Larson, R. B. 1998, unpublished, in The Orion Complex Revisited, ed. M. J. McCaughrean & A. Burkert (ASP Conference Series, in press), available at www.astro.yale.edu/larson/pubs.html

Larson, R. B. 1999, in Star Formation 1999, ed. T. Nakamoto (Nobeyama Radio Observatory, Nobeyama), p. 336

Larson, R. B. 2000, in Star Formation from the Small to the Large Scale, 33rd ESLAB Symposium, ed. F. Favata, A. A. Kaas, & A. Wilson (ESA SP-445, ESA Publications, Noordwijk), p. 13

Larson, R. B. 2002, MNRAS, 332, 155

Luhman, K. L., & Rieke, G. H. 1999, ApJ, 525, 440

Luhman, K. L., Rieke, G. H., Young. E. T., Cotera, A. S., Chen, H., Rieke, M. J., Schneider, G., & Thompson, R. I. 2000, ApJ, 540, 1016

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

McLure, R. J., & Dunlop, J. S. 2002, MNRAS, 331, 795

Meyer, M. R., Adams, F. C., Hillenbrand, L. A., Carpenter, J. M., & Larson, R. B. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Univ. of Arizona Press, Tucson), p. 121

Miller, G. E., & Scalo, J. M. 1979, ApJS, 41, 513

Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150

Motte, F., & André, P., 2001, in From Darkness to Light: Origin and Evolution of Young Stellar Clusters, ASP Conf. Ser. Vol. 243, ed. T. Montmerle & P. André (ASP, San Francisco), p. 301

Muench, A. A., Lada, E. A., Lada, C. J., & Alves, J. 2002, ApJ, 573, 366

Ostriker, E. C., Gammie, C. F., & Stone, J. M. 1999, ApJ, 513, 259

Portegies Zwart, S. F., & McMillan, S. L. W. 2002, ApJ, 576, 899

Portegies Zwart, S. F., Makino, J., McMillan, S. L. W., & Hut, P. 1999, A&A, 348, 117

Portegies Zwart, S. F., Makino, J., McMillan, S. L. W., & Hut, P. 2002, in Stellar Collisions, Mergers, and Their Consequences, ASP Conf. Ser. Vol. 263, ed. M. M. Shara (ASP, San Francisco), p. 95

Reylé, C., & Robin, A. C. 2001, A&A, 373, 886

Robin, A. C., & Reylé, C. 2003, in Galactic Star Formation Across the Stellar Mass Spectrum, ASP Conf. Ser. Vol. 287, ed. J. M. De Buizer & N. S. van der Bliek (ASP, San Francisco), p. 104 (this volume)

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

Scalo, J. 1986, Fundam. Cosmic Phys., 11, 1

Scalo, J. 1998, in The Stellar Initial Mass Function, ASP Conf. Ser. Vol. 142, ed. G. Gilmore & D. Howell (ASP, San Francisco), p. 201

Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23

Simon, M. 1997, ApJ, 482, L81

Spitzer, L. 1968, in Nebulae and Interstellar Matter, ed. B. M. Middlehurst & L. H. Aller (Univ. of Chicago Press, Chicago), p. 1

Spitzer, L. 1978, Physical Processes in the Interstellar Medium (Wiley-Interscience, New York)

Stahler, S. W., Palla, F., & Ho, P. T. P. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Univ. of Arizona Press, Tucson), p. 327

Stolte, A., Grebel, E. K., Brandner, W., & Figer, D. F. 2003, in Galactic Star Formation Across the Stellar Mass Spectrum, ASP Conf. Ser. Vol. 287, ed. J. M. De Buizer & N. S. van der Bliek (ASP, San Francisco), p. 433 (this volume),

Testi, L., Palla. F., & Natta, A. 1999, A&A, 342, 515

Testi, L. 2003, in Galactic Star Formation Across the Stellar Mass Spectrum, ASP Conf. Ser. Vol. 287, ed. J. M. De Buizer & N. S. van der Bliek (ASP, San Francisco), p. 163 (this volume)

Vázquez-Semadeni, E., Ostriker, E. C., Passot, T., Gammie, C. F., & Stone, J. M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Univ. of Arizona Press, Tucson), p. 3

Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823

Williams, J. P., Blitz, L., & McKee, C. F. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Univ. of Arizona Press, Tucson), p. 97

Zinnecker, H. 1982, in Symposium on the Orion Nebula to Honor Henry Draper, ed. A. E. Glassgold, P. J. Huggins, & E. L. Schucking (Ann. New York Academy of Sciences, Vol. 395, New York), p. 226

Zinnecker, H., McCaughrean, M. J., & Wilking, B. A. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Univ. of Arizona Press, Tucson), p. 429