The Stellar Initial Mass Function: Constraints from Young Clusters, and Theoretical Perspectives

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We summarize recent observational and theoretical progress aimed at understanding the origin of the stellar initial mass function (IMF) with specific focus on galactic star–forming regions. We synthesize data from various efforts to determine the IMF in very young, partially–embedded stellar clusters and find: i) no significant variations in the low–mass IMF have been observed between different star–forming regions; and ii) the mass distributions of young stars just emerging from molecular clouds are consistent with having been drawn from the IMF derived from field stars in the solar neighborhood. These results apply only to gross characterizations of the IMF (e.g. the ratio of high to low mass stars); present observations do not rule out more subtle regional differences. Further studies are required in order to assess whether or not there is evidence for a universal turnover near the hydrogen–burning limit. We also provide a general framework for discussing theories of the IMF, and summarize recent work on several physical mechanisms which could play a role in determining the form of the stellar initial mass function.

I The Stellar Initial Mass Function

A fundamental question in star formation is the origin of stellar masses. Considerable progress has been made in recent years in understanding the formation of single stars, and we now have a working paradigm of the process. Yet quantitative understanding of the distribution of stellar masses formed within molecular clouds remains elusive.

One estimate of the initial distribution of stellar masses comes from studies of volume–limited samples of stars in the solar neighborhood. Combining a variety of parallactic, spectroscopic, and photometric techniques, a luminosity function is derived for main sequence stars. A main sequence mass–luminosity relationship is then applied in order to derive the *present day mass function*, or PDMF, from the luminosity function. Next, the effects of stellar evolution are taken into account in order to derive the *initial mass function*, or IMF. In constructing the "solar neighborhood IMF," the higher mass stars are typically drawn from young associations out to distances of a few kpc, whereas the lower mass stars are drawn from well-mixed disk populations at distances out to tens of pc. Furthermore, because of their short main sequence lifetimes, the high mass stars used in constructing the IMF are quite young ($0.01 - 1 \times 10^8$ yr), while lower mass stars found in the solar neighborhood are systematically older ($1 - 100 \times 10^8$ yr). For these reasons, even a consistent definition of the IMF requires the assumption that it does not vary in time and space within the disk of the galaxy. This implies that the molecular clouds which produced the stars currently found in the solar neighborhood each formed stars with the same IMF as the regions producing stars today. It is precisely this assumption we wish to test with the work reviewed below.

The first comprehensive determination of the IMF over the full range of stellar masses was given by Miller and Scalo (1979; hereafter MS79), subsequently updated by Scalo (1986). Significant revisions have been made more recently at the low mass end (e.g. Kroupa 1998; Reid 1998) and at the high mass end (Garmany et al. 1982; Massey 1998). The reader is referred to Scalo (1986) for a detailed discussion of the ingredients that go into deriving the IMF and Scalo (1998) for a general review of the field. Here we refer to the IMF as the number of stars per unit logarithmic mass interval, and will use the power-law notation $\Gamma = d \log F(\log m_*)/d \log m_*$ to characterize the IMF over a fixed mass range. In this notation, the slope of Salpeter (1955) is $\Gamma = -1.35$.

The IMF deduced from studies of OB associations and field stars in the solar neighborhood exhibits two main features that are generally agreed upon. First, for masses greater than about $5 M_\odot$, the IMF has a nearly power-law form. Massey (1995a; 1995b) find a slope $\Gamma = -1.3 \pm 0.3$ for massive stars in clusters and a steeper power law for high mass stars in the field. Secondly, the mass function becomes flatter for masses $< 1 M_\odot$ (Kroupa, Tout, & Gilmore 1993; KTG). Deriving the field star IMF near 1 $M_\odot$ is severely complicated by corrections for stellar evolution, which require detailed knowledge of the star formation history of the galaxy. Young open clusters may be the best place to measure the IMF between 1–15 $M_\odot$ (e.g. Phelps & Janes 1993). At the lowest masses, there is considerable debate whether or not the IMF continues to rise, is flat, or turns over between $0.1 - 0.5 M_\odot$ (Reid and Gizis 1997; Mera et al. 1996; Kroupa 1995; Gould et al. 1997).

That the IMF seems to change from a pure power–law to a more complex distribution between 1–5 $M_\odot$ provides an important constraint on theories for the origin of stellar masses. Of even greater importance would be the clear demonstration of a peak in the IMF at the low mass end. Considerable observational effort has been focussed on establishing whether or not such a peak exists, and if so, characterizing its location and width (see Figure 1).

In addition, it is extremely important to know whether or not the time– and space–averaged distribution of masses characterizing the solar neighborhood is universal. Do all star–forming events give rise to the same distribution of stellar masses? If star formation is essentially a self-regulating process, then one might expect the IMF to be strictly universal. Alternatively, if stellar masses are determined only by the physical structure of the interstellar medium (e.g. fragmentation), then one might expect differences in the IMF which depend on local conditions such as cloud temperature. Certainly the details of either process depend on the physical conditions of the clouds of gas and dust from which the stars form. The unanswered question is: how sensitively does the distribution of stellar masses depend on the initial conditions in the natal environment?

In this contribution, we outline the observational and theoretical progress which has been made toward understanding the origin of the IMF in star–forming regions. In Section 2, we review advances in deriving mass distributions for very young clusters and attempt to summarize the ensemble of results. In Section 3, we review various theoretical constructs that have been put forward to explain the expected shape of the IMF and its dependance on initial conditions. In Section 4, we summarize our conclusions.

II Stellar Mass Distributions in Star–Forming Regions

Instead of providing a complete survey of the literature, we focus instead on a summary of approaches used and a comparison of results. We begin by describing why young clusters are helpful in understanding of the origin of the IMF. We then outline techniques employed to derive stellar mass distributions in very young clusters, highlighting the advantages and disadvantages of each method. Next, we describe several direct comparisons of mass distributions assembled from the literature on star–forming regions. We then discuss a statistic which provides a gross characterization of the IMF, the ratio of high-to-low-mass stars, and use data from the literature to constrain its variation. Finally, we compare work on star–forming regions with IMF studies of resolved stellar populations in the Milky Way and other galaxies.

A. The Utility of Young Clusters

Astronomers have long used studies of galactic clusters to answer questions concerning the formation and early evolution of stars (Clarke et al. and Elmegreen et al. this volume). Bound open clusters provide a useful starting point, but because they are rare and long–lived it is thought that they do not contribute significantly to the field star population of the galactic disk (cf. Roberts 1958). In contrast, most young embedded clusters are thought to evolve into unbound associations, which comprise the majority of stars that populate the galactic disk (Lada & Lada 1991). Embedded clusters are useful for studying the form of the IMF for several practical reasons. First, because of their youth, evolutionary corrections needed to translate the present day distribution of stellar masses into an IMF are minimized. Second, observations of such clusters are more sensitive to low mass objects because the mass–luminosity relationship for stars in the pre–main sequence phase is not as steep a function of mass as for stars on the main sequence. Third, because of their compactness, they occupy small projected areas on the sky, reducing the contamination by foreground stars that plague studies of larger optically–visible associations. Finally, the molecular cloud cores that contain embedded clusters provide natural screens against background stars, which would otherwise contaminate the sample. Thus, we can attempt to derive distributions of stellar masses for particular star–forming events associated with individual molecular cloud cores. We can then determine whether or not the IMF varies as a function of cloud conditions, providing insight into its origin (cf. Williams et al. this volume).

B. Approaches Used to Study Emergent Mass Distributions of Young Clusters

Of course, partially–embedded young clusters also present difficulties to astronomers interested in deriving their stellar mass distributions. First of all, on–going star formation is typically observed in these clusters. As such, the observed mass distribution is only a "snap–shot" of the IMF for the star–forming event, and may not represent the integrated final product of the cloud core. In order to keep this distinction clear between the *initial mass function* (as defined from the solar neighborhood sample) and the observed mass distributions of embedded young clusters, we will refer to these "snap–shots" of the IMF as *emergent mass distributions* (EMDs). Another complication in studying embedded clusters is the time dependent nature of the mass–luminosity (M–L) relationship (required for translating an observed luminosity function into a mass distribution) for PMS stars. Third, large and variable obscuration makes correction for extinction on an individual star–by–star basis important for many embedded clusters. Uncertainties in extinction–corrected absolute magnitudes can be reduced by observing embedded clusters at longer wavelengths. For example, interstellar extinction in the K–band (2.2 μm) is $\times$ 10 smaller than in the V–band (0.55 μm) and $\times$ 3 smaller than in the J–band (1.25 μm). However, at wavelengths beyond 2.0 μm, the observed flux from PMS cluster members is frequently contaminated by excess emission. The near–IR excess (associated with hot circumstellar dust located in the inner–disk region) complicates the interpretation of monochromatic near–IR luminosity functions as *stellar* bolometric luminosity functions (e.g. Meyer et al. 1997). Most recent attempts to derive emergent mass distributions from observations of embedded young clusters are based on: i) modeling of monochromatic near–infrared luminosity functions; ii) analysis of multi–color photometric data; iii) spectroscopic survey samples; or iv) some combination of these techniques. We discuss each of these methods (along with their pros and cons) below.

A comprehensive review of embedded cluster work published before PPIII is given by Zinnecker, McCaughrean, and Wilking (1993; ZMW). Many of these studies compared the observed distribution of K–band magnitudes with that expected from a standard IMF convolved with a main–sequence M–L relationship (e.g. Lada, Young, & Greene 1992; Greene & Young 1992). In contrast, ZMW constructed models for the *evolution* of embedded cluster luminosity functions by transforming theoretical PMS evolutionary tracks into an observational plane. They generated synthetic K–band luminosity functions (KLFs) for clusters with ages 0.3–2 Myr from an assumed input IMF. Ali and DePoy (1995; see also Megeath 1996) made allowances for spatially–variable extinction and excess emission due to circumstellar disks in their analyses of KLFs. Lada and Lada (1995; see also Giovannetti et al. 1998) extended these approaches by considering continuous as opposed to discretized star formation.

With multi–color photometry, one increases the amount of information and thus decreases the number of assumptions needed to derive an EMD. Strom et al. (1993; see also Aspin et al. 1994) attempted to deredden individual embedded sources by assuming the same intrinsic color for each star; they also considered dereddened J–band luminosity functions (as opposed to K–band) to minimize the effect of infrared excess emission. Many studies of embedded young clusters assume an input mass distribution which is combined with analysis of an observed luminosity function to derive the cluster age or age distribution. In principle, extensions of these techniques could place constraints on the stellar mass distribution. By making the shape of the input mass spectrum a variable, certain distributions could be ruled out if found inconsistent with the observed luminosity function for any reasonable input age distribution (e.g. Lada, Lada, and Muench 1998). In practice, treating both mass and age distributions as variables makes it difficult to find a unique best–fit solution.

Comeron et al. (1993) developed a novel technique for analyzing multi–color photometric data of embedded clusters. By modeling spectral energy distributions of embedded sources, one can estimate the exinction, intrinsic luminosities, and the spectral slopes of the SEDs. The spectral slopes are taken as an indicator of evolutionary state and volume–corrections are applied to the sample as a function of intrinsic luminosity. This latter step takes into account the fact that more luminous objects probe larger volumes in flux–limited samples. Adopting M–L relationships deemed appropriate for the evolutionary state of the objects in question, the luminosity function is then transformed into an emergent mass distribution. Comeron et al. (1996) expanded on this approach by adopting appropriate M–L relationships in a Monte Carlo fashion from an assumed age distribution. Meyer (1996) developed an alternate method which utilizes multi–color photometry to deredden individual embedded sources, explicitly taking into account the possibility of near–infrared excess emission. Then by adopting an age (or age distribution) for a cluster, dereddened absolute J–band magnitudes are used to estimate stellar masses. In this case, an extinction–limited sample is used to derive an emergent mass distribution that is not biased toward higher mass stars seen more deeply into the cloud.

Ultimately, the construction of reliable IMFs for a large number of young clusters, forming under a wide range of conditions, requires a combination of deep photometric survey work and follow–up spectroscopic analysis. Spectra allow one to derive the photospheric temperatures for the embedded objects and place them in the H–R diagram. Comparing the positions of sources in the H–R diagram with PMS evolutionary models provides estimates of the mass and age distributions of the sample. Ideally, we would like to have *complete* spectroscopic samples for each cluster. In practice, often the best we can do is obtain spectra for a sub–set of the photometric sample (either representative or flux–limited), providing an estimate of the cluster age. With this constraint on the age–dependent M–L relationship, one can characterize the dereddened luminosity function in terms of the emergent mass distribution for the cluster and compare it to the solar neighborhood IMF. While the spectroscopic techniques allow a more unambiguous accounting for the effects of extinction, infrared excess and a stellar age distribution, the photometric techniques have the distinct advantage that they can be applied to fainter stellar populations at much greater distances. It is important to remember that in all of these methods, the masses derived for individual stars depend sensitively on the adopted PMS evolutionary tracks. As a result, estimates of mass scales at which inflections are observed in the detailed distribution functions are necessarily uncertain until we have a better calibration of PMS evolutionary tracks.

C. Three Techniques for Direct Comparison of EMDs

Direct comparisons between observations of two independent star–

forming regions provide the best means to uncover differences in the emergent mass distributions of clusters. Statistical tests (such as the Kolmogorov–Smirnov test; Press et al. 1993) between individual distributions are more informative than comparisons to uncertain analytic functions such as those derived for the field star IMF. Provided that studies of young clusters are performed in a uniform way, we can overcome uncertainties in the various techniques by making relative rather than absolute comparisons. However, care must be taken in applying such statistical tests, since any systematic differences in the observations between two studies can easily produce a significant signal in the KS test. Here, we restrict ourselves to three datasets, each of which has been assembled using the same analysis so that meaningful comparisons for different clusters can be made. We begin with the KLF analyses of IC 348 and NGC 1333. Next we review the multi–color photometric surveys of Ophiuchus and NGC 2024, informed by follow–up spectroscopy. Finally, we compare the extensive spectroscopic surveys for the Orion Nebula cluster and IC 348.

K–Band Luminosity Functions: IC 348 vs. NGC 1333

IC 348 and NGC 1333 are both young clusters in the Perseus cloud, located at a distance of 320 pc (Herbig 1998). Lada and Lada (1995) present near–IR imaging of IC 348; 380 sources are identified in excess of the measured field star population. Because of low extinction and the low fraction of association members exhibiting strong near–infrared excess emission (< 25 %), the observed KLF gives a reasonable estimate of the stellar luminosity function, albeit convolved with an age distribution. Lada, Alves, and Lada (1996) performed a similar near–IR survey of NGC 1333, identifying a "double–cluster" of 94 sources. However, in this case, differential extinction seriously affects the observed KLF and, in addition, $\sim$50% of the association members displayed strong infrared excess emission. To correct for extinction, the cluster populations were dereddened using $(H - K)$ colors. This dereddened KLF was compared with that observed for IC 348 and with that published for the Trapezium cluster by ZMW, corrected for the difference in distance. The KLF's for NGC 1333 and the Trapezium are consistent with having been drawn from the same parent population. As both clusters are thought to be the same age and to have similar IR excess frequencies, this result suggests that the underlying mass functions are similar. Comparison of the KLFs for NGC 1333 and IC 348 yields a different result: there is only a 20 % chance that they were drawn from the same distribution. Lada, Alves, and Lada (1996) point out that the observed KLFs of all three clusters could be derived from the same underlying mass functions, but convolved with different age distributions. Without independent estimates of the cluster ages based on spectroscopic observations, it is difficult to draw robust conclusions.

Combining Spectroscopy & Photometry: Ophiuchus vs. NGC 2024

Comeron et al. (1993; CRBR) conducted a K-band imaging survey of the Ophiuchus cloud core (d $\sim$ 150 pc) within the $A_V > 50^m$ molecular contour and obtained follow–up four color photometry for all sources $K < 14.5^m$. Strom, Kepner, and Strom (1995; SKS) published a comparable multi–color imaging survey, focusing on the "aggregates" associated with dense cores located within the $A_V > 50^m$ contour. Greene and Meyer (1995) combined infrared spectroscopy of 19 embedded sources with photometry from SKS in order to place them on the H–R diagram and to estimate masses and ages directly. Williams et al. (1995) obtained spectra for three candidate low mass objects from the sample of CRBR. They compared the IMF results of CRBR and SKS and found them to be in broad agreement. Combining results from both studies of Ophiuchus yielded an emergent mass distribution from 0.1–5.0 $M_\odot$ with $\Gamma \sim -0.1$.

Comeron et al. (1996) performed a deep near–infrared survey of several fields toward the embedded cluster associated with NGC 2024 (d $\sim$ 470 pc). Assuming an age distribution for the cluster, they derive a mass function between 0.08–2.0 $M_\odot$ that is nearly flat with no evidence for a turnover at the low mass end ($\Gamma = -0.2 \pm 0.1$) consistent with the CRBR results for Ophiuchus. Meyer et al. (1999) present a multi–color near–IR survey of the innermost 0.5 pc of NGC 2024, sampling 0.1 $M_\odot$ stars viewed through $A_V < 19.0^m$. Combining this photometric survey with near–IR spectra for two dozen sources in the region, an H–R diagram was constructed. Taking the age derived from the H–R diagram as characteristic of the entire embedded population, they estimate the extinction toward each star and construct a stellar luminosity function complete down to 0.1 $M_\odot$.

Given that existing near-infrared surveys of the embedded clusters associated with NGC 2024 and the Ophiuchus molecular cloud are of comparable sensitivity ($M_K < 4.5^m$ & $A_V < 19^m$) and physical resolution($d \sim 400$ AU), we can directly compare the derived luminosity functions. The K–S test reveals that there is a small chance that the stellar luminosity distributions were drawn from the same parent population ($P = 0.04$). Meyer et al. (1999), in making this comparison, investigate three factors that can affect the shape of the stellar luminosity function for an embedded cluster: age distribution, accretion properties, and emergent mass distribution. Comparison of the H–R diagrams shows that the evolutionary states of both clusters are similar. Comparison of the JHK color–color diagrams for complete samples in each cluster reveals that they are consistent with having been drawn from the same parent population, suggesting that the accretion properties of NGC2024 and Ophiuchus are also similar. Although the KS test suggests differences in the luminosity functions which could be attributed to differences in the mass functions, the uncertainties make it difficult to argue that the emergent mass distributions are significantly different.

Complete Spectroscopic Samples: IC 348 vs. The Orion Nebula Cluster

Herbig (1998) conducted an extensive photometric and spectroscopic survey of IC 348, placing $\sim$ 80 optically–visible stars on the H–R diagram. The derived age distribution was used to study the mass distribution of a larger photometric sample in the $(V-I)$ vs V color–magnitude diagram. Based on a sample of 125 stars fitted to the PMS evolutionary models of D'Antona and Mazzitelli (1994; DM94) in the $(V-I)$ vs V color–magnitude diagram, the derived mass function is similar to the Scalo (1986) IMF down to 0.3 $M_{\odot}$. Luhman et al. (1998) independently conducted an infrared and optical spectroscopic study of the IC 348 region. Spectra were obtained for 75 sources from the photometric survey of Lada & Lada (1995). Luhman et al. claim completeness of the spectroscopic sample down to 0.1 $M_{\odot}$. Masses are estimated for the sources lacking spectra by adopting the M–L relationship suggested by the extant spectroscopic sample, and a corrected emergent mass distribution is constructed for the cluster. The Orion Nebula Cluster (ONC) is the richest young cluster within 1 kpc and has been the target of several photometric studies in the last decade (Herbig and Terndrup 1986; McCaughrean & Stauffer, 1994; Ali & DePoy 1995). Hillenbrand (1997) present results from an optical spectroscopic survey of nearly 1000 stars located within $\sim$ 2 pc of the Trapezium stars. ¿From the resulting distribution of stellar masses derived from the H–R diagram (down to 0.1 $M_{\odot}$), Hillenbrand concludes that the cluster mass function turns over at $\sim$ 0.2 $M_{\odot}$.

IC 348 and the ONC have the most complete EMDs derived to date among the very young clusters studied spectroscopically. As a result, it is desirable to compare them directly (Figure 2). We use masses derived from the DM94 tracks in this excercise, and note that even this direct comparison using identical observational techniques is only "model independent" to the extent that the clusters exhibit similar age distributions – such that we are using comparable theory to translate observables into stellar masses. Comparison of the EMD derived globally for the ONC cluster (605 stars $A_V < 2.0^m$) with that presented for IC 348 (73 stars $A_V < 5.0^m$) over the mass range 0.1–2.5 $M_{\odot}$ indicates that the two mass distributions were not drawn from the same parent population ($P = 5.92 \times 10^{-5}$). However, when a restricted sample from the inner ONC is taken (133 stars within $r < 0.5$ pc, comparable to the physical size of the Luhman et al. region in IC 348), we cannot rule out that they were drawn from the same distribution ($P = 0.06$), despite $\times 100$ difference in central stellar density! This latter result could be due in part to the smaller sample considered;

the smaller the differences between the EMDs of different regions, the larger the sample size needed to discern them.

D. Synthesis of Results for an Ensemble of Clusters

To study the IMF over the full range of stellar masses, we require photometric observations that are sensitive below the hydrogen burning limit for the distance and age of the cluster. We also wish to sample the stellar population through some well–determined and significant value of extinction. Finally, we need follow–up spectroscopy in order to inform cluster age estimates – crucial for adopting an appropriate M–L relationship. Why have so few quantitative results emerged from the study of EMDs in very young clusters? Since PPIII, comprehensive spectroscopic studies of young stellar populations have been conducted towards a variety of star–forming regions (e.g. Alcala et al. 1997; Allen 1996; Hughes et al. 1994; Lawson et al. 1996; Walter et al. 1994; 1997). These studies, while providing crucial tests of many aspects of PMS evolution, are not ideally suited for studying emergent mass distributions. For example, Hα, x–ray, and variable star samples impose activity–related selection effects which make it difficult to assess completeness. Even in the well–studied Taurus dark cloud (Kenyon and Hartmann 1995) only now are samples complete down to the hydrogen burning limit becoming available (Briceno et al. 1998). Armed with deep photometric surveys, often we are still faced with a statistical problem. The clusters and aggregates found in typical molecular clouds contain only tens to hundreds of stars; populous regions like the ONC are rare. As demonstrated above, detailed comparisions of mass/luminosity functions based on sample sizes $\ll 1000$ are inconclusive unless gross differences exist in the underlying distributions. In this section, we compare results from a variety of recent studies and ask whether the ensemble of results can tell us something about the shape of the IMF.

One approach is to use mass bins that are significantly wider than the errors in the assigned stellar masses from the methods described above. For example, in the study of nearby star-forming regions, a particularly useful diagnostic is the ratio $\mathcal{R}$ of intermediate-to-low-mass stars,

$$\mathcal{R} = N(1 - 10M_{\odot})/N(0.1 - 1M_{\odot}).$$

Each of the techniques outlined above for characterizing the emergent mass distribution can be collapsed into such a ratio. In Table 1, we present the $\mathcal{R}$ values for various regions for which the ratio of intermediate-to-low-mass stars can be constructed, based on data assembled from the literature. We restrict this analysis to regions located within 1kpc of the Sun, for which a flux–limited survey down to a well–defined completeness limit exists, along with complementary spectroscopy to constrain the age distribution of the association members. In Figure 3, we compare the ratio of intermediate-to-low-mass stars derived for nine such regions to the same ratio predicted from various analytic forms of the IMF.

The range and errors in the values measured for the ratio $\mathcal{R}$ of intermediate-to-low-mass stars suggest a conservative conclusion: *most extremely young, compact star–forming regions exhibit EMDs consistent with having been drawn from the field star IMF within our ability to distinguish any differences.* The small sizes of existing observational samples, and the coarse nature of the tests we have been able to perform, allow us to detect only gross differences between the observed mass distributions and various forms of the field star IMF. For example, it is clear that the Salpter (1955) IMF does not hold below 1.0 $M_{\odot}$, as it predicts a ratio of intermediate to low mass stars of $\mathcal{R}$ = 0.04, compared to $\mathcal{R}$ = 0.17 for the MS79 IMF. Furthermore, the IMF does not have a sharp truncation at masses well above 0.1 $M_{\odot}$. If the MS79 IMF were truncated at 0.4 $M_{\odot}$, the expected ratio of intermediate to low mass stars would be 0.4, which is also excluded by the data. Finally, based on the information in Table 1, we can can rule out dramatic dependencies of the IMF on environmental characteristics such as cloud temperature (as measured from molecular line observations) or mean stellar volume density (averaged over a region $r \sim 0.3$ pc).

E. Comparisons to Other Estimates of the Galactic IMF

Because differences in observational technique could introduce important systematic errors, it is dangerous (though interesting!) to compare results derived for young clusters in star–forming regions with other constraints on the IMF. Much recent work has focussed on nearby open clusters with ages < 1 Gyr which share some of the attributes that make star–forming regions excellent places to search for variations in the IMF. Bouvier et al. (1998; see also Williams et al. 1996; Zapatero Osorio et al. 1997) have derived the IMF for the Pleiades open cluster well into the brown dwarf regime. Although the ratios $\mathcal{R}$ for the Pleiades (120 Myr) and the much younger Trapezium are both consistent with having been drawn from the field star IMF, the detailed mass distributions are much different ($P(d > obs) = 1.9 \times 10^{-38}$!). This is probably due largely to differences in the techniques used and the adopted PMS tracks, although it could reflect true differences in the IMF. Hambly et al. (1995) studied the IMF below 1.0 $M_{\odot}$ in the 900 Myr–old metal–rich cluster Praesepe, finding a slope $\Gamma = -0.5$ between 0.1–1.0 $M_{\odot}$ though Williams et al. (1995a) find a somewhat shallower $\Gamma = -0.34 \pm 0.25$. Pinfield et al. (1997) have extended this work down into the brown dwarf regime and find a steeper rise in the mass function. There has been additional work identifying low mass stars and brown dwarf candidates in other clusters including α Per (Zapatero

Osorio et al. 1996) and the twin clusters IC 2602/2391 (Stauffer et al. 1996), though detailed investigations of the IMF are not yet available.

Phelps and Janes (1993) derive the IMF between 1.4–9.0 $M_\odot$ for a dozen older open clusters observed in the disk of the Milky Way. Although most regions are consistent with a power–law slope of $\Gamma = -1.4 \pm 0.13$, two regions exhibit significantly different IMFs (NGC 581 & NGC 663). Similar results are reported by Sagar et al. (1996) though intriguing differences between clusters are found over small mass ranges. Further support for a roughly universal IMF comes from von Hippel et al. (1996), who demonstrate that the observed turn–overs in luminosity functions observed in a variety of cluster environments are correlated with metallicity (as expected, given the dependence of the mass–luminosity relationship on metallicity). Studies of the low metallicity "Pop II" component of the Milky Way are in surprisingly good agreement concerning the shape of the low mass IMF. Results from globular clusters (cf. Chabrier & Mera 1997; Cool et al. 1998 and references therein), spheroid populations (Gould et al. 1997), and the bulge (Holtzman et al. 1998) indicate that $\Gamma \sim 0.0 \pm 0.5$, consistent with the field star IMF and our results for young clusters.

Massey and collaborators (1998 and references therein) also find that the high mass end of the IMF does not change with metallicity; their results suggest that the IMF is well fit by a similar power–law in the LMC, the SMC, and the Milky Way. These results are generally confirmed by other studies of resolved galactic and extragalactic OB associations (e.g. Brown 1998; Bresolin et al. 1998). However, the mass distribution of "field" OB stars does seem to differ from that for stars found in clusters. In studies of the low mass component of giant HII regions in the Milky Way (NGC 3603, Eisenhauer et al. 1998; W3, Megeath et al. 1996) and the LMC (R136 in 30 Dor; Hunter et al. 1996; Brandl et al. 1996), the distributions of stellar masses are consistent with the field star IMF, at least down to 1.0 $M_\odot$. Deeper observations obtained at higher spatial resolution will be required to sample the IMF down to the hydrogen–burning limit.

Taken as a whole, the preponderance of the evidence suggests that crude characterizations of the IMF (such as the ratio of high to low mass stars) do not vary strongly as a function of metallicity, star–forming environment, or cosmic time. That said, there are indications of possible variations in the IMF; the ONC vs. IC 348, results for NGC 581 & 663 compared to other open clusters, and the massive star IMF derived from the field sample compared to results from associations. It is these differences which may provide clues to help unravel the mystery surrounding the origins of stellar masses. Finally, we note that all the results discussed above are for the "system IMF", not accounting for unresolved binary stars. In order to quantify this effect, we need not only the distribution of masses for the composite systems, but also the distribution of companion mass ratios (Mathieu et al. this volume). Knowing both the IMF and the distribution of companion mass ratios is crucial to understanding the process of star formation. However in what follows, we concentrate on theories which might explain the origin of the system IMF.

III Some Theoretical Ideas on the Origin of the IMF

Although the current theory of star formation remains incomplete, we can begin to consider approaches to the IMF problem. In this section, we discuss briefly some current theoretical ideas that may be relevant to the origin of the stellar IMF. Given the limited space available, we can only discuss some of the many ideas that have been proposed. We also emphasize that we still have only rather speculative ideas to discuss. Additional theoretical reviews can be found elsewhere (e.g. Clarke 1998, Larson 1998, Elmegreen 1998).

A. Towards a General Formulation

Within the context of the current theory of star formation, it is often useful to conceptually divide the process which determines the IMF into two subprocesses: **[1]** The spectrum of initial conditions produced by molecular clouds or other star forming environment. **[2]** The transformation between a given set of initial conditions and the properties of the final (formed) star.

In this section, we outline one particular approach to constructing theories of the initial mass function. In an IMF theory, the final mass of a forming star must be determined through some physical mechanism. The identification of that mechanism, which could include many different physical processes, lies at the heart of determining a theory of the IMF. In practical terms, we need to specify the transformation between the initial conditions and the final stellar properties (Adams & Fatuzzo 1996; Khersonsky 1997). For example, the mass of the star M_* could be given by a "semi-empirical mass formula" (SEMF) or "transfer function" of the form $M_* = M_*(\alpha_1, \alpha_2, \alpha_3, \ldots)$, where the α_j are the physical variables that determine the mass of the star. In the limit in which a large number of physical variables is required to determine stellar masses, we obtain a particularly simple result, suggesting a statistical approach to the calculation of the IMF.

We would like to find a relationship between the distributions of the initial variables and the resulting distribution of stellar masses (the IMF). For many (but certainly not all) cases of interest, the transformation can be written as a product of variables, i.e.,

$$M_* = \prod_{j=1}^{N} \alpha_j \, , \tag{3.1}$$

where the α_j represent the relevant physical variables (which could be the sound speed a, the rotation rate Ω, etc., taken to the appropriate powers). Each of these variables has a distribution $f_j(\alpha_j)$ with a mean value $\ln \bar{\alpha}_j \equiv \langle \ln \alpha_j \rangle$ and a corresponding variance σ_j^2.

In the limit of a large number N of variables, the composite distribution (the IMF) approaches a log-normal form. This behavior is a direct consequence of the central limit theorem (Richtmyer 1978) and has been invoked by many authors (Larson 1973, Elmegreen & Mathieu 1983, Zinnecker 1984, Adams & Fatuzzo 1996). Whenever a *large* number of independent physical variables are involved in the star formation process, the resulting IMF can be *approximately* described by a log-normal form. The departure of the IMF from a purely log-normal form depends on the shapes of the individual distributions f_j and on the number of relevant variables. However, in the limit that the IMF can be described to leading order by a log-normal form, there are simple relationships between the distributions of the initial variables and the shape parameters m_C and $\langle \sigma \rangle$ that determine the IMF. The mass scale m_C is determined by the mean values of the original variables α_j, and the dimensionless shape parameter $\langle \sigma \rangle$ is determined by the widths σ_j of the initial distributions, i.e., $m_C \equiv \prod_j \exp[\langle \ln \alpha_j \rangle]$ and $\langle \sigma \rangle^2 = \sum_j \sigma_j^2$.

In the limit that star formation involves a large number of statistically independent variables, we would obtain a "pure" log-normal distribution. In this limit, the only relevant parameters are the total width of the distribution $\langle \sigma \rangle$ and the mass scale of the distribution m_C, and these parameters are constrained by observations of the IMF; The quantities $\langle \sigma \rangle$ and m_C are determined by the distributions of the physical variables in the problem. In a complete theory, we could calculate these initial distributions from *a priori* considerations. In the absence of a complete theory, however, we can use observations of the physical variables to estimate their distributions and hence determine $\langle \sigma \rangle$ and m_C.

Although the number of physical variables involved in the star formation process may be large, it is certainly not infinite. An important challenge of the future will be to unambiguously identify the relevant physical variables in the problem. In any case, the IMF will never *completely* converge to a log-normal form. Instead, *the distribution will retain tails*, departures from a log-normal form, at both the high mass and low mass ends. Even though the composite distribution does not obtain a purely log-normal form, however, the theoretical predictions for the mass scale m_C and total variance $\langle \sigma \rangle$ must be consistent with the constraints from the observed IMF.

B. Gravitational Instability and the Jeans Criterion

In order for a clump of gas to collapse and form stars, its self-gravity must overcome the effects tending to prevent collapse. On large scales, turbulence and magnetic fields provide the dominant form of support against gravity, while in the densest core regions of molecular clouds, thermal pressure is the dominant supporting force. A minimal requirement for collapse to occur is thus the classical Jeans criterion that the self-gravity of a dense core must overcome its thermal pressure; for a given temperature and density, this implies a minimum size and mass called the Jeans length and Jeans mass. For density fluctuations in an infinite uniform medium with density ρ and isothermal sound speed a, the minimum unstable mass is $\pi^{3/2}a^3/G^{3/2}\rho^{1/2}$ (Jeans 1929; Spitzer 1978). Although this result is not self-consistent in that it neglects the overall collapse of the medium, dimensionally equivalent results are obtained from analyses of the stability of equilibrium configurations. For a sheet, disk, or filament with surface density μ, the minimum unstable mass is a few times $a^4/G\mu^2$ (Larson 1985). For an isothermal sphere confined by an external pressure P, the minimum unstable mass is $1.18\,a^4/G^{3/2}P^{1/2}$ (Ebert 1955; Bonnor 1956; Spitzer 1968). These expressions are all dimensionally equivalent since $P = \rho a^2$ and since $P \sim G\mu^2$ in a self-gravitating configuration; thus they are basically different expressions for the same quantity, for which the term 'Jeans mass' is a convenient name. If star-forming cores are created by turbulence in molecular clouds (Larson 1981), and if they are confined by a characteristic non-thermal pressure arising from the cloud formation process (Larson 1996; Myers, 1998), then the best estimate of the Jeans mass may be the mass of a critically stable 'Bonnor-Ebert sphere' bounded by this pressure. For a typical molecular cloud temperature of 10 K and a typical non-thermal cloud pressure of 3×10^5 cm^{-3} K, this quantity is about $0.7\,\mathrm{M}_\odot$, similar to the observed typical stellar mass (Larson 1998).

Direct evidence for the existence of gravitationally bound clumps having about the Jeans size and mass in a star-forming cloud has been found in recent millimeter continuum mapping of the ρ Ophiuchus cloud (Motte, André, & Neri 1998). The observed clumps have masses between 0.05 and $3\,\mathrm{M}_\odot$ and a mass spectrum that closely resembles the stellar IMF, becoming flatter below $0.5\,\mathrm{M}_\odot$; thus they may be the "direct progenitors of individual stars or systems" (Motte et al. 1998). The separations between these clumps are comparable to the predicted fragmentation scale of about 0.03 pc in the ρ Oph cloud, and this suggests that they have been formed by gravitational fragmentation of the cloud.

Since a forming star grows in mass by accretion from a surrounding envelope, the final mass that it attains depends on how much matter is accreted. Within the thermally supported inner region, the standard picture of nearly radial infall from a nearly spherical envelope may apply, but outside this region turbulence and magnetic fields dominate the dynamics, and further accretion may be inhibited by these effects. A rigorous treatment of the problem is possible in the case where the envelope is supported by a static magnetic field, as in the standard model where collapse is initiated by slow ambipolar diffusion in a magnetically supported configuration. According to a number of recent studies, even in this case a central region having approximately the thermal Jeans mass begins to collapse dynamically at an early stage, producing a high initial accretion rate but leaving behind a magnetically supported envelope that is accreted more slowly (e.g., Basu 1997; Safier et al. 1997; Ciolek & Königl 1998). Most of the final stellar mass is probably acquired during the early phase of rapid accretion, but infall may not stop completely after a Jeans mass has been accreted. The final termination of accretion may be caused by the onset of a stellar wind, as discussed below.

C. The Role of Outflows

In this section, we explore the possibility that stars themselves determine their masses through the action of stellar winds and outflows. Protostellar outflows are sufficiently energetic to affect the overall support of a molecular cloud (Norman & Silk 1980) and have been conjectured to halt the inward accretion flow of a forming star (Shu 1985). This idea has been used as the basis for constructing various theoretical models of the IMF (e.g., Silk 1995, Nakano et al. 1995, Adams & Fatuzzo 1996).

Molecular clouds provide the initial conditions for the star forming process. These clouds are supported against gravity by both turbulent motions and by magnetic fields. As the fields gradually diffuse outward, the clouds produce centrally condensed structures, molecular cloud cores, which represent the initial conditions for protostellar collapse. In the simplest picture, these cores can be characterized by two physical variables: the effective sound speed a and the rotation rate Ω. The effective sound speed generally contains contributions from both magnetic fields and turbulence, as well as the thermal contribution.

When molecular cloud cores undergo dynamic collapse, the central regions fall in first and successive outer layers follow as pressure support is lost from below (Shu 1977). Because the initial state contains angular momentum, some of the infalling material collects into a circumstellar disk surrounding the forming star. The collapse flow is characterized by a mass infall rate $\dot{M} \approx a^3/G$, the rate at which the central star/disk system gains mass from the collapsing core. The total amount of mass available to a forming star is generally much larger than the final mass of the star.

In this rotating accretion flow, the ram pressure of the infall is weakest at the rotational poles of the object. The central star/disk system gains mass until it is able to generate a powerful stellar wind which breaks through the infall at the rotational poles and thereby leads to a bipolar outflow configuration. Although the mechanism which generates these winds remains under study (e.g. Shu et al.; Königl & Pudritz this volume), the characteristics of outflow sources have been well determined observationally (Padman et al. 1997; Richer et al. this volume). The basic working hypotheses of the "outflow conjecture" is that these outflows help separate nearly formed stars from the infalling envelope and thereby determine, in part, the final masses of the stars. In this scenario, the transformation between initial conditions and stellar masses is accomplished through the action of stellar winds and outflows. The central star/disk system gains mass at a well–defined mass infall rate. As the nascent star gains mass over time, it becomes more luminous, and produces an increasingly more powerful stellar outflow. When the strength of this outflow becomes larger than the ram pressure of the infalling material, the star separates itself from the surrounding molecular environment and thereby determines its final mass.

We can use this idea to calculate a transformation between the initial conditions in a molecular cloud core and the final mass of the star produced by its collapse. Using the idea that the stellar mass is determined when the outflow strength exceeds the infall strength, we can write this transformation (the SEMF) in the form

$$L_* M_*^2 = 8 m_0 \gamma^3 \delta \frac{\beta}{\alpha \epsilon} \frac{a^{11}}{G^3 \Omega^2} = \Lambda \, \frac{a^{11}}{G^3 \Omega^2} \, , \tag{3.2}$$

where the parameters α, β, γ, δ, and ϵ are efficiency factors (Adams & Fatuzzo 1996; Shu et al. 1987). This formula specifies a transformation between initial conditions (the sound speed a and the rotation rate Ω) and the final properties of the star (the luminosity L_* and the mass M_*). Since the protostellar luminosity L_* as a function of mass is known, we can find the final stellar mass in terms of the initial conditions. In general, all of the quantities on the right hand side of equation [3.2] will have a distribution of values. These individual distributions ultimately determine the composite distribution of stellar masses M_*.

In principle, the physical variables appearing in equation [3.2] can be measured observationally. If we use the observed distributions of these variables to estimate the shape parameters appearing in the IMF, we obtain $m_C \approx 0.25$ and $\langle \sigma \rangle \approx 1.8$. These values are in reasonably close agreement with those required to fit the MS79 IMF, namely $m_C = 0.1$ and $\langle \sigma \rangle = 1.57$. Although a quantitative comparison with observations is premature, this approach to the IMF contains some predictive power and is roughly consistent with observations.

The main weakness of this outflow approach is that the interaction between stellar outflows and the inward accretion flow has not yet been calculated. Highly collimated outflows can only reverse the infall along the poles of the system. The outflows must therefore widen with time and must be able to suppress accretion over most of the solid angle centered on the star. Although some observational evidence suggests that outflows can successfully reverse the inward accretion flow (Velusamy & Langer 1998), this issue remains open, on both the theoretical and observational fronts.

D. Hierarchical Fragmentation

Since the Jeans mass decreases with increasing density, it is possible that a collapsing cloud can fragment into successively smaller pieces as its density increases. This hypothesis of hierarchical fragmentation (Hoyle 1953) has formed the basis of many theories of the IMF. In principle, a wide spectrum of stellar masses can be produced in this way, depending on how many clumps stop subdividing and collapse directly into individual stars at each stage of the overall collapse. For example, if the probability of further subdivision of a cloud fragment is the same for each unit logarithmic increase in density, a log-normal IMF is produced (Larson 1973).

Numerical simulations of fragmentation in collapsing clouds suggest that hierarchical fragmentation is of limited importance. For example, a rotating cloud does not fragment significantly until it has collapsed to a disk, since the development of subcondensations is inhibited by pressure gradients and does not get ahead of the overall collapse (Tohline 1980; Monaghan & Lattanzio 1991). This result reflects the inconsistency of the original Jeans analysis, which neglected the overall collapse, and suggests that significant fragmentation does not occur until large-scale collapse has stopped and a near-equilibrium configuration has formed. Such a configuration may then fragment as expected from linear stability theory (Larson 1985). The formation of an equilibrium disk is an idealized case, but transient near-equilibrium structures such as sheets or filaments may often be created by turbulence in molecular clouds. Much of the observed structure of these clouds is in fact filamentary, and many observed star-forming cores may have formed by the fragmentation of filaments (Schneider & Elmegreen 1979). Thus, star-forming cores may form directly by a single stage of fragmentation, rather than through a series of stages of hierarchical fragmentation.

Hierarchical fragmentation may still be relevant to the formation of low-mass stars in the binary and small multiple systems that are the typical outcome of the collapse of Jeans-mass cloud cores (Larson 1995). Numerical simulations show that multiple systems containing several accreting and interacting 'protostars' are often formed in this case (Burkert, Bate, & Bodenheimer 1997), and these objects are often surrounded by disks or spiral filaments that can fragment into yet smaller objects, so that some amount of hierarchical fragmentation is possible. However, coalescence can also occur and reduce the number of fragments, and more work is needed to determine the final outcome (Bodenheimer et al. this volume). Such small-scale fragmentation processes may be responsible for the formation of the least massive stars, and may help to determine the form of the lower IMF. At present, however, both observations and simulations suggest that only a small fraction of the mass participating in such processes goes into the smallest objects or 'proto-brown-dwarfs'.

We can place this hierarchical fragmentation scenario into the general picture of §3.A. As a cloud core fragments into successively smaller pieces, we can follow one particular chain of fragmentation events to the final fragment mass. After one round of fragmentation, the piece that we are following has mass $M_1 = f_1 M_0$, where f_1 is a fraction of the original core mass M_0. After N iterations of this hierarchy, the fragment mass will be M_N. Although one could identify the final fragment mass M_N with the mass of the star M_* formed therein, in practice, the final fragment is not yet a star. Instead, it provides the initial conditions for the star formation process. To account for the additional physical processes that occur as the fragment collapses into a star, we can write $M_* = f_E M_N = M_0 f_E f_1 f_2 \dots f_N$, where f_E is the star formation efficiency factor of the final fragment. We thus obtain another SEMF and §3.A applies. For example, the total variance of the distribution is given by $\langle\sigma\rangle^2 = \sigma_E^2 + \sum \sigma_j^2$ where the σ_j are the variances of the distributions of the fragmentation fractions f_j.

E. Accretion and Agglomeration Processes

Star formation could also involve continuing accretion or agglomeration processes, especially for the most massive stars which typically form in dense clusters containing many less massive stars. Jeans fragmentation seems unlikely to be relevant to the formation of these stars, and some kind of accumulation process may instead be required (Larson 1982). Radial accretion of gas is inhibited for very massive stars because of the effects of radiation pressure (Wolfire et al. 1985), but rotation may allow infalling material to collect into a disk which can then accrete onto the star (Jijina & Adams 1996). Alternatively, the material that builds massive stars may already be in the form of dense clumps which may then accumulate into larger objects. An extreme case of this scenario would be the merging of already formed stars (Stahler et al., this volume).

No convincing prediction of the form of the upper IMF has yet emerged from any of these ideas, but since accretion or agglomeration processes have no preferred scale, they could in principle proceed in a scale-free manner and build up the observed power-law upper IMF. As a simple example, if each star accretes matter from a diffuse medium at a rate proportional to the square of its mass, the upper IMF becomes a power law with a slope not very different from the original Salpeter form (Zinnecker 1982). Models involving the agglomeration of randomly moving clumps have also been studied, and these models can yield approximate power-law mass functions (e.g., Nakano 1966; Silk & Takahashi 1979; Pumphrey & Scalo 1983; Murray & Lin 1996), but their predictions are sensitive to the assumed properties of the clumps and their evolution between collisions. Fractal concepts have been invoked to relate the form of the upper IMF to the possible self-similar structure of molecular clouds (Larson 1992; Elmegreen 1997), but in these theories strong assumptions must be made about how matter accumulates into stars at each level of the fractal hierarchy. Finally, it has been suggested that already formed stars might sometimes merge to form more massive stars, a mechanism that would readily overcome the problems posed by radiation pressure and winds (Bonnell, Bate, & Zinnecker 1998; Stahler et al., this volume). The dynamics of systems dense enough for frequent mergers to occur is likely to be chaotic, but since no new mass scale is introduced, such processes might proceed in a scale-free way and build up a power-law upper IMF.

In summary, accretion and agglomeration processes almost certainly play an important role in the formation of the most massive stars, and they could plausibly proceed in a scale-free way and build up a power-law upper IMF. However, a quantitative understanding of these processes does not yet exist, and much more work will be needed before a reliable prediction of the slope of the upper IMF is possible.

IV Summary of Conclusions and Future Directions

In this contribution, we have reviewed the techniques used to analyze recent observations of mass distributions in very young clusters and attempted to summarize results. We have also endeavored to review current theoretical arguments that have been put forth to explain these observations. While the observational results are still not definitive, several clear trends are emerging:

[1] Detailed comparisons of emergent mass distributions for the best studied young clusters suggest that the IMF does not vary wildly from region to region though more subtle differences could still be uncovered.

[2] The ensemble of results which characterize the mass distributions of embedded clusters, such as the ratio of intermediate to low mass stars, is consistent with having been drawn from the field star IMF and *rule out* a single power–law Salpeter IMF that extends from 0.1–10 $M_\odot$.

[3] Although the evidence remains preliminary, the emergent mass distributions derived for the two best studied young clusters (IC 348 and

the ONC) hint at turnovers between 0.1 – 0.5 $M_{\odot}$.

Currently, several limitations prevent us from drawing more robust conclusions. Pre-main sequence evolutionary tracks remain uncertain and hence we cannot determine stellar masses with the requisite accuracy. We also need to measure the distribution of companion mass ratios to properly account for unresolved binaries, especially for the low mass end of the IMF. Next, we must search for variations in the substellar mass function, as well as extreme environments (starburst analogs etc.) in order to test whether the IMF is truly universal. Improved statistical methodology is also needed to help push our data to the natural limits imposed by information theory. Finally, it will soon become possible to combine detailed IMF studies in young clusters with determinations from other resolved stellar populations in the Milky Way and other galaxies in order to search for variations over cosmic time.

Theoretical progress is being made in understanding the origin of the IMF, but the problem is formidable. Stellar masses are determined by a complex interplay between the initial conditions in the natal cloud environment and the stars that are formed therein. In this review, we have suggested a general framework for discussing theories of the IMF, and we have outlined briefly some of the physical mechanisms that come into play including gravitational instability and the Jeans scale, the effect of outflows, hierarchical fragmentation, and accretion or agglomeration processes. While it is still too premature to make meaningful comparisons between theories and observations of the IMF, it is our expectation that in the coming years such a comparison can be effected.

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FIGURE CAPTIONS

Figure 1. Initial mass function for field stars in the solar neighborhood taken from a variety of recent studies. These results have been normalized at 1 $M_\odot$. For both the MS79 and Scalo 86 IMFs we have adopted 15 Gyr as the age of the Milky Way. Current work suggests that the upper end of the IMF ($> 5M_\odot$) is best represented by a power–law similar to Salpeter (1955) while the low mass end ($< 1M_\odot$) is flatter (Kroupa, Tout, and Gilmore 1993). The shape of the IMF from 1–5 $M_\odot$ is highly uncertain. See the references listed for details.

Figure 2. Emergent mass distributions for the young clusters IC 348 (Luhman et al., 1998; Herbig, 1998) and the ONC (Hillenbrand, 1997). Also shown is the distribution of stellar masses derived from the log–normal form of the Miller–Scalo IMF. Given the uncertainties in the PMS tracks we cannot conclude that the observed mass distributions are different. Both are broadly consistent with the field star IMF and suggest that the IMF below 0.3 $M_\odot$ is falling in logarithmic units.

Figure 3. Ratio of intermediate ($1M_\odot - 10M_\odot$) to low ($0.1M_\odot - 1M_\odot$) mass stars for star–forming regions as listed in Table 1. Also shown are the expected distributions if the measurements were drawn from the Salpeter (1955), Miller & Scalo (1979), or Kroupa, Tout, and Gilmore (1993) mass distributions. Based on results from the KS test, the probability that the observed distributions were drawn from these parent populations is 3.28×10^{-8}, 0.121, and 0.053 respectively. We conclude that the observations are inconsistent with the Salpeter IMF extending over the range 0.1–10 $M_\odot$.