A Universal Stellar Initial Mass Function? A Critical Look at Variations

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Abstract

Whether the stellar initial mass function (IMF) is universal or is instead sensitive to environmental conditions is of critical importance: The IMF influences most observable properties of stellar populations and thus galaxies, and detecting variations in the IMF could provide deep insights into the star formation process. This review critically examines reports of IMF variations, with a view toward whether other explanations are sufficient given the evidence. Studies of the field, young clusters and associations, and old globular clusters suggest that the vast majority were drawn from a universal system IMF: a power law of Salpeter index ($\Gamma = 1.35$) above a few solar masses, and a log normal or shallower power law ($\Gamma \sim 0$–0.25) for lower mass stars. The shape and universality of the substellar IMF is still under investigation. Observations of resolved stellar populations and the integrated properties of most galaxies are also consistent with a universal IMF, suggesting no gross variations over much of cosmic time. Indications of "nonstandard" IMFs in specific local and extragalactic environments clearly warrant further study. However, there is no clear evidence that the IMF varies strongly and systematically as a function of initial conditions after the first few generations of stars.

1. INTRODUCTION

As every undergraduate astronomy student knows, a star's mass (and, to a lesser degree, its chemical composition) determines its subsequent evolutionary path. In some sense, the important question for stellar evolution becomes: How are stellar masses determined? This is also one of the central questions in developing a theory of star formation.

Foremost among the tools we have to investigate the origin of stellar masses is the initial mass function (IMF). The IMF was first introduced by Salpeter (1955) and provides a convenient way of parameterizing the relative numbers of stars as a function of their mass. In addition to informing our understanding of stellar origins and evolution, the IMF is an important input to many astrophysical studies. Indeed, most problems in modern astrophysics can be "solved" by invoking an IMF that varies in some specific way. By changing the IMF as a function of cosmic time, for example, one can derive star-formation histories (SFHs) of the Universe that turnover, remain flat, or even continue to rise to very high redshift. The explanatory power of these solutions, however, is rather limited without independent observational evidence of IMF variations.

Where we do have observations of the IMF, however, any predictive theory of star formation must explain its shape, as well as how it might vary with initial conditions. Turned the other way around, we can ask: Is the IMF universal or does its shape vary? If we can confidently observe variations in the IMF, we can hope to study those variations to understand the critical scales or conditions under which stars of a certain mass form, informing a quantitative prescription for star formation (e.g., McKee & Ostriker 2007).

1.1. Functional Forms

In his famous 1955 paper, E. Salpeter introduced a power-law IMF of the form

$$\Phi(\log m) = dN/d\log m \propto m^{-\Gamma}, \tag{1}$$

where m is the mass of a star and N is the number of stars in some logarithmic mass range $\log m + d\log m$. Integrating this function and deriving a proper normalization, we can calculate the number of stars within a logarithmic mass interval. Hereafter, we refer to single power-law IMFs as Salpeter-like IMFs; those IMFs with $\Gamma \sim 1.35$ we refer to as having a Salpeter slope (note that by "slope" we are referring to the logarithmic slope throughout this review).

It was recognized in the late 1970s that the IMF was probably not a single power law over all stellar masses. Through the 1980s and early 1990s, various alternatives were explored, including a multisegment power law (Kroupa, Tout & Gilmore 1993), where the slope of the IMF at lower masses was found to be shallower than the Salpeter value obtained at higher masses. Hereafter, we refer to these segmented power-law IMFs as Kroupa IMFs.

The IMF can also be discussed in the context of a mass spectrum, formulating a distribution function in linear mass units,

$$\chi(m) = dN/dm \propto m^{-\alpha}, \tag{2}$$

and enabling an estimation of the number of stars within some mass range. Notice that

$$\chi(m) = 1/(m \ln 10)\Phi(\log m), \tag{3}$$

yielding the relation

$$\alpha = \Gamma + 1. \tag{4}$$

Quoting (and misquoting) results for the slope of the IMF in linear rather than logarithmic units (or vice versa) has led to enormous confusion in the literature. The numerical values of Γ and α

are often misinterpreted, but perhaps more pernicious are the subtle implications of confusing less precise descriptions of the mass function slope: An IMF that is "flat" or "falling" in logarithmic units can still be rising in linear units! A key reference point in this discussion is the relative amount of mass contained within equally sized logarithmic mass bins. Taking the first moment of the distribution described by Equation 2 with respect to mass, we can calculate the total mass within a logarithmic interval. The critical slope is $\alpha > 2$ ($\Gamma > 1$), where the amount of mass per equal-sized logarithmic bin is larger for the lower mass bins.

The logarithmic formalism of the IMF is preferred by some researchers for two reasons: (*a*) It provides a quick estimate of the relative stellar mass in decadal bins, and (*b*) it permits description of the IMF as a log-normal function. The log-normal form of the IMF was first introduced by Miller & Scalo (1979), and a theoretical explanation was offered by Zinnecker (1984; see also Larson 1973), who invoked the central limit theorem. The central limit theorem states that any function resulting from the sum of an infinite number of independent variables can be described by a normal or Gaussian distribution function. If we imagine star formation as a complex transformation where stellar mass is determined by the product of several variables and then take the log, we have that $\log m$ is the sum of a series of possibly independent distribution functions. If the series is infinite and the variables are truly independent, we can then expect the distribution of $\log m$ to follow a Gaussian form. In short, if star formation is very complex, it would not be a surprise if the distribution of $\log m$ were Gaussian, that is, log-normal (see Adams & Fatuzzo 1996) and have the form

$$\phi(m) \sim e^{-\frac{(\log m - \log m_c)^2}{2\sigma^2}}. \tag{5}$$

Hereafter, we refer to the variable m_c as the characteristic mass in a log-normal IMF. A log-normal function is shown as a solid line in **Figure 1** as the base of the IMF. It is useful to note that the power-law form of the IMF ($dN/d\log m$) is a straight line in this log-log plot. If we imagine that

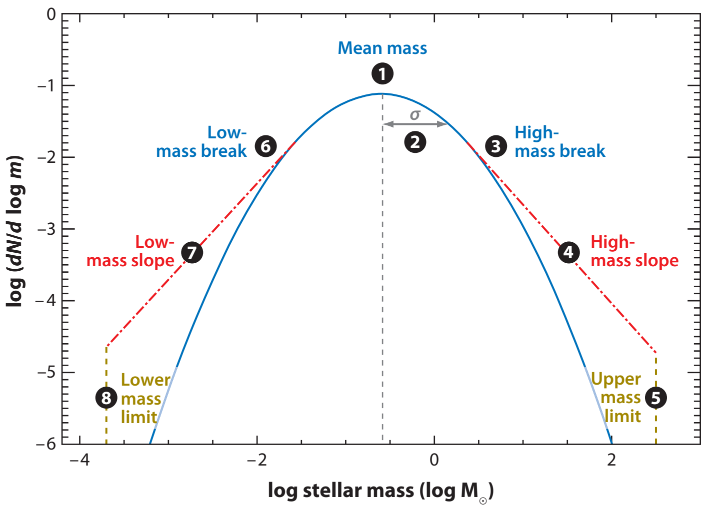

Figure 1

Schematic of an eight-parameter initial mass function (IMF). The "base" of the IMF is approximated as a log-normal distribution (shown as a *solid blue line*) with a (*1*) characteristic mass and (*2*) dispersion (σ). On the high-mass side are the additional parameters of the (*3*) high-mass break, (*4*) high-mass slope (shown as a *dashed-dotted red line*) and (*5*) upper mass limit (represented by a *dashed dark yellow line*). Parameters 6, 7, and 8 are the equivalent on the low-mass end.

the Salpeter law holds above some limit (high-mass break), and that below this limit the IMF is log-normal, we can describe the IMF with four parameters: characteristic mass, dispersion, power-law slope, and break point between the two distributions. In fact, this description appears to be a useful one for many applications: Chabrier (2003) reviewed numerous observational constraints and presented a new formulation of the log-normal IMF. [Dabringhausen, Hilker & Kroupa (2008) have shown that the Chabrier IMF is extremely similar to a two-part power law, hence, distinguishing between a Kroupa-type or Chabrier-type IMF is very difficult.]

Detailed studies of the IMF over the full stellar/substellar mass range, however, may require an eight-parameter description of the IMF. In addition to the four parameters described above, we have the reflection of the high-mass parameters for the low-mass end, namely the break point between the log-normal and a low-mass power-law slope and the value for this slope. Finally, to "cap" the ends of the distribution, we need to introduce the lower and upper limits, both being subjects of great debate.

An additional parameterization of the IMF that is quite practical is that of a "tapered power law" (de Marchi, Paresce & Portegies Zwart 2005). This has the form

$$\chi(m) = \frac{dN}{dm} \propto m^{-\alpha} \left[1 - e^{(-m/m_p)^{\beta}}\right], \tag{6}$$

where m_p is the peak mass (similar to m_c in a Equation 5), α is the index of the power law in the upper end of the mass function (similar to α in Equation 2), and β is the tapering exponent to describe the lower end of the IMF.

1.2. Observational Challenges

Aside from the conceptual difficulty of adopting a succinct mathematical description of the IMF, there are significant challenges that must be overcome to provide a robust empirical measurement of the IMF in various environments. Scalo (1986) provides an excellent introduction to the methodology used in constructing the IMF, and we simply highlight the issues most relevant to our discussion of IMF measurements in various environments.

1.2.1. Star-formation history and multiplicity. A primary motivation for many IMF studies is to search for IMF variations. Ironically, many of these studies require the implicit assumption that the IMF is constant over some spatial or temporal scale. Measuring the IMF of a complex, multicomponent stellar population like the Milky Way disk provides a useful case study. The first step appears straightforward: Count stars within a limited volume as a function of mass. Low-mass stars are more numerous in the Galactic field than high-mass stars, however, so large volumes must be used to construct samples with significant numbers of high-mass stars. The volume density of stars in each sample can be appropriately normalized, but constructing one IMF from these data requires the assumption that the IMF does not vary between those two volumes.

The second implicit assumption is required due to finite stellar lifetimes. If one counts stars in a population spanning a large range of ages (as in the disk of the Milky Way), one can only construct the present-day mass function (PDMF). In this example, some fraction of the more massive stars with lifetimes shorter than the age of the Galaxy (<10 Gyr) will have evolved off the main sequence and are no longer present in the Galactic disk, and thus will not be represented in the PDMF. Every star with $M \leq 0.8\,M_{\odot}$ (that is, spectral type mid-K or later) that was ever formed is still present in the Galactic disk, however, and thus will be represented in the PDMF. Correcting the PDMF for the loss of previous generations of high-mass stars therefore requires the assumption that the IMF does not vary in time, as well as knowledge of the SFH of the Milky

Way! Elmegreen & Scalo (2006) provide a detailed exploration of the degeneracies involved in inferring a stellar population's IMF from its measured PDMF and adopted SFH. It is somewhat disconcerting that the break from the Salpeter law identified in many IMF studies needs to be invoked near the place where the correction becomes important (around 1 $M_{\odot}$).

Knowledge of the SFH of the Galaxy is also required to understand the opposite end of the mass spectrum. Substellar objects never stabilize through hydrogen burning, so their mass-luminosity relation evolves strongly with time. A brown dwarf's luminosity can therefore be reconciled with numerous degenerate combinations of mass and age, such that measuring the substellar IMF in the Galactic field requires good source counts down to very faint magnitudes and a very detailed knowledge of the SFH of the Galaxy (Reid et al. 1999).

The last observational problem for determining the IMF that we address is stellar (and substellar) multiplicity. Many stellar objects are found to have gravitationally bound companions of lower mass (by conventional definition) and at a variety of orbital separations. If we consider that many determinations of the IMF start with monochromatic luminosity functions (LFs), we can guess that unresolved companions of a range of mass (and therefore added luminosity) could wreak havoc on the IMF. Indeed they do (Kroupa 2001, Chabrier 2003, Maíz Apellániz 2008), but correcting for this effect is difficult because the impact of multiplicity on IMF studies is sensitive to both the binary fraction and the mass ratio of the systems involved. It is straightforward that a higher multiplicity fraction produces a larger multiplicity correction, but the mass ratio dependence is somewhat more subtle: Systems with high-mass ratios are effective at "hiding" stars and are also quite difficult to detect as a multiple system. By contrast, equal-mass systems will hide a star, but the system's increased luminosity allows it to be detected over a larger volume, which compensates to some extent for the missing companions in LFs constructed from the field population (Reid & Hawley 2005).

Correcting for this effect requires knowledge of the mass dependence of the multiplicity fraction and mass ratio distribution. Observations indicate that multiplicity declines with primary mass (e.g., Lada 2006): The initial binary frequency of O stars may be as high as 100% (Mason et al. 2009), dropping to ~60% for solar-type stars (Duquennoy & Mayor 1991; Duquennoy, Mayor & Halbwachs 1991), ~30% for early M stars (Fischer & Marcy 1992, Reid & Gizis 1997, Leinert et al. 1997, Delfosse et al. 2004), and to 20% or less for very-low-mass objects ($M < 0.1\ M_{\odot}$; Bouy et al. 2003, Burgasser et al. 2007). The mass ratio distribution appears similarly mass dependent, with typical O star mass ratios near unity (Zinnecker & Yorke 2007), a flat distribution of (detectable) mass ratios between 0.1 and 1.0 for solar-type stars, and a preference toward equal-mass systems for the lowest mass binaries. These multiplicity rates and mass ratio distributions can be used to crudely correct observed mass functions for missing detections of unresolved secondaries. In the 0.1–1.0 $M_{\odot}$ regime, converting from a system IMF to a single-star IMF typically corresponds to a ~0.2 steepening of a rising power-law slope (that is, the Salpeter distribution would change from $\Gamma = 1.35$ to $\Gamma = 1.55$). Corrections for stellar multiplicity require yet another implicit assumption, in this case that multiplicity properties are spatially and temporally constant. Investigations of the mass function of companions is an interesting area of ongoing research (e.g., Goodwin & Kouwenhoven 2009, Metchev & Hillenbrand 2009). For the purposes of this review, we are only concerned with differences between two IMF determinations: We do not attempt to determine whether those differences are due to changes in the system IMFs, the companion mass function, or both.

1.2.2. Statistical considerations for initial mass function measurements of resolved stellar populations. Aside from the observational difficulties described above, substantive claims about IMF variations require a statistical assessment of the agreement (or lack thereof) between the IMF measured in different environments. Most researchers conduct this analysis by fitting a power-law or log-normal IMF to their measurements and then compare the parameters of their fit to those derived in other IMF studies. A disagreement between the derived parameters is typically interpreted as indicative of astrophysically meaningful IMF variations.

The statistical significance of disagreements between IMF parameters derived in different studies can be difficult to infer, however. Some studies do not provide uncertainties associated with their analytic fits, and fewer provide a quantitative justification of the functional form they adopt to describe the IMF. Functional forms with more free parameters can better capture the structure in a given IMF measurement, but that structure may not be statistically significant. Moreover, applying different functional forms to a single derived IMF reveals that the functional form adopted can influence the perceived character of the resultant measurement (e.g., Jeffries et al. 2004). Statistical tests such as the F-test can inform the selection of an appropriate analytic form for a given IMF measurement, indicating if a fit with more degrees of freedom produces a large enough improvement in the χ^2 value to justify their inclusion (e.g., Covey et al. 2008). Similarly, robust statistical techniques can be used to minimize biases in the output parameters (e.g., Maschberger & Kroupa 2009).

Even when using well-motivated functional forms to describe an empirical IMF, care must be taken in interpreting the derived parameters. If the IMF varies smoothly with mass, as with the log-normal characterization, the shape one expects to measure will depend on the mass range over which the measurement is made. This is demonstrated in **Figure 2**, where the value of Γ derived from a power-law fit to a log-normal IMF varies linearly with log mass, from 1.0 at 1 $M_{\odot}$ to -0.6 at 0.1 $M_{\odot}$ and -2 at 0.01 $M_{\odot}$. The parameters derived from an analytic IMF fit may also be sensitive to the manner in which the data were binned (Maíz Apellániz & Ubeda 2005, Cara & Lister 2008). Two IMF measurements could therefore be consistent with being drawn from the same parent population, but produce very different analytic fits, depending on what range of masses they sample and how the data were binned. Statistical tests such as the Kolmogorov-Smirnov test can address whether two distributions are consistent with having been drawn from the same underlying parent population directly without the artifice of binning the data. Of course, the results of such tests can be sensitive to systematic differences in how two datasets (in this case stellar masses) were constructed.

1.3. The Utility of the Initial Mass Function

The IMF is used in countless ways to describe stellar populations from star clusters to galaxies. In some of our nearest galactic companions (e.g., those in the local group), the IMF is probed in much the same way as in the Milky Way. However, crowding and sensitivity can limit studies of the IMF to $>0.4\,M_{\odot}$ in the Large Magellanic Cloud (LMC)/Small Magellanic Cloud (SMC) with *Hubble Space Telescope* (HST) imaging and above 1 $M_{\odot}$ beyond. Yet in the search for variations in the IMF, it is vital to sample the most extreme conditions where star formation could be very different. As such conditions are rare, we need to probe larger volumes to encounter these extremes in density, metallicity, star-formation rate (SFR), radiation field, and other properties. Furthermore, the IMF is a very useful tool for studying the integrated properties of distant galaxies where we cannot resolve individual stars.

The observable properties of a galaxy (that is, color and magnitude), or any part thereof, are determined in large part by its IMF and SFH. To aid in the understanding of a myriad of extragalactic observations, stellar population synthesis models (e.g., Leitherer et al. 1999, Anders & Fritze-v. Alvensleben 2003, Bruzual & Charlot 2003, Maraston 2005) have been developed, which, when given an input IMF, can integrate evolutionary models as a function of SFH to predict observed colors and luminosities. Observations can then be used to constrain the inferred SFHs

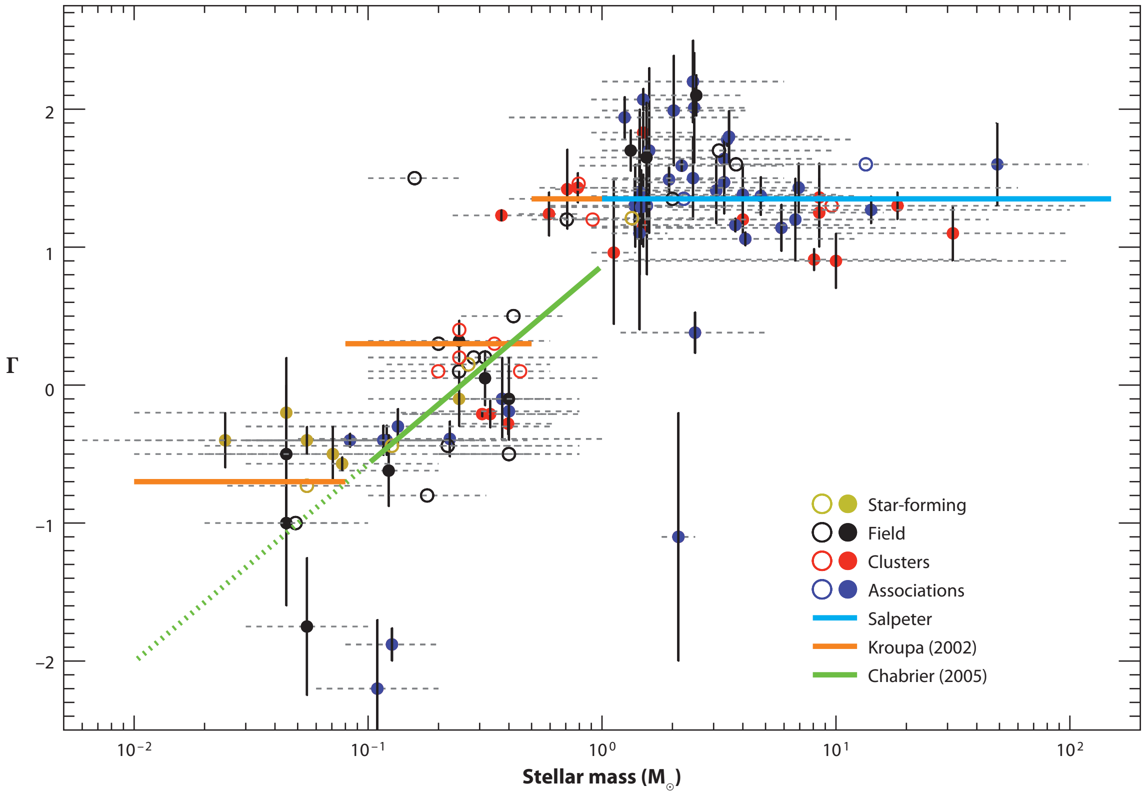

Figure 2

A representation of the "alpha plot" by Scalo (1998) and Kroupa (2002). We show the derived index, Γ, of the initial mass function (IMF) in clusters, nearby star-forming regions, associations, and the field as a function of sampled stellar mass (*points* are placed in the center of the log *m* range used to derive each index, with the *dashed lines* indicating the full range of masses sampled). The data points are from studies discussed in the text and are not meant to be a complete review of the field. Additionally, we have added a sample of clusters compiled by Kroupa (2002). Open circles denote studies where no errors on the derived Γ are given, whereas filled circles are accompanied with the corresponding error estimate (shown as *solid vertical lines*). The observed scatter in the Γ measurements presented here is likely to be larger than in the literature as a whole, as "outliers" are emphasized in this review. The colored solid lines represent three analytical IMFs: Shown in green is the Chabrier (2003) IMF (*dashed line* indicates extrapolation into the substellar regime), with a Salpeter (1955) IMF in light blue, and a Kroupa (2002) IMF in orange (which is essentially Salpeter above 1 $M_\odot$).

as well as the mass of a given stellar population. Specific observations (e.g., B-band luminosity, near-IR color, etc.) often preferentially sample a given stellar mass range. For all but the most massive stars, multiple epochs of star formation contribute to each mass range. Hence, a detailed knowledge of the SFH (and metallicity) of the population is needed if one wants to constrain the underlying IMF. These degeneracies between SFH, metallicity, and the IMF, are even more important for unresolved systems and are highlighted throughout this review.

If the IMF varies systematically with environment or metallicity (both of which could depend on cosmic look-back time), then it is possible, even likely, that the inferred SFHs, stellar masses, and, hence, stellar mass-density estimates would be systematically in error. This could strongly bias our understanding of many important topics, from chemical evolution to how galaxies are formed. One important quantity often measured for local and high-redshift galaxies is their present SFRs. By constraining the amount of ionizing radiation emitted by a galaxy (traced by UV, *Hα*, or

IR luminosity and correcting for extinction as needed), one can estimate the number of high-mass stars present. Combined with estimates of their lifetimes, these data can then be used to estimate the rate at which massive stars are forming. However, massive stars make up only a very small fraction (in number and mass) of all the stars formed, so understanding the relative number of high- to low-mass stars (that is, the IMF) is necessary to determine the total mass that is being formed in stars (cf. Kennicutt 1998). Hence, the assumed IMF has a large impact in converting observed properties (e.g., Hα luminosities) to SFRs.

1.4. The Scope of This Review

In this review, we do not attempt to examine all work on the IMF. The reader is referred to the classic works of Salpeter (1955), Miller & Scalo (1979), and, in particular, Scalo (1986) for a discussion of previous IMF studies. More recently, the excellent review by Chabrier (2003) synthesizes important work in many areas and adopts the log-normal form of the IMF. A comprehensive overview of the methodology and results of IMF studies at the low-mass end can also be found in chapters 8 and 9 of the text *New Light on Dark Stars* by Reid & Hawley (2005). Some important updates can be found in "The IMF at 50" conference proceedings celebrating 50 years since the publication of Salpeter's landmark paper. Elmegreen (2009) also discusses many topics related to the IMF from an extragalactic point of view.

Two important aspects of IMF studies that we do not cover in this review are (*a*) the first generation of stars (that is, Population III stars) and (*b*) the implications of a universal or variable IMF on star-formation theories. For the former topic we refer the interested reader to the recent reviews by Bromm & Larson (2004), Glover (2005), and Norman (2008). For the latter topic, we refer the reader to McKee & Ostriker (2007) and Zinnecker & Yorke (2007).

We focus in this review on more recent determinations of the IMF; particular attention is given to claims of nonstandard/varying IMFs. Of course, any two finite samples drawn from a distribution function will have small differences owing to Poisson statistics. We consider these variations trivial and concern ourselves mainly with observations where the inferred IMF is reported to be inconsistent with having been drawn from the same distribution function that is thought to characterize the IMF elsewhere [that is, with a low probability that two IMFs were drawn from the same parent population; see Elmegreen (1999) and Gilmore (2001) for discussions on stochasticity in the IMF]. While investigating claims of nonuniversal IMFs, we ask the question: Is an unusual IMF required by the observations or is another more pedestrian explanation suitable?

2. STELLAR POPULATIONS IN THE GALACTIC DISK

We begin by considering IMFs measured for various stellar populations within the disk of the Milky Way: volume-limited samples of stars at the solar circle in the Milky Way, otherwise known as the field (Section 2.1); open clusters (simple stellar populations of fixed age and metallicity, Section 2.2); nearby regions of active star formation (Section 2.3); and young star clusters representing the extremes of star formation in parameters such as cluster mass, SFR, and galactic potential (Section 2.4). The oldest Galactic stellar populations, namely the bulge and globular clusters (GCs), are discussed in Section 4.2.

2.1. The Field Star Initial Mass Function

Nearby stars with high-quality trigonometric parallax measurements are a valuable sample from which to measure a stellar IMF. Imaging surveys of these stars provide the most detailed census of stellar multiplicity and, thus, the purest measurement of the single-star IMF and the multiplicity correction to be applied to system IMFs measured in more distant environments. As the mass of an isolated star can only be inferred from its luminosity (adopting a metallicity-dependent mass-luminosity relation), distance determinations from trigonometric parallax measurements also provide a solid foundation for accurate stellar luminosity, and thus mass, estimates with which to construct the stellar IMF.

Through the late 1990s, most measurements of the stellar IMF based on trigonometric parallax catalogs were restricted to the volume within 5.2 pc of the Sun, the completeness limit originally adopted by van de Kamp (1971) for his compilation of nearby stars. Jointly analyzing the LFs of the 5.2-pc sample and a magnitude-limited sample of more distant stars, Kroupa, Tout & Gilmore (1993) demonstrated that a single IMF could be reconciled with both datasets after accounting for binarity, Galactic structure, and observational biases. The broken power-law fit derived in these works forms the basis of the Kroupa-type IMF, which has been applied successfully to many galactic and extragalactic systems.

Reid & Gizis (1997) subsequently used the compilation of nearby stars assembled by Gliese & Jahreiss (1991) to extend the boundary of the reliably volume-complete sample to a distance of 8 pc. The most recent revision of the 8-pc sample contains 146 stars and brown dwarfs in 103 systems, with 95% possessing distances derived directly from trigonometric parallax measurements. A single power-law fit to the IMF of the 8-pc sample returns $\Gamma = 0.2 \pm 0.3$ in the 0.1–0.7 $M_\odot$ mass range, and comparisons with the 5.2-pc sample limit any significant (that is, $>1\sigma$) incompleteness to $M_V \sim 14$, or equivalently, spectral types M4 or later (Reid et al. 2003). Above this mass range, the 8-pc sample represents the PDMF, and corrections must be applied based on the SFH of the Galactic disk to recover the IMF. Significant effort has been invested over the past decade to extend the volume-complete sample yet further, to 10 pc, and address incompleteness at low Galactic latitudes and southern declinations, and for intrinsically faint objects (e.g., Scholz et al. 2005, Henry et al. 2006, Reyle et al. 2006). New members continue to be found (e.g., Lepine et al. 2009, Schmidt et al. 2010), but the sample will soon be complete enough to enable an important reduction in the uncertainties associated with the mass function of the immediate Solar Neighborhood and the crucial multiplicity correction for IMF studies containing unresolved binaries.

To achieve a more statistically precise IMF measurement than can be derived from relatively small parallax-limited catalogs, many investigators have assembled larger samples of Solar Neighborhood field stars with less accurate photometric or spectroscopic distances. In his seminal study, Salpeter (1955) adopted this technique to measure an IMF that is well described above 1 $M_\odot$ by a $\Gamma = 1.35$ power law. Subsequent studies of the supersolar ($M > 1\,M_\odot$) field mass function have focused on the 1–10 $M_\odot$ mass range. The highest mass stars possess such short lifetimes, and require sufficiently complex spectroscopic mass determinations, that it is more efficient to measure the IMF above 10 $M_\odot$ in OB associations (Section 2.3.3) and massive young clusters (Section 2.4.1). Studies of the supersolar IMF in the Galactic field have measured power-law IMFs slightly steeper than, but marginally consistent with, the canonical Salpeter slope.

As Scalo (2005) demonstrates, this apparent consistency partially reflects a paucity of measurements of the supersolar field star IMF. We find only four measurements of the high-mass field star IMF following that of Scalo (1986). Rana & Basu (1992), Maciel & Rocha-Pinto (1998), and Reid, Gizis & Hawley (2002) all derived the supersolar IMF by assuming specific prescriptions for the SFH of the Milky Way [the empirical SFHs of Soderblom, Duncan & Johnson (1991), Rocha-Pinto & Maciel (1997) and a constant SFR, respectively]. Schroder & Pagel (2003) performed a joint fit of the Milky Way IMF and SFH. The high-mass IMF measurements are all consistent with a $\Gamma = 1.65 \pm 0.2$ power law. The only (partial) exception is the IMF derived by Schroder & Pagel, who derived a slightly steeper IMF ($\Gamma = 2.1$) in the 1.6–4 $M_\odot$ regime.

In general, these measurements are in good agreement with those of OB associations, which are discussed in Section 2.3.3.

More attention has been devoted in recent years to determining the IMF of subsolar ($M < 1$ $M_\odot$) field stars, partially motivated by a desire to understand whether very-low-mass stars and brown dwarfs could contribute significantly to the baryonic dark matter in galaxies (Flynn, Gould & Bahcall 1996; Graff & Freese 1996). Comprehensive reviews of subsolar IMF measurements in the Galactic field are provided by Scalo (1986), Bessell & Stringfellow (1993), and Chabrier (2003): The results of a sample of 14 subsolar field star IMF measurements are presented in **Figure 2**. The earliest studies supplemented the parallax-limited samples of nearby (5–8 pc) stars described above with magnitude-limited samples of rarer, brighter, and more distant stars detected by *Hipparcos* or in all-sky photographic surveys (Kroupa, Tout & Gilmore 1993; Reid & Gizis 1997; Chabrier 2005). Beginning in the mid-1990s, analyses were increasingly conducted using data from very deep pencil-beam surveys sampling more modest areas of the sky (<5 square degrees), often primarily motivated by extragalactic science goals (Gould, Bahcall & Flynn 1997; Martini & Osmer 1998; Zheng et al. 2001; Schultheis et al. 2006; Robin et al. 2007; Vallenari et al. 2006). The recent emergence of fully digital, wide area sky surveys has enabled a new generation of mass function analyses that leverage uniform, moderately deep photometry over a large area of the sky to generate large, magnitude-limited samples of subsolar field stars (Covey et al. 2008; Deacon, Nelemans & Hambly 2008; Bochanski et al. 2010).

The underlying consensus in subsolar field star IMF measurements is visible in **Figure 2**, where the power-law slope characterizing the IMF of thin disk field stars declines from $\Gamma = 1.7$ above 1 $M_\odot$ to $\Gamma \sim 0$ for samples of 0.1–0.7 $M_\odot$ field stars. The strongest outlier to this trend is the IMF measurement obtained by Schultheis et al. (2006), who fit optical star counts observed in deep CFHT (Canada-France-Hawaii Telescope) fields to predictions of synthetic Galactic structure and stellar populations models (shown as an *open circle* at a stellar mass of 0.18 $M_\odot$ and $\Gamma = 1.5$). These models are characterized by numerous parameters, however, of which the adopted thin disk IMF is only one. Schultheis et al. did not perform a robust exploration of this multidimensional parameter space, and it is possible that the star count discrepancy they interpret as a steepening IMF could be reconciled by changing another model parameter.

Two studies have attempted to constrain the subsolar IMF of the thick disk (Reyle & Robin 2001, Vallenari et al. 2006), comparing similar datasets to predictions of synthetic stellar population models of the Milky Way. Both studies measure a best-fit thick disk IMF of $\Gamma = -0.5$ for 0.2–0.8 $M_\odot$ stars. No formal uncertainties are quoted in either study, but changes in the analysis (e.g., adopted binary prescription) induce changes in Γ of $\sim$0.25. These slopes are somewhat shallower than are observed for a similar range of masses in the thin disk. Given the uncertainties seen earlier in comparisons between observed star counts and multiparameter synthetic stellar population models, and given the difficulty that theoretical models encounter reproducing stellar colors and luminosities in this mass and metallicity regime, we do not consider this strong evidence for a metallicity dependence of the IMF in the Galactic disk.

Figure 2 also includes results from four recent studies, which analyzed the IMF of substellar objects in the Galactic field (Reid et al. 1999, Allen et al. 2005, Metchev et al. 2008, Pinfield et al. 2008). As noted in Section 1.2.1, analyses of the IMF of field brown dwarfs must model the SFH of the Galaxy to statistically transform the distribution of cool object luminosities into a distribution of masses, inevitably introducing additional uncertainties into the measurement. Moreover, only the sample analyzed by Allen et al. (2005) exceeds 25 objects, limiting the strength of any conclusions that can be currently drawn concerning the Galactic substellar IMF. Nonetheless, the results of these Galactic field studies are consistent with a $\Gamma \sim -1.0$ substellar IMF over similar mass ranges.

2.2. Open Clusters

As bound physical objects and simple stellar populations, open clusters are well suited for observational studies of the IMF. Stars in open clusters possess modest (or nonexistent) age and metallicity spreads and share a common distance, obviating large uncertainties that plague studies of the field star IMF. Substellar objects in young open clusters are also still relatively warm and bright, and thus relatively easy to detect. Unlike younger clusters still deeply embedded in their parent molecular clouds, however, optically visible open clusters possess modest, relatively uniform extinction, enabling greater sensitivity to intrinsically faint objects and reducing uncertainties associated with spatially varying reddening corrections. The one major caveat in studying stellar clusters is that they dynamically evolve over time, systematically losing their low-mass stars to the field and becoming dynamically mass segregated (see Section 2.1 and the review by Portegies Zwart, McMillan & Gieles 2010, in this volume).

Significant deviations from a Salpeter slope have been reported in measurements of the supersolar ($M_* > 1\,M_\odot$) IMF in various open clusters. Scalo (2005) identified the most notable discrepancies in a review of results from the prior decade. It should be kept in mind, however, that these deviations represent a small minority of cases: Most analyses of large, homogeneous cluster samples (e.g., Bonatto & Bica 2007, Maciejewski & Niedzielski 2007) or high-quality observations of individual clusters (e.g., Carraro et al. 2005; Santos, Bonatto & Bica 2005) derive supersolar IMFs consistent with a Salpeter slope. In those cases where non-Salpeter slopes are reported, the results are often attributable to low statistical significance or systematic differences between approaches: We summarize a few illustrative cases here. Phelps & Janes (1993) summarized the study of several open clusters over the mass range from about 1–8 $M_\odot$. Most clusters studied possessed power-law slopes consistent with the Salpeter value with $\Gamma = 1.4 \pm 0.13$, but two clusters (NGC 581 and NGC 663) exhibited significant variations from this mean. Incorporating proper motions as well as photometry to select members of NGC 581, Sanner et al. (1999) confirmed a steep IMF slope ($\Gamma = 1.8 \pm 0.2$), but the measurement uncertainties are such that this discrepancy is only at the $\sim 2\sigma$ level. NGC 663 has also been studied more recently: Observations that cover a larger area of the cluster indicate that the IMF is indeed consistent with Salpeter (Pandey et al. 2005). Sanner & Geffert (2001) derive a power-law slope for Stock 2 of $\Gamma = 2.01 \pm 0.4$, but comment that the distance to the cluster, the colors of some objects, and the dispersion in proper motions are all problematic for this cluster. Prisinzano et al. (2003) present a photometric study of NGC 2422, arguing for a steeper-than-Salpeter IMF with $\Gamma = 2.07 \pm 0.08$. A similarly steep mass function is found for NGC 2323 ($\Gamma = 1.94$) by Kalirai et al. (2003). Both clusters (NGC 2422 and NGC 2323) warrant future studies to confirm their non-Salpeter slope.

Surveying the state of the field, Sagar (2002) argues that, given the large uncertainties in any individual measurement, the data on galactic open clusters are consistent with a universal IMF of roughly Salpeter form from 1 to 20 $M_\odot$ (cf. Massey, Johnson & Degioia-Eastwood 1995, Massey et al. 1995). Given the difficulties inherent in these studies, it would be extremely valuable for future work in this area to address whether a given dataset is inconsistent at the 3σ level with having been drawn from the field star IMF, rather than re-deriving a new (binning-dependent) slope from the data (see Section 1.2.2).

In recent years, many studies of open cluster IMFs have been devoted to determining the subsolar IMF down to substellar masses. The Pleiades, in particular, has been the focus of significant effort. Moraux et al. (2003) present a comprehensive study of the cluster IMF down to 0.03 $M_\odot$ and find the results consistent with a log-normal form over a broad mass range (0.03–10 $M_\odot$): $m_c = 0.25\,M_\odot$ with $\sigma_{logm} = 0.52$, and a marginally steeper ($\Gamma = 1.7$) than Salpeter slope above 1.5 $M_\odot$ (cf. Bouvier et al. 1998). Bihain et al. (2006) combine photometry with proper motion information in some cases to identify low-mass members down to 0.02 $M_\odot$. The mass function they derive is consistent with earlier work. Lodieu et al. (2007a) identify Pleiades members with wide-field IR photometry from the U.K. Infrared Deep Sky Survey (UKIDSS) survey, measuring a mass function that is consistent with Moraux et al. (2003), and report a substellar binary frequency much higher than that characterizing older ultracool field L and T dwarfs. Casewell et al. (2007) present deep I and z photometry as well as proper motion confirmation for some candidate L and T dwarf members with suggested masses as low as 0.01 $M_\odot$, and they derive a preliminary $\Gamma = -0.5 \pm 0.3$ for the substellar IMF.

The Pleiades provides a key touchstone for comparison with other open clusters. M35 is slightly older than the Pleiades (~175 Myr versus 120 Myr), exhibits evidence for modest mass segregation, and sports a PDMF consistent with that measured in the Pleiades (Barrado y Navascues et al. 2001). The slightly younger α Per cluster (90 Myr) shows less dynamical evolution, but possesses a mass function that is also consistent with the Pleiades (Barrado y Navascues et al. 2002). Jeffries et al. (2004) present a photometric study of the structure and IMF for the even younger (~30 Myr) cluster NGC 2547. They find evidence for (perhaps primordial, although see Section 2.3.1) mass segregation above 3 $M_\odot$, an IMF similar to the Pleiades between 0.07 and 0.7 $M_\odot$, and tentatively suggest a dearth of substellar objects in the cluster. The young (50–100 Myr) cluster IC 4665 was studied by de Wit et al. (2006), who also find a mass function similar to that of the Pleiades down to 0.04 $M_\odot$. Moraux et al. (2007) present the IMF for the 100–150-Myr-old cluster Blanco I, again finding a log-normal to be a good fit between 0.03 and 3.0 $M_\odot$ with $m_c = 0.36 \pm 0.07\, M_\odot$ and $\sigma_{log m} = 0.58 \pm 0.06$.

Disentangling IMF variations from dynamical evolution becomes more difficult for older open clusters. Bouvier et al. (2008) studied the ~625 Myr Hyades cluster, which shows signs of significant dynamical evolution but is consistent with the Pleiades IMF above about 1.0 $M_\odot$. Boudreault et al. (2010) recently obtained a mass function for the similarly aged (590 Myr) Praesepe cluster, however, finding no deficiency in low-mass members as expected from dynamical evolution. This wealth of low-mass members is also present in the Praesepe IMF constructed by Kraus & Hillenbrand (2007). Neither study definitively confirmed each star's membership with spectroscopic observations, but Kraus & Hillenbrand did incorporate proper motions into their membership analysis, obtaining a $\Gamma = 0.4 \pm 0.2$ power-law slope over the mass range of 0.12–1.0 $M_\odot$, consistent with the field star IMF. Boudreault and colleagues, by contrast, find a steeper $\Gamma = 0.8 \pm 0.1$ IMF over the narrower 0.15–0.5 $M_\odot$ mass range. Disagreement between the Praesepe and Hyades PDMFs could arise from variations in the clusters' IMFs, or from differences in the dynamical evolution each cluster has undergone. Confirming the differences between the PDMFs of these benchmark clusters, and developing a better understanding of their origin, is a promising area for future work.

In summary, nearly all open clusters exhibit PDMFs that resemble (and many are formally consistent with) a dynamically evolved Kroupa-/Chabrier-type IMF (see **Figures 2** and **3**). In a recent study, G. de Marchi, F. Paresce, and S. Portegies Zwart (submitted) compile a list of open clusters (along with nearby star-forming regions and GCs) from the literature and fit these mass functions with tapered power laws (Equation 6). For the denser clusters, where mass segregation is likely to have occurred, these researchers determine the mass function for the full (global) cluster, or if not possible, at the half light radius, which is not expected to be strongly affected by mass segregation. They find that all young clusters and star-forming regions are well fit by $\alpha = 2.1 \pm 0.2$ (consistent with the Salpeter value), $\beta = 2.4 \pm 0.4$, and $m_p = 0.23 \pm 0.1\, M_\odot$. A selection of their full sample is shown in **Figure 3**. Some of the dynamically older clusters in their sample (e.g., M35, the Pleiades, and GCs) have systematically higher m_p values; however, this shift likely represents dynamical evolution where the lowest mass stars "evaporate" (Baumgardt, de Marchi & Kroupa

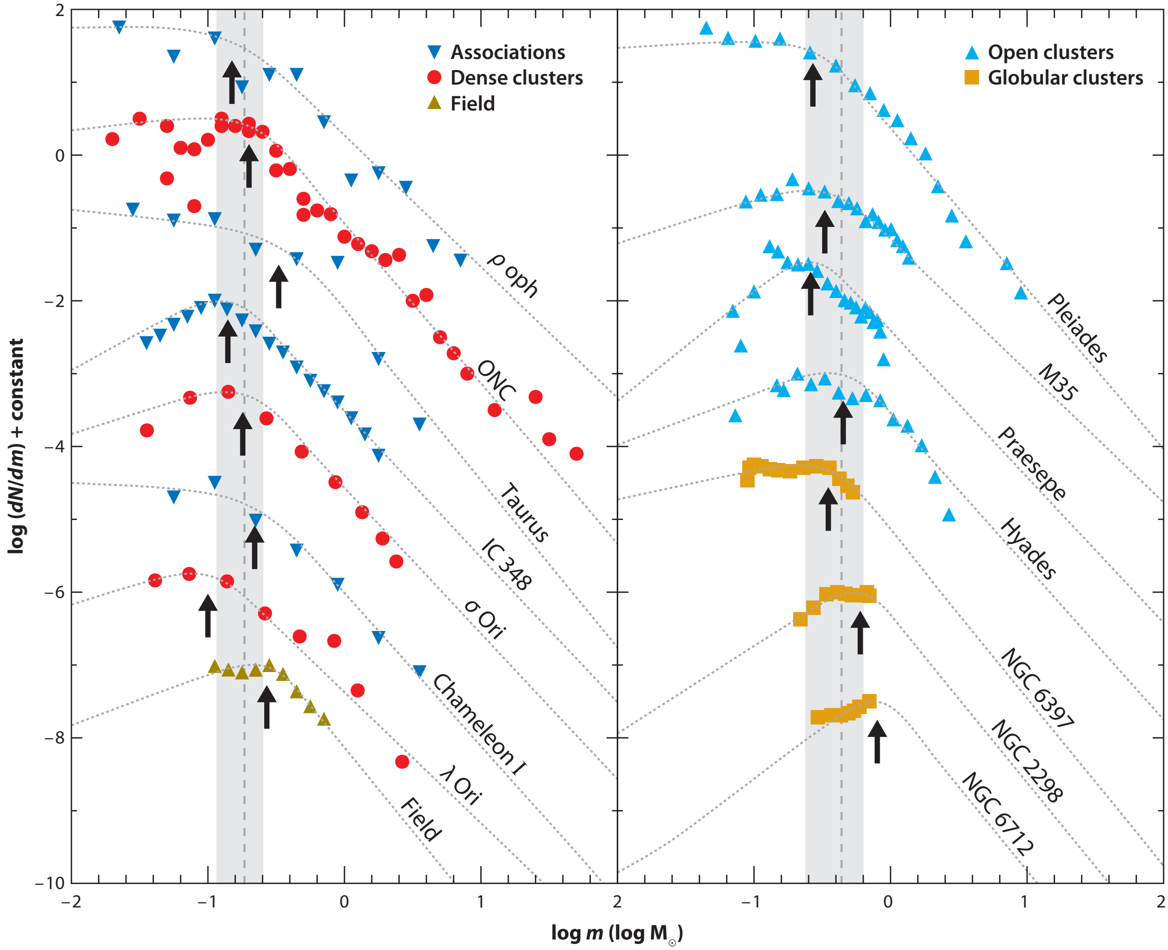

Figure 3

The derived present-day mass function of a sample of young star-forming regions (Section 2.3), open clusters spanning a large age range (Section 2.2), and old globular clusters (Section 4.2.1) from the compilation of G. de Marchi, F. Parsesce, and S. Portegies Zwart (submitted). Additionally, we show the inferred field star initial mass function (IMF) (Section 2.1). The gray dashed lines represent "tapered power-law" fits to the data (Equation 6). The black arrows show the characteristic mass of each fit (m_p), the dotted line indicates the mean characteristic mass of the clusters in each panel, and the shaded region shows the standard deviation of the characteristic masses in that panel (the field star IMF is not included in the calculation of the mean/standard deviation). The observations are consistent with a single underlying IMF, although the scatter at and below the stellar/substellar boundary clearly calls for further study. The shift of the globular clusters characteristic mass to higher masses is expected from considerations of dynamical evolution.

2008; Kruijssen 2009). Hence, there is an expected, and observed, correlation of m_p with the cluster relaxation time (G. de Marchi, F. Paresce, and S. Portegies Zwart, submitted).

2.3. Young Clusters and Associations

2.3.1. Primordial and dynamical mass segregation. An additional complication in IMF studies comes from the spatial distribution of stars within a cluster or association. The most massive stars in large, young clusters are often located in a cluster's innermost regions. This phenomenon is known as mass segregation, and there are two proposed causes. The first is that mass segregation is primordial, with massive stars forming preferentially at the center of the cluster potential. Primordial mass segregation requires that high-density regions within a star-forming cloud form a larger proportion of massive stars than lower density regions. Theoretical explanations for primordial mass segregation range from coagulation models, where massive stars are formed through coalescence, to competitive accretion models, where massive stars form in the center of a potential well, to high-mass stars forming in high-pressure turbulent cores with high-infall rates (see Zinnecker & Yorke 2007 for a recent review). Primordial mass segregation would represent a clear violation of the hypothesis of a spatially and temporally invariant IMF, even if only over relatively small spatial scales.

The second explanation is that mass segregation is simply the result of a cluster's dynamical evolution, where more massive stars sink to the center of the cluster in about a relaxation time owing to energy equipartition (e.g., Binney & Tremaine 1987). Mass segregation in young clusters is often regarded as evidence for primordial mass segregation because their ages are smaller than their current relaxation timescale, and thus there has not been sufficient time for dynamical mass segregation to take hold. The Orion Nebula Cluster provides a useful example: It has been known for nearly a century that the cluster's most massive stars (the Trapezium stars) sit in the cluster's center, and Bonnell & Davies (1998; see also Hillenbrand & Hartmann 1998) concluded this mass segregation was primordial, a relic of the cluster's initial state. Several recent theoretical studies, however, suggest that the timescale for dynamical mass segregation may be shorter than previously thought. Many young clusters are currently expanding (Mackey & Gilmore 2003, Bastian et al. 2008), and possibly formed through the merger of several smaller subclusters. Both of these effects suggest that stars in clusters may have inhabited smaller, denser environments in the past, with correspondingly shorter relaxation timescales and faster dynamical evolution into a mass segregated state (McMillan, Vesperini & Portegies Zwart 2007; Allison et al. 2009; Moeckel & Bonnell 2009).

The literature abounds with reports of mass segregation, but confident detections are difficult. The challenge is that observational selection effects (e.g., crowding, brightening completeness limit near the core) produce the same observational signatures as genuine mass segregation (Ascenso, Alves & Lago 2009). Allison et al. (2009) and Moeckel & Bonnell (2009) have introduced a new method to detect and quantify mass segregation, based on the average distance between the massive stars, relative to a randomly drawn sample of lower mass stars. Their methods appear to overcome many of the shortcomings of previous methods (that is, it is not biased by the presence of substructure) and these researchers have begun applying their method systematically to a sample of young clusters, in particular the Orion Nebula Cluster. Future kinematic studies will be extremely valuable for assessing the dynamical state of young clusters and will be able to attribute differences in present-day spatial distributions as a function of stellar mass to either formation processes or the effects of dynamical evolution (e.g., Proszkow & Adams 2009).

Due to the observational effects of present-day mass segregation, it is important to measure the global mass function of a cluster, not just the inner regions. In some extreme cases, dynamical evolution may force a significant number of low-mass stars out of the cluster altogether, hence the dynamical state of a cluster is important to note when carrying out mass function studies of very dense stellar systems. This issue is addressed in detail in Portegies Zwart, McMillan & Gieles (2010, in this volume).

2.3.2. Young and embedded clusters. The vast majority of stars are thought to be born in unbound aggregates that dissipate as they disperse their parental molecular cloud (Lada & Lada 2003). It is therefore vital to determine if all star-forming events sample a single, universal IMF or if the field star IMF merely represents the average distribution produced from IMFs unique to each region. Deep measurements of the IMF within embedded clusters may even detect a minimum mass below which no cluster members exist; this limit would presumably correspond to mass of the smallest clumps in a cloud that can undergo thermal fragmentation (Low & Lynden-Bell 1976, Rees 1976, Spitzer 1978, Boss 2001, Larson 2005, Whitworth et al. 2007; see extended discussion in Section 4). The minimum mass for fragmentation is the final product of the convolution of a number of physical parameters (e.g., density, temperature, pressure, metallicity, magnetic field strength, turbulent velocity spectrum, etc.), which could vary from cloud to cloud, and whose influence we could hope to infer from measurements of the stellar IMFs in differing cloud environments. (We note, however, that inferring a cloud core's initial conditions from its post star-formation properties is a bit like sifting through the wreckage of a car that was hit by a train to determine what radio station the driver was listening to.)

The unique opportunities that young clusters provide for IMF studies are, however, associated with significant challenges. A number of complications must be addressed to empirically measure a young star's temperature and bolometric luminosity (and thus infer the mass and age through comparison with theoretical models): non-photospheric emission in the UV/blue (from material accreting onto the star) and IR (from the circumstellar disk), significant extinction due to dust along the line of sight to the star, and surface gravity effects that shift the conversion from spectral type to temperature. Differences in input physics adopted in the theoretical models required to infer each star's mass and age introduce additional uncertainties: Systematic offsets between the masses and ages predicted by different model grids can be as large as a factor of two, and the unknown accretion history of a given young stellar object (YSO) can introduce additional random/stochastic errors (e.g., Hartmann, Cassen & Kenyon 1997; Baraffe, Chabrier & Gallardo 2009). Comparing model predictions for pre-main sequence stars with robust dynamical mass measurements indicates that mass errors at the 30–50% level are typical (Hillenbrand & White 2004), and errors in more poorly characterized systems are likely larger still.

Despite these challenges, much work was invested in the 1990s to search for variations in the IMF as a function of initial conditions. Many IR photometric surveys of several embedded clusters were undertaken, critically supported by optical and IR spectroscopy to estimate the cluster's age and adopt an appropriate mass-luminosity relation. The wide range of extinctions present within a cluster, ranging from $A_V < 2.0^m$ for the cloud's surface population to $A_V > 30^m$ for stars buried in the cloud's core, creates an observational bias whereby the cluster's most luminous members (that is, the youngest and/or highest mass stars) can be detected to greater depth within the cloud. These bright stars are therefore over-represented in a magnitude-limited sample, necessitating the construction of an extinction-limited subset of the cluster's members to produce an unbiased measure of the cloud's IMF (Meyer et al. 2000).

These techniques have been applied extensively to the Orion Nebula Cluster, a valuable young cluster for star-formation studies due to its proximity and richness (see review by Muench et al. 2008). Numerous studies of the IMF of the Orion Nebular Cluster have been made over the past decade (Hillenbrand 1997; Hillenbrand & Carpenter 2000; Luhman et al. 2000; Muench, Lada & Lada 2000; Muench et al. 2002; Slesnick, Hillenbrand & Carpenter 2004; Lucas, Roche & Tamura 2005; Weights et al. 2009). These independent IMF determinations are strikingly consistent, deriving results that strongly resemble a Kroupa-/Chabrier-type IMF: a Salpeter-like slope in the supersolar regime that breaks below 1 $M_\odot$ to a broad peak (in logarithmic space) at 0.2–0.3 $M_\odot$. The Orion IMF is well sampled across a wide range of stellar masses, providing a useful benchmark for comparison with the IMF shapes measured in different star-forming regions. These comparisons require yet more care, however, to avoid systematic errors arising from gross differences in the underlying models and observations, and more subtle effects such as the identification and treatment of unresolved multiple systems. As an example, Meyer et al. (2000) perform a Kolmogorov-Smirnov test between the stellar mass distributions measured in the Pleaides (Bouvier et al. 1998) and the Orion Trapezium cluster (Hillenbrand 1997). The results suggest a very small probability that they share the same parent population, but this most likely reflects systematic differences in the way the masses were derived rather than a true astrophysical difference. Summarizing results from several studies, Meyer et al. (2000) were able to demonstrate that the IMFs between 0.1 and 10 $M_\odot$ in young clusters were (*a*) consistent with each other, (*b*) consistent with having been drawn from the field star IMF, and (*c*) not consistent with a Salpeter power-law slope IMF extended down to the hydrogen burning limit.

The Taurus dark cloud, one of the nearest sites of active star formation suffering relatively low extinction, has been the target of intense observational scrutiny for decades. Hundreds of YSOs have been identified as candidate association members located throughout the boundary of the molecular gas and beyond (Kenyon, Gómez & Whitney 2008). Yet, the completeness of these surveys as a function of stellar mass remains a controversial topic today. The distribution of spectral types for known Taurus members has a significant peak at K7–M0, although until recent years this was assumed to be largely due to selection effects. The size of the Taurus dark cloud complex (>20 square degrees) makes it difficult to survey the whole cloud with the sensitivity required to detect objects near the hydrogen burning limit, but recent surveys have covered larger areas to increasingly impressive photometric depths. Briceno et al. (2002) performed the first statistical test of the apparent discrepancy in the distribution of spectral types in Taurus. They found a 0.1% chance that the distribution of objects in the Taurus dark cloud with masses between 0.02 and 1.0 $M_\odot$ is consistent with that found in the Trapezium: The Trapezium appeared to have relatively more brown dwarfs than Taurus. Recent surveys have identified more brown dwarfs in Taurus (e.g., Luhman 2004, Guieu et al. 2006), which diminished this apparent difference, but the observed IMF in Taurus remained anomalous with respect to the field and other star-forming regions.

Most recently, Luhman et al. (2009) analyzed *Spitzer* observations and X-ray data obtained from the XMM satellite (XEST, i.e., XMM-Newton Extended Survey of Taurus; Güdel et al. 2007). Follow-up spectroscopy of candidate members detected in the XEST survey and comparisons to catalogs of previously known members suggest that the fields covered should be complete down to 0.02 $M_\odot$ for the more evolved Class III YSOs, but that incompleteness may affect the census of Class I and late-type (that is, M5 or later) Class II objects. Luhman et al. (2009) perform a Kolmogorov-Smirnov test to compare the IMF they measure from the XEST fields to those previously measured using similar methods in IC 348 (Luhman et al. 2003b) and Chameleon I (Luhman 2007): They find a 0.04% chance that the Taurus IMF could be drawn from the same parent distribution as the IC 348 and Chameleon I IMFs. The best data available therefore indicate a significant difference between the Taurus IMF and that found in other young star-forming regions.

Infrared surveys of Taurus continue to find new members, however, which may yet again bring the IMF of Taurus into closer agreement with other young star-forming regions. Rebull et al. (2010) obtained spectroscopic follow-up of candidate young stars identified in the *Spitzer* Taurus Legacy Survey, confirming 37 new Taurus members, 16 of which appear to be new identifications that were not present at the time of the Luhman et al. analysis. Half of these possess spectral types of M5 or later, highlighting the difficulty of identifying a complete census of the lowest mass members of Taurus. Nonetheless, the peak of K7/M0 members in Taurus is sufficiently strong that many more new late-type members would need to be identified to reconcile the discrepancy. If no such sample is forthcoming, it will represent a significant breakthrough in the search for IMF variations as a function of initial conditions. The next task will be understanding which of Taurus' many unusual properties (low total mass, low stellar density aggregates, apparent coordination of star formation across the cloud) is responsible for its anomalous IMF.

Taurus represents the only star-forming region where significant IMF differences have been reported in the stellar regime, but unusual substellar IMFs have been reported in various regions. A review of substellar objects in young star-forming regions can be found in Luhman et al. (2007). We focus here only on the reports of IMF variations. Lyo et al. (2006) report that the IMF of η Cha is deficient at substellar masses. Moraux, Lawson & Clarke (2007) explored whether this apparent deficiency could be due to dynamical evolution, but Luhman et al. (2009) find that the deficiency is not statistically significant. An excess, rather than a dearth, of brown dwarfs has also been reported in σ Ori (Béjar et al. 2001; Caballero, Kroupa & Matteucci 2007). Sherry, Walter & Wolk (2004) report that the stellar portion of σ Ori's IMF is consistent with the field star IMF, but an analysis of UKIDSS observations of the cluster by Lodieu et al. (2009) indicates preliminary evidence for mass segregation and an IMF that rises smoothly across the stellar/substellar boundary. An excess of brown dwarfs above what is seen in the field has also been reported in Upper Sco. Lodieu, Hambly & Jameson (2006) identified candidate members using UKIDSS photometry (with subsequent spectroscopic confirmation for most candidates; Lodieu et al. 2007b) and measured a value for $\Gamma = -0.4 \pm 0.1$ IMF from 0.01–0.3 $M_{\odot}$. Slesnick, Hillenbrand & Carpenter (2008) also find more brown dwarfs in Upper Sco than reported for the field or other star-forming regions, with the IMF peaking at 0.1 $M_{\odot}$ compared to 0.2–0.3 $M_{\odot}$. These differences in the substellar IMF are tantalizing, but their statistical significance has not yet been determined via rigorous tests for consistency with the field star IMF.

Statistical tests that have been applied to the substellar IMF have resorted to comparisons of the ratio of stars to substellar objects. This ratio is essentially an extremely coarse sampling of the IMF that reduces the importance of random errors in inferred brown dwarf masses. Star–brown dwarf ratios have been calculated for several nearby star-forming regions, including Taurus (Briceno et al. 2002, Luhman et al. 2003a, Luhman 2004), IC 348 (Luhman et al. 2003b), Orion (Hillenbrand & Carpenter 2000; Luhman et al. 2000; Muench et al. 2002; Slesnick, Hillenbrand & Carpenter 2004), and Chameleon I (Luhman 2007). These studies indicate apparent cloud-to-cloud variations in the star–brown dwarf ratio at the factor of two level but do not provide strong evidence for IMF variations given the uncertainties involved. Merging their own data with that of Wilking et al. (2004), Greissl et al. (2007) attempted to construct the stellar/substellar ratio in NGC 1333. Although each study had measured an IMF consistent with that of the field over a different mass range, Greissl and colleagues were unable to reconcile the combined stellar/substellar ratio with that found for the field IMF. Scholz et al. (2009) have since measured a ratio of stars to substellar objects consistent with that of the field, but they suggest the presence of a low-mass cutoff below 0.02 $M_{\odot}$. Andersen et al. (2008) calculated the ratios of stars to substellar objects from studies of seven star-forming regions (Mon R2: Andersen et al. 2006; the Pleaides: Moraux et al. 2003; NGC 2024: Levine et al. 2006; and Taurus, the Orion Nebular Cluster, Chameleon I, and IC 348: see above for references for these latter clusters) in the mass range 0.03–1.0 $M_{\odot}$. They found that these ratios were (*a*) consistent with a single underlying IMF, (*b*) that the ensemble data are inconsistent with an IMF that rises into the substellar regime (that is, requires $\Gamma < -1.0$), and (*c*) the star–brown dwarf ratios are consistent with extrapolation of the log-normal form of the stellar IMF into the substellar regime.

To summarize, most star-forming regions appear to have stellar IMFs consistent with that seen in Orion and the Galactic field. The most significant differences found to date are those between Taurus and other well-studied regions, and perhaps between Upper Sco and the Trapezium and the Pleiades. Below the hydrogen burning limit, most star-forming regions appear to possess substellar IMFs with $\Gamma \lesssim -0.5$.

2.3.3. OB associations. Although OB associations are not as dense as the clusters that are discussed in the next section, their capacity to form large numbers of high-mass stars makes them very important sites of star formation in terms of galactic chemical enrichment and ISM energetics. Optically visible OB associations are attractive regions to study the IMF above 1.0 $M_\odot$ before they disperse into the field. Photometric surveys covering the UBV bands can provide initial estimates of extinction, temperature, and luminosity, with follow-up spectroscopy required to distinguish between stars evolving toward, or away from, the main sequence in the HR diagram. In a comprehensive study of OB associations in the Milky Way as well as other Local Group galaxies, Massey and colleagues (Massey, Johnson & Degioia-Eastwood 1995; Massey et al. 1995) found that the IMF for high-mass stars appears to follow a standard $\Gamma = 1.35$ Salpeter slope and that it is not sensitive to metallicity. They do note, however, that isolated OB stars appear to have a power-law mass distribution with a steeper slope (see Massey 2003). More recent studies of massive star-forming regions within a few kiloparsecs of the Sun also find power-law IMFs in the high-mass regime. Slesnick, Hillenbrand & Massey (2002) find $\Gamma = 1.3 \pm 0.2$ for the double cluster h and χ Persei, with similar results reported for the massive star-forming regions W49 ($\Gamma = 1.6$, $20 < M_\odot < 120$; Homeier & Alves 2005), NGC 3576 ($\Gamma = 1.6$, $3 < M_\odot < 60$; Figueredo et al. 2002), and a host of other HII regions in the Galaxy.

Finally, we point the reader to the review by Massey (2003; see also Zinnecker & Yorke 2007), who summarized the measured value of Γ for massive stars in a variety of Galactic OB associations and clusters that were all analyzed in a consistent fashion. Although there is variance in the measured values, the majority of the observations (and the mean) are consistent with the Salpeter value. We also note that some of these values have changed considerably due to new deeper imaging (also the application of new stellar isochrones), e.g., Cyg OB2 has $\Gamma = 0.9$ in the Massey and colleagues (Massey, Johnson & Degioia-Eastwood 1995; Massey et al. 1995) compilation, $\Gamma = 1.6$ in the study by Knödlseder (2000), and $\Gamma = 1.27$ in the most recent study by Wright et al. (2010).

2.4. Extreme Star Formation in the Milky Way

If the IMF does vary with environment, extreme star-formation sites may have mass functions that deviate significantly from what we see locally. Some such "extreme sites" are found in the Galaxy, namely in starburst clusters, which have stellar densities orders of magnitude larger than nearby clusters. Additionally, the Galactic center is equally exotic, as the dynamics are dominated by a super massive black hole. Studies have reported strange, noncanonical, IMFs for both environments, and in this Section we investigate these claims in turn.

2.4.1. Starburst clusters. The discovery of young Milky Way clusters with masses and densities comparable to or larger than Galactic GCs has prompted a major paradigm shift in our understanding of cluster formation. These young clusters are analogous to the extragalactic "starburst clusters" that are discussed in Section 3.2.1, but owing to their proximity, can be studied in much greater detail. Most of the extreme clusters in our Galaxy reside at distances of 3–8 kpc from the Sun, so we cannot study their mass functions in comparable detail to clusters in the Solar Neighborhood. Nevertheless, they provide crucial laboratories to examine if the IMF varies in extreme star-forming environments.

The young (2–4 Myr) Arches cluster is a prime example. Located ~25 pc away from the Galactic center in projection, the Arches is one of the most massive and densest ($\rho \simeq 2 \times 10^5$ $M_\odot$ pc^{-3}) clusters in the Galaxy, and it has been the focus of numerous studies to determine its mass function and any variance with cluster radius. In the first such study, Figer et al. (1999) used the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) on HST to measure the mass function above ~6 $M_\odot$, finding a mass distribution that was significantly flatter ($\Gamma = 0.65$) than the Salpeter value. Using adaptive optics (AO)-assisted near-IR imaging on Gemini-North, Stolte et al. (2002) subsequently found a slightly steeper slope ($\Gamma = 0.8$ over the same mass range), but still significantly flatter than the Salpeter law. Stolte et al. (2002) also reported a turnover in the mass function at ~6 $M_\odot$, implying that the characteristic turnover mass is ~20 times higher near the Galactic center than it is locally. Kim et al. (2006) observed the Arches with the AO system on Keck, revealing a yet slightly steeper IMF ($\Gamma = 0.9$). These researchers also found that the mass function continues down to ~1.3 $M_\odot$ as a single power law, and they showed that the reported turnover at ~6 $M_\odot$ was either a local bump or simply an artificial excess of stars due to the conversion of stellar luminosities to mass. Most recently, Espinoza, Selman & Melnick (2009) used AO on the Very Large Telescope (VLT) to measure the Arches' global mass function index above ~10 $M_\odot$, paying particular attention to differential extinction, and obtained a present-day IMF index of $\Gamma = 1.1 \pm 0.2$, marginally consistent with the Salpeter value.

All the studies of the Arches described above report strong radial gradients in the index of the mass function, indicating the presence of a large amount of mass segregation. Kim et al. (2006) calculated that, given the age of the cluster, dynamical mass segregation could flatten the observed IMF index by ~0.1–0.2. However, if the cluster formed via the hierarchical merging of subclumps (e.g., McMillan, Vesperini & Portegies Zwart 2007; Allison et al. 2009), then the current IMF may in fact tell us more about the dynamical history of the cluster than the IMF.

Given the distance to the Arches cluster, observations have so far not been able to detect individual subsolar mass stars. In a complimentary approach to resolved studies of individual stars, Wang, Dong & Lang (2006) have attempted to constrain the low-mass IMF by comparing the diffuse X-ray emission of the Arches with the amount expected by extrapolating the X-ray flux of the Orion Nebula Cluster. Wang, Dong & Lang conclude that the Arches likely has an order of magnitude fewer low-mass stars than predicted by a Miller & Scalo (1979) IMF, normalized to match the number of $M > 60\,M_\odot$ stars identified in the Arches by Stolte et al. (2002). The log-normal form of the Miller & Scalo IMF, however, produces an extremely steep ($\Gamma = 2.3$) IMF for masses $>60\,M_\odot$, leading to an extremely large low-mass population given a fixed number of high-mass stars. Indeed, Wang, Dong & Lang demonstrate that the Arches diffuse X-ray emission is consistent with that expected from the low-mass population implied by a simple extrapolation of the Stolte et al. (2002) $\Gamma = 0.9$ IMF, even without invoking a subsolar flattening of the IMF. Recently, much more sensitive X-ray images of the Arches have been obtained (Hong et al. 2009); a similar analysis of the diffuse X-ray emission in these images may provide an improved understanding of the Arches' subsolar IMF.

The most massive known young cluster in the Galaxy, Westerlund 1 (4–7 Myr), is slightly older than the Arches cluster (2–4 Myr) and is one of the closest young massive clusters (YMCs) (3–5 kpc from the Sun). Brandner et al. (2008) derived the mass function within the inner 1.5 pc of the cluster for stars with masses between 3.4 and 27 $M_\odot$ and found $\Gamma = 1.3$, which is consistent with the Salpeter value. They also report a significant flattening in the IMF in the inner parts of the cluster and a steepening in the outer parts, showing that this cluster also has significant mass segregation.

NGC 3603 is another young (2–3 Myr), dense and massive cluster in the Galaxy, located ~6 kpc from the Sun (Stolte et al. 2004). Nürnberger & Petr-Gotzens (2002) used the K-band LF of stars to constrain the IMF and found that it was consistent with the Salpeter distribution for stars with masses above 0.5 $M_\odot$. Using high-resolution VRI HST data, Sung & Bessell (2004) derived $\Gamma = 0.9$ for the inner 20 arcmin (~0.6 pc) of the cluster over the mass range of 1–100 $M_\odot$. Stolte et al. (2006) confirmed this value using deep near-IR VLT imaging. Harayama, Eisenhauer & Martins (2008) used AO near-IR imaging and report a flatter mass function, $\Gamma = 0.74$ from

0.4–20 $M_\odot$. As in the other starburst clusters, all the above studies found evidence for a radially varying mass function, that is, evidence for mass segregation.

Many of the clusters discussed in this Section (see also Section 3.2.1) contain large numbers of high-mass stars that are expected to significantly affect their surroundings. For example, these clusters may be expected to lack low-mass stars; as the formation timescales of low-mass stars are longer than the lifetime of the most massive stars, the presence of large numbers of ionizing stars could disrupt the natal cloud and terminate further low-mass star formation (c.f. McKee & Ostriker 2007). Hence, the shape of the low-mass end ($<1\ M_\odot$) of the IMF in these clusters, which will be accessible with the next generation of telescopes, will be extremely important in understanding the effects of feedback. Additionally, the presence of feedback can have large implications as to how a given IMF is sampled, that is, in what order the stars are formed, a point that we return to in Section 3.2.2.

2.4.2. Galactic center. The central region of the Galaxy is a rather unique place as the dynamics are heavily influenced by the presence of a massive black hole, $M_{\rm BH} \sim 3 \times 10^6\ M_\odot$ (e.g., Ghez et al. 2003, Schödel et al. 2003). The tidal forces due to the massive black hole should render the gravitational collapse from a cold molecular cloud virtually impossible (Morris 1993). Thus, it is surprising that a large population of young stars exists within the central parsec (e.g., Krabbe et al. 1995). The origin of these stars is actively debated: Did they form in situ or outside the central parsec, later arriving at their current positions dynamically? There is also a nuclear cluster composed of stars that formed at a near constant rate that is surrounded by two warped disks of young stars with ages of 6 ± 1 Myr (Paumard et al. 2006, Bartko et al. 2009). Outside the region of these disks is again a normal stellar population. How the disks formed (in situ or through the spiralling in of a dissolving star cluster due to dynamical friction) is still under investigation. These stellar populations in the Galactic center represent an extreme case of star formation and as such their mass functions have been under intense scrutiny.

Using AO-assisted integral field observations, Paumard et al. (2006) identified 41 OB supergiant, giant, and main sequence stars. From this sample, they generated the K-band LF in two ways. The first was a sample of all stars, where late-type stars (those not thought to be associated with the inner parsec) have been removed. The second was a selection based on orbit (that is, associated with one of the disks in the inner region) and projected distance from the Galactic center. The derived K-band LF was substantially flatter in the first method, indicating that the results were dependent on how the sources were selected. They then constructed the expected LF based on a Salpeter IMF, normalized to pass through the observations at a given magnitude. The predicted LF for a Salpeter IMF is steeper than the observations and the researchers suggest that a much flatter IMF ($\Gamma = -0.15$ compared to $\Gamma_{\rm Salpeter} = 1.35$) is needed to fit the observations. However, no statistical comparison was carried out between the observations and the expected K-band LF of a Salpeter IMF. The researchers also note that a large section of the observations ($m_K < 11$) is dominated by very bright evolved stars whose evolution is quite uncertain. The adoption of a single K-band extinction estimate for the entire region may contribute additional uncertainty to the derived IMF, as subsequent work identified a range of extinctions ($\Delta A_K \sim 1$) in this cluster (Maness et al. 2007).

Bartko et al. (2010) present an updated AO integral field study of the Galactic center and split their sample into three subsamples based on projected radius and dynamics. In the very inner region (<0.8 arcsec, <0.03 pc), the observed K-band LF was consistent with that expected from a Salpeter IMF, and so were the outer regions ($12'' < R < 25''$). However, the region between these two, which includes the nuclear stellar disks ($0.8'' < R < 12''$), was much flatter. These disks represent a particularly extreme environment of star formation and further detailed studies of them and their origin would be very insightful.

Extremely flat (that is, top-heavy) IMFs also produce large amounts of stellar mass black holes, due to the overabundance of high-mass stars. These dark objects will have a large impact on the dynamics of the Galactic center, and it appears their presence in the nuclear stellar cluster is inconsistent with observations of stellar motions (Loeckmann, Baumgardt & Kroupa 2010). Additionally, Loeckmann, Baumgardt & Kroupa report that the Galactic center is consistent with a canonical (e.g., Kroupa-/Chabrier-type) IMF and a constant SFH by modeling the mass-to-light ratio and total stellar mass.

Nayakshin & Sunyaev (2005) probed the mass function of the inner few parsecs of the Galaxy, using the ratio of high-mass stars to X-ray flux as a proxy for the IMF. Nayakshin & Sunyaev found that the Galactic center X-ray flux was significantly lower than expected from scaling Orion's X-ray flux by the same factor required to reconcile the number of high-mass stars in each region, indicating a deficit of low-mass stars in the Galactic center. These observations motivate follow-up by the next generation of AO-assisted telescopes, which should be able to directly measure the Galactic center IMF into the subsolar mass regime.

3. THE LOCAL UNIVERSE

We now consider extragalactic investigations of the IMF, beginning with our nearest galactic neighbors, the Magellanic clouds and other Local Group galaxies. For these, we are still in a regime where individual stars can be resolved with high-resolution imaging, although the distance to these objects precludes us from probing substantially into the subsolar mass regime. We then consider the integrated properties of parts of these galaxies and those further afield, namely their associations and stellar clusters. As we move further from the Galaxy, we begin to deal only with the integrated properties of full galaxies and we consider reports that the integrated galactic IMF (that is, the sum of all the IMFs of individual star-forming regions within a galaxy) may be different than the IMF of a single region. We pay particular attention to recent studies that compare the expected Hα and UV luminosities of galaxies and individual regions in order to place constraints on the IMF. We conclude this Section with an analysis of studies on the dynamical properties and chemical evolution of galaxies, and what they suggest regarding IMF variations.

3.1. Nearby Galaxies

3.1.1. The Large and Small Magellanic Clouds. Due to their proximity, the Magellanic Clouds offer an excellent opportunity to study the IMF in lower metallicity environments. Massive star-forming regions (e.g., R136) in the LMC provide additional opportunities to test for IMF variations in quiescent and extreme environments, whereas the SMC allows us to probe the IMF outside of disk galaxies.

The 30 Doradus region, and the central cluster R136, is unique in the LMC, having a mass that rivals the young Westerlund 1 in the Galaxy with an age of ∼3 Myr. Due to its prominence, 30 Dor has been the subject of many IMF studies, with often contradictory results, highlighting the difficulty in determining the IMFs of even relatively nearby systems. Brandl et al. (1996) used AO imaging to derive a global mass function for R136 with an index of $\Gamma = 1.6$ for stars more massive than $\sim 5\,M_{\odot}$, but with a strong radial gradient that is consistent with dynamical mass segregation. Massey & Hunter (1998) revisited R136 using HST photometry and spectroscopy and found the IMF index to be $\Gamma = 1.4$ from 2.8–120 $M_{\odot}$. Sirianni et al. (2000) used deeper HST V and I photometry to push to lower masses and reported a flattening in the IMF at $\sim 2\,M_{\odot}$.

Using NICMOS data, Andersen et al. (2009) show that the low-mass end is consistent with the predictions of a Chabrier type IMF and explore the effects of differential reddening on previous work. In addition, Selman & Melnick (2005) measured a $\Gamma = 1.35$ from 7–40 $M_\odot$ in the 30 Dor region as a whole (excluding R136).

Kerber & Santiago (2006) similarly analyzed five stellar clusters in the LMC and, though they found evidence for mass segregation in all, the global PDMFs for all five were consistent with a Salpeter distribution from $0.9 \leq m/M_\odot \leq 2.5$. The clusters range in age from 10 Myr to 1.75 Gyr, and span a factor of 10 in central densities; the lowest density cluster (NGC 1818) is ~3 orders of magnitude less dense than R136, and yet still well fit with a Salpeter slope above 1 $M_\odot$. Hunter et al. (1997) and de Grijs et al. (2002) also found an index for the IMF of NGC 1815 consistent with a Salpeter value from 1–10 $M_\odot$. Additionally, Da Rio, Gouliermis & Henning (2009) found that the IMF in the young star-forming region LH 95 in the LMC was consistent with a Kroupa-/Chabrier-type IMF into the subsolar regime (>0.4 $M_\odot$).

The SMC has a lower SFR than the Galaxy or LMC, and it is not currently producing clusters as massive as R136. Its irregular morphology and sub-LMC metallicity make it an interesting object in which to search for IMF variations. Recent work using deep imaging with ACS (Advanced Camera for Surveys) and WFPC2 (Wide Field Planetary Camera 2) on HST have measured mass functions in SMC clusters that appear to be indistinguishable from the classical Salpeter value. Examples include NGC 346 (Sabbi et al. 2008; where $\Gamma = 1.43 \pm 0.18$ from 0.8–60 $M_\odot$), NGC 602 (Schmalzl et al. 2008, which is consistent with a Salpeter IMF from 1–40 $M_\odot$), and NGC 330 (Sirianni et al. 2002, consistent with Salpeter >0.8 $M_\odot$).

Looking at young clusters and OB associations in the LMC/SMC, Massey (2003) concluded that the massive star population in all observed regions is consistent with a Salpeter distribution. He comments on the remarkably small scatter observed, considering the expected deviations due to the way that the data are processed (see also Maíz Apellániz 2008). In the more remote regions of the LMC, and assuming a constant SFR over the past 10 Myr, Massey (2002) derived a much steeper $\Gamma = 4 \pm 0.5$ IMF slope. This led him to conclude that the IMF was environment dependent, in particular varying with density. Similarly steep mass functions have been derived by Gouliermis, Brandner & Henning (2006) using HST WFPC2 data of a field near the bar of the LMC. Parker et al. (1998) used the Ultraviolet Imaging Telescope to derive the IMF of the LMC field and also found a steeper distribution (although not as extreme as the above studies) of $\Gamma = 1.8 \pm 0.09$ for the mass range of 7–35 $M_\odot$. Because the field is composed of stars of multiple ages, it is subject to the SFH-IMF degeneracy. Elmegreen & Scalo (2006) have shown that a decreasing SFR will be interpreted as a steeper Γ if a constant SFR was assumed.

Based on the above studies of clusters and associations of the Galaxy and Magellanic clouds, it already appears that strong variations in the high-mass end of the IMF (>1 $M_\odot$) due to density ($35 < \rho_0[M_\odot\,pc^{-3}] < 3 \times 10^4$; ρ_0 is the central density of the cluster from Mackey & Gilmore (2003) for NGC 1818 and R136, thus we note that the range in density would be even greater if OB associations were included) and metallicity ($1/5\,Z_\odot - 1\,Z_\odot$) can effectively be ruled out.

3.1.2. The Local Group. Moving further out into the Local Group, we are naturally restricted to only probing the high-mass end of the IMF through resolved star counts. M33, being a relatively face-on spiral, has offered the best laboratory to study the IMF beyond the Galaxy and the Magellanic Clouds. Most studies to date have been based on giant HII regions associated with large OB associations. Hunter et al. (1996) found an index of the IMF of $\Gamma = 1.6 \pm 0.7$ for stars with masses between 6.5 and 18 $M_\odot$ based on HST imaging of NGC 604. Similarly, Malumuth, Waller & Parker (1996) found $1.3 \leq \Gamma \leq 1.0$ for stars more massive than 4 $M_\odot$ in NGC 595. These studies, like those carried out on populations in the LMC/SMC are subject to resolution/blending effects (e.g., Maíz Apellániz 2008).

In addition to resolved star counts with high-resolution imaging, numerous studies have used lower spatial resolution UV-integrated spectroscopy of HII regions in M33 to constrain the IMF. A discussion of this method will be given in Section 3.2.4; here we just present results derived in the Local Group. González Delgado & Pérez (2000) found that the high-mass end of the IMF in NGC 604 is consistent with a Salpeter IMF. Jamet et al. (2004) found the same for NGC 588 based on integrated spectroscopy and photometric star counts. Jamet et al. do warn, however, that stochastic sampling of the IMF can cause deviations in the integrated properties of the OB associations, given their relatively low masses. This was also found by Pellerin (2006) for five HII regions in M33, which were best fit with slightly flatter IMFs when fit with standard population synthesis models, but were consistent with a Salpeter slope when stochasticity was taken into account. We return to the use of UV spectral features to constrain the IMF in Sections 3.2.4 and 4.1.1, where these techniques have been applied to local and high redshift starburst galaxies, respectively.

3.2. Unresolved Stellar Populations

3.2.1. Super star clusters. Early results from HST revealed partially resolved star clusters in starburst environments with masses and densities rivaling those of GCs (e.g., Holtzman et al. 1992). These massive clusters have been referred to by many names: super star clusters (SSCs), YMCs, starburst clusters, and populous clusters, just to name a few. Subsequent work has found such clusters in all star-forming environments, from relatively quiescent dwarf galaxies to Milky Way types (e.g., L_* spirals) and galactic mergers (e.g., Larsen 2006). Due to their high luminosity, SSCs can be sampled at great distances (and thus in a variety of galactic environments), providing valuable insights into potential environmental dependences. We point the interested reader to Portegies Zwart, McMillan & Gieles (2010, in this volume) for a review of the properties of these clusters.

The IMFs of these massive extragalactic clusters are particularly interesting as they represent the most extreme sites of star formation, in terms of SFR density, in the Universe. For example, a massive cluster in NGC 1316 has an inferred SFR surface density of $\sim 5 \times 10^4\ M_\odot\ \mathrm{kpc}^{-2}\ \mathrm{year}^{-1}$ within its half-light radius (Bastian et al. 2006; assuming it formed over a 3-Myr period), orders of magnitude larger than even the most extreme galaxy-wide starbursts in the near or far Universe. Even fairly common objects like R136 in the LMC attain SFR densities of $\sim 10^4\ M_\odot\ \mathrm{kpc}^{-2}\ \mathrm{year}^{-1}$, showing these "extreme objects" may in fact represent a widespread mode of star formation.

Ho & Fileppenko (1996) suggested that dynamical light-to-mass ratios of young SSCs could place important constraints on their IMFs. Combining velocity dispersions (σ_v), measured from high-resolution ground-based echelle spectra, with cluster half-light radii (r_h), measured from HST imaging, enables the determination of cluster dynamical masses (M_{dyn}) through the application of the Virial Theorem. This mass can then be compared to the mass derived by measuring the brightness of a cluster and applying age-dependent L/M ratios from simple stellar population models (SSP) that adopt an IMF. These stellar population–based masses will be referred to as M_{pop}. Due to the difficulty of these measurements, this method is only sensitive to gross deviations from the nominal Kroupa-/Chabrier-type IMF (e.g., if the clusters are highly deficient in low-mass stars).

An early attempt to constrain the IMF of SSCs was performed by Sternberg (1998), who used velocity dispersion measurements made by Ho & Fileppenko (1996) to derive L_V/M_{dyn} for the YMCs NGC 1569A and NGC 1705-1. Comparing the measured L_V/M_{dyn} to the fitted L_V/M_{pop}

ratios, Sternberg (1998) concluded that the IMF of NGC 1569A was close to the Salpeter value, whereas NGC 1705-1 was depleted in low-mass stars (at the 1–2 σ level).

A host of similar L_V/M_{dyn} studies have followed, with widely varying results: Some analyses indicate SSC L_V/M_{dyn} values consistent with a standard Salpeter or Kroupa-/Chabrier-type IMF (Larsen, Brodie & Hunter 2004; Maraston et al. 2004), whereas others measure SSC L_V/M_{dyn} values that imply an overabundance of low-mass stars (a so-called bottom-heavy IMF; Mengel et al. 2002) or high-mass stars (a top-heavy IMF; Smith & Gallagher 2001). More worrisome is that some of these results have been derived within the same galaxy (e.g., M82; McCrady, Gilbert & Graham 2003). Bastian et al. (2006) noted that there was a trend in how well cluster L_V/M_{dyn} ratios were fit by SSP models, in the sense that older clusters (>20 Myr) were well fit (with one exception to be discussed below) with a canonical IMF, while there exists a significant scatter in young clusters. Additionally, they showed that NGC 1705-1 is only deviant by 1–2 σ from a Kroupa-type IMF. The older clusters (>20 Myr) from the Bastian et al. sample are shown in **Figure 4** as solid red boxes (data taken from Bastian et al. 2006, Goodwin & Bastian 2006). In **Figure 4*a***, we show the mass derived through dynamical measurements (M_{dyn}) versus that derived using the observed luminosity and age-dependent mass-to-light ratios from SSP models (M_{pop}) that adopt a Kroupa IMF. In **Figure 4*b***, we show the M_{dyn} versus the ratio M_{dyn}/M_{pop}, where a value of 1 is expected if a Kroupa IMF is the underlying mass function and ~1.55 if the IMF is better described by a Salpeter distribution. The SSCs cluster around the expected value of a Kroupa distribution, and the variance is within the observational errors.

One cluster has received a particularly large amount of attention, the massive cluster known as F in the starburst galaxy, M82. Smith & Gallagher (2001) measured a L_V/M_{dyn} ratio for M82F and found it was about three times larger than the L_V/M_{pop} ratio predicted for a population with a Kroupa IMF. This measurement suggests M82F is highly deficient in low-mass stars. McCrady, Graham & Vacca (2005) measured the velocity dispersion of the cluster in the near-IR and remeasured its size on HST High Resolution Camera imaging, and came to the same conclusion. Based on a filter-dependent size (that is, the cluster appears larger in redder bands), these researchers suggest that M82F may suffer from a high degree of mass segregation. If true, this would make the measured M_{dyn} a lower limit as the light is dominated by the most massive stars, which would be preferentially found in the center, hence having a lower than expected velocity dispersion. Bastian et al. (2007) revisited M82F and found evidence for strong differential extinction across the face of the cluster ($\Delta A_V > 1$) and that a large HII region lies between the cluster and the observer; they suggest that both effects may complicate the measurements. Even with these caveats, M82F represents the strongest case for IMF variations in SSCs.

The youngest clusters (<20 Myr) that have been analyzed show a much larger spread in their inferred L_V/M_{dyn} ratios, in particular having lower L_V/M_{dyn} ratios (by factors of 2–5) compared to that expected from SSP models. If interpreted in terms of IMF variations, the result would be a bottom-heavy IMF. This is opposite to what is often reported in the literature, that starbursts are depleted in low-mass stars (see Sections 3.2.5 and 4). Additionally, these clusters would be more likely to survive the effects of mass loss due to stellar evolution and, hence, we should observe older clusters with low L_V/M_{dyn} as well. There are two alternative explanations for the high dynamical masses measured. The first possibility is that removal of the cluster's natal gas has left it in a supervirial state for the subsequent 10–20 Myr. The cluster's velocity dispersion therefore has an additional expansion component, which will cause virial analyses to overestimate its mass (Bastian & Goodwin 2006, Goodwin & Bastian 2006).

The second possible explanation for the high M_{dyn} measurements of young clusters is that binary stars artificially broaden the velocity dispersion of a cluster. If the binary fraction depends on stellar type, with more massive stars being exclusively in binaries (e.g., Preibisch et al. 1999,

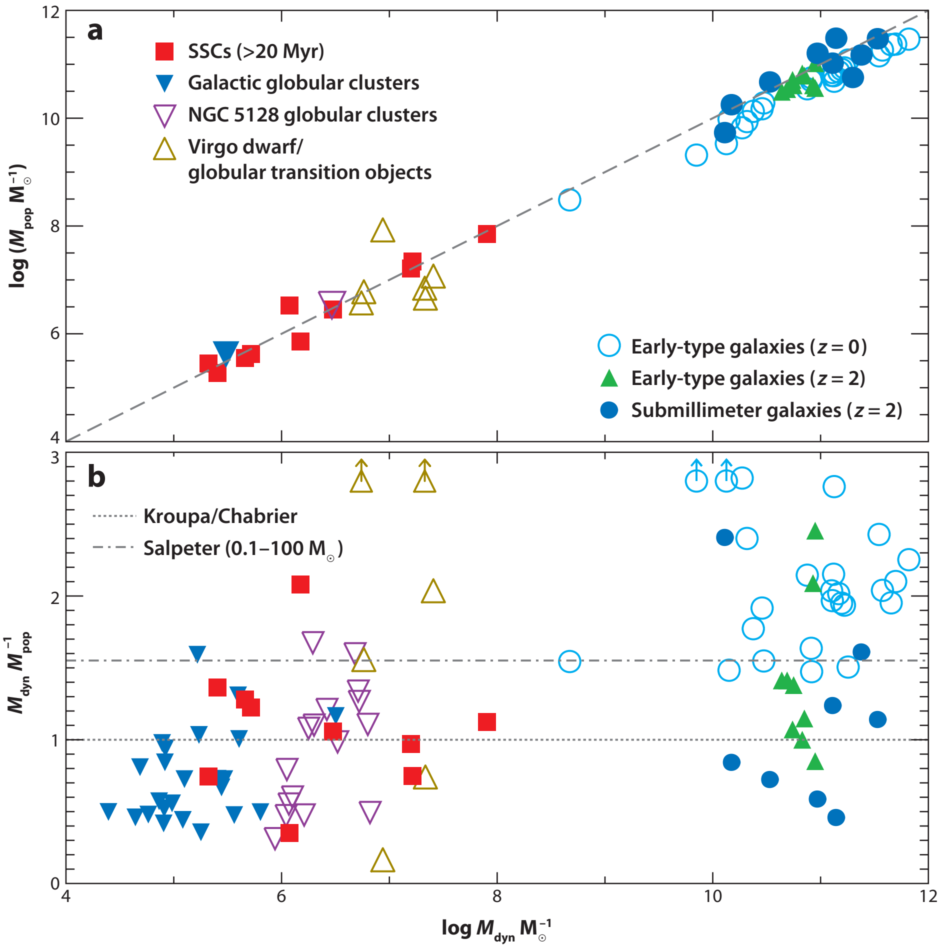

Figure 4

(*a*) The measured dynamical mass $M_{\rm dyn}$ (or through Jeans dynamical modeling in the case of the early-type galaxies; see Cappellari et al. 2006) versus the stellar mass derived through modeling of their integrated light using simple/composite stellar population models, which adopt a Kroupa-type initial mass function (IMF). The solid red squares are super star clusters with ages greater than 20 Myr (Section 3.2.1); the upside down solid blue triangle and upside down open purple triangle represent the mean of 24 Galactic globular clusters (GCs) and 16 GCs in NGC 5128, respectively (Section 4.2.1); open light blue circles show early-type galaxies in the local Universe (Section 3.2.5); and filled green triangles and filled dark blue circles show early-type galaxies and submillimeter galaxies at high redshift (Section 4.1.2). (*b*) The same as panel *a* except now the ratio between $M_{\rm dyn}$ and $M_{\rm pop}$ is shown. If the underlying IMF was well described by a Kroupa-type distribution, a ratio of 1 is expected in this representation (shown as a *dotted line*). If a Salpeter IMF (down to 0.1 $M_\odot$) is a good representation of the underlying IMF, a value of 1.55 is expected (*dash-dotted line*). Note that the galaxy points are upper limits, as a fraction of the $M_{\rm dyn}$ measurement is expected to come from dark matter.

Zinnecker & Yorke 2007), this could cause young clusters to have low $L_V/M_{\rm dyn}$ ratios and older clusters to fit the SSP model predictions. Preliminary estimates of the effect of binaries reported that this is unlikely to be affecting the clusters so far observed, as their velocity dispersion is dominated by the gravitational potential, due to their high masses (Kouwenhoven & de Grijs 2008). However, recently Gieles, Sana & Portegies Zwart (2010) found that realistic mass-dependent binary fractions could indeed affect the measured velocity dispersions of many of the young clusters in the sample discussed above.

The integrated optical light from most young stellar populations is dominated by high-mass stars, making the detection of low-mass stars difficult or impossible. In extremely young clusters, however, low-mass pre-main sequence stars are bright enough in the near-IR that their spectral features can be detected in high S/N spectra (Meyer & Greissl 2005). Quantitative analysis of these spectra can then place constraints on the ratio of high-to-low mass stars in the cluster. This technique should be applicable for clusters young enough not to have evolved red giant stars (that is, younger than 6–8 Myr) and is currently within the limits of 8–10-m class telescopes for starburst clusters in the local Universe (Greissl et al. 2010), and further afield with the next generation of extremely large telescopes.

3.2.2. The upper mass cutoff and the integrated galactic initial mass function theory. How large can the most massive stars be? Does this vary with environment and what causes this limit? From our perspective, an upper mass cutoff to the IMF is simply another parameter of the IMF that we might expect to vary as a function of initial conditions. Zinnecker & Yorke (2007) have reviewed the literature of massive clusters (>few × 10^3 $M_\odot$) in the Galaxy/LMC and concluded that within these clusters an upper mass limit of ∼150 $M_\odot$ exists for the most massive stars. The physics that imposes this cutoff is a critical, but separate issue; demonstrating that there is an upper mass limit can reveal some of the fundamental physics of star formation. We now turn to the question of whether all clusters are subject to this same limit or if lower mass clusters have a different upper limit to their mass function.

Summing the IMFs of a galaxy's constituent stellar populations (that is, clusters, associations, and distributed field populations) produces an integrated galaxy initial mass function (IGIMF; Weidner & Kroupa 2005). The IGIMF characterizes the bulk output of a galaxy's star-formation activity and provides an opportunity to investigate the sensitivity of the IMF on large-scale environmental effects. Assuming that the stellar IMF is universal and sampled completely stochastically (that is, a star forming in isolation is as likely to be an O star as a star forming in a much more populous region), then the IMF and IGIMF will be the same. This is equivalent to saying that 100 clusters, each with a mass of 1,000 $M_\odot$, will have a composite IMF that is indistinguishable from that of a single 10^5 $M_\odot$ cluster.

The IMF will not be sampled completely in all cases, however, if the maximum mass of a star inside a cluster is proportional to the mass of the host cluster (e.g., Vanbeveren 1982, Weidner & Kroupa 2006). Stochastic sampling in clusters larger than a few $\times 10^4$ $M_\odot$ will fully populate the IMF up to an upper mass limit of 150 $M_\odot$, but lower mass clusters do not possess enough mass to fully sample the high-mass end of the IMF (Bruzual & Charlot 2003). This should be the case if stars derive their masses from the resources in their surroundings (which they do): Certain environments may simply not have enough material to form a high-mass star. Hence, there would be a lack of high-mass stars in low SFR galaxies, as these galaxies only form low-mass clusters/associations (e.g., Larsen 2006). The high-mass end of the IGIMF in low SFR galaxies would therefore be steeper than in high SFR galaxies, because there would be no high-mass clusters capable of populating the highest mass end of the stellar IMF. If true, this would have important effects on a wide range of astrophysical problems, most notably, on the inferred SFRs of (low SFR) galaxies based on Hα luminosities (e.g., Pflamm-Altenburg, Weidner & Kroupa 2007, 2009; this same effect would in principle be revealed by comparing 500 regions of 200 young stars to a 10^5-$M_\odot$ cluster, but in practice is almost impossible to observe).

An analogy for this somewhat subtle, but important difference is the distribution of heights and wealth in villages and large cities (Clarke 2009). On average, the tallest person in a village will be shorter than that in a large city, simply because the sample size is smaller. There are no physical conditions restricting growth, so sampling statistics are the cause. However, the wealthiest person in a large city is expected to be much richer than his/her equivalent in a village, and in this case sampling statistics and an underlying physical cause (as the richest individual in a large city can draw from a larger economic base) are to blame. Which of these comparisons is most applicable to how the IMF is sampled will have a strong impact on star-/cluster-formation theories.

Weidner & Kroupa (2006) have suggested that "sorted-sampling" must be at play within young clusters (that is, clusters form stars from low to high mass progressively). Depending on the available gas reservoir (presumably related to the total emergent cluster mass), the mass of the most massive star is limited as the IMF is sampled from bottom to top. An argument in favor of such a scenario is that if high-mass stars form first, the feedback caused by their ionizing radiation may effectively remove any remaining gas, hence, stopping the formation of low-mass stars. Others argue that clusters are built entirely stochastically, as the relatively large (compared to the mass of individual stars) amount of molecular gas present in star-forming reservoirs allows high-mass stars to form even in low SFR regimes (Elmegreen 2006). [The observations of young clusters are consistent with small age spreads, though relative ages of high- to low-mass stars are notoriously difficult to assess (Hillenbrand 2009)].These two scenarios predict different relationships between a cluster's total mass and the mass of its most massive star. The recent compilation of Maschberger & Clarke (2008; see also Parker & Goodwin 2007) of cluster masses and most massive stars includes several examples of low-mass clusters containing high-mass stars. Maschmerger & Clarke note that previous compilations were biased by not including studies of massive stars surrounded by low-N clusters. Their results tentatively suggest that random sampling is the preferred algorithm for forming clusters, in which case the IMF and IGIMF would be identical. However, Weidner, Kroupa & Bonnell (2010) come to the opposite conclusion (that the most massive star does depend on the mass of the host cluster) based on a search of the current literature. Determinations of the cluster mass and the mass of the most massive stars (due to the presence of unresolved binaries) are difficult and potential stumbling blocks for all studies of this sort. Clearly, this issue remains to be resolved.

An additional component of the IGIMF model is the cluster/association IMF, which is also approximated as a power law with index $-\beta$, similar to Equation 2 ($N\,dM \propto M^{-\beta} dM$, where M is the mass of a cluster and N is the number of clusters with mass between M and $M+dM$). The steeper the cluster IMF the more pronounced the difference between the IMF and the IGIMF, as one has fewer high-mass clusters to form high-mass stars. Pflamm-Altenburg, Weidner & Kroupa (2007) and Weidner & Kroupa (2006) adopt $\beta = 2.2$, whereas direct measurements of the cluster mass function are generally shallower, having $\beta = 2.0$ (e.g., de Grijs et al. 2003). This rather small difference in β has a significant effect on whether or not the IMF and IGIMF are the same (Kroupa & Weidner 2003, Elmegreen 2006).

In **Figure 5** we show the difference between the input IMF and the resulting IGIMF for various assumptions on how stars are sampled from the underlying IMF and the mass function of the clusters/associations (different power-law indices and lower mass truncations). Lada & Lada (2003) suggest a turnover in the embedded cluster mass function at $\sim 50\,M_\odot$, although this value is somewhat uncertain due to selection effects. As such, observations of clusters appear to prefer the upper most example in **Figure 5**, which results in very similar IMF and IGIMF for any sampling scenario considered. The critical parameter is the ratio of $M_{\rm low}$(cluster) to $M_{\rm upper}$(star).

To test the validity of the IGIMF theory, several new, and challenging, observations will be needed. The first is the exact form of the relationship between the mass of the most massive star and mass of the host cluster for large samples of clusters, as discussed by Maschberger & Clarke (2008). The second is to understand in more detail the exact shape of the cluster mass function, in

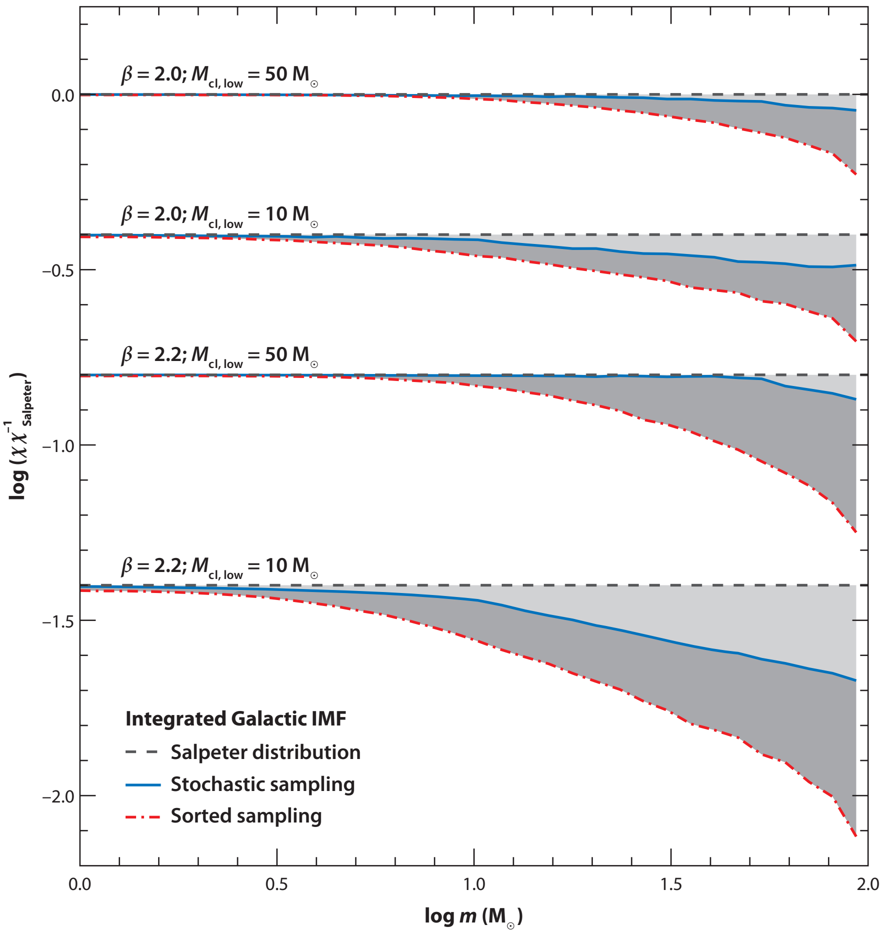

Figure 5

The difference between the initial mass function (IMF) (drawn from a Salpeter distribution) and the integrated galactic IMF (IGIMF) in the "stochastic sampling" (Elmegreen 2006) and "sorted sampling" (Weidner & Kroupa 2006) scenarios. Shown is the fraction of stellar mass (see Equation 2) in the IGIMF normalized to the expected mass (as a function of stellar mass) from the analytic Salpeter IMF (that is, if the distribution is consistent with a Salpeter IMF, the result is a flat line in this representation). The various lines are for different assumptions on the underlying cluster IMF; β is the index of the power law in the cluster mass function, whereas $M_{\mathrm{cl,low}}$ is the adopted lower mass limit for clusters. The light-shaded regions represent the relative lack of stars as a function of mass in the stochastic sampling scenario, whereas the dark-shaded regions are the same, but for the sorted sampling scenario. Because the fraction of high-mass stars changes in each of the scenarios considered, the ratio of stellar-mass-dependent observations (e.g., Hα flux or UV luminosity) will differ from the canonical values. (Adapted from Haas & Anders 2010.)

particular its index (β) and its lower mass limit (because $\beta \approx 2$, the cluster mass function diverges as the mass approaches 0; hence there must be a turnover at some lower mass). Finally, we need to determine the birth places for large samples of high-mass stars using kinematic studies to provide a definitive answer whether they can form in isolation or are always found associated with low-mass stars. We discuss other consequences of the IGIMF theory in the following sections.

3.2.3. Hα, ultraviolet and infrared studies of integrated stellar populations. The UV, optical and IR light of a galaxy is dominated by stars, either directly or through reprocessing of stellar light by dust and gas in the ISM. In a typical stellar population composed of stars with a range of ages, stars of different masses contribute differently to a galaxy's integrated light: far-UV emission is dominated by young (<10 Myr), massive ($\geq 15 - 20\,M_\odot$) stars that can ionize hydrogen, generating optical recombination lines such as *Hα*; near-UV emission is dominated by somewhat older (<300 Myr), less massive ($\geq 3\,M_\odot$) stars; and optical broad band colors are typically dominated (in quiescent galaxies) by even older solar-mass (0.6–3 $M_\odot$) stars (e.g., Leitherer et al. 1999). Comparing the relative strength of emission detected in these wavelength regimes can therefore provide an indirect constraint on galaxy-wide IMF variations. An important caveat is that the IMF is not the only parameter that affects these observable properties; we must also account for the influence of metallicity, extinction, and the SFH of the galaxy.

Hoversten & Glazebrook (2008) estimated the index of the stellar mass function for $\sim 10^5$ galaxies with Sloan Digital Sky Survey (SDSS) photometry and spectroscopy by comparing each galaxy's broadband SDSS colors with its Hα equivalent width, a method first developed by Kennicutt (1983). They found a trend between the mass function index (Γ) of their best fitting model and the luminosity of the galaxy; in the sense that faint galaxies have steeper IMFs, galaxies similar to the Milky Way exhibit Salpeter slopes, and the most massive galaxies also have slopes steeper than the Salpeter value. This is qualitatively consistent with the predictions of the IGIMF theory. However, the stellar upper mass limit was not allowed to vary in their models. These results depend on the assumed SFH, which in general is not precisely constrained with optical spectroscopy (e.g., Wild et al. 2009). The ensemble is consistent with a $\Gamma = 1.5 \pm 0.1$, which is close to the Salpeter value.

Several recent studies have used UV and Hα measurements to characterize the high-mass IMF in external galaxies. Meurer et al. (2009) investigated a sample of galaxies with UV observations from the GALEX (*Galaxy Evolution Explorer*) satellite and found a relationship between the Hα-to-UV ratio and the Hα surface brightness ($\Sigma_{H\alpha}$) of a galaxy. This relationship indicates that galaxies with low SFRs also possess low Hα-to-UVratios, which Meurer et al. interpreted as a signature of a bottom-heavy IMF. Subsequent studies by Lee et al. (2009) and Hunter, Elmegreen & Ludka (2010) have confirmed this basic observational relationship between UV-to-Hα luminosity ratio and SFR.

Although these studies agree concerning the observed correlation between a galaxy's SFR and its Hα-to-UV ratio, they do not agree on the subsequent interpretation. Meurer et al. and Lee et al. show that part of the relationship, though not all of it, can be explained by stochastic sampling, where low SFR galaxies are less likely to produce the highest mass stars, even if they were sampling from a universal IMF. They also note that their results are well fit by the Weidner & Kroupa (2005) IGIMF theory (Pflamm-Altenburg, Weidner & Kroupa 2009; see Section 3.2.2). Meurer et al. also found that the observed Hα-to-UV ratios could be explained by a population of post-starburst dwarf galaxies in their sample (although they note that this is unlikely as many galaxies would need to be observed in a post-starburst phase). Lee et al. also investigated additional explanations for this observed correlation, such as internal dust attenuation, uncertainties in the stellar models used, metallicity effects, and ionizing photon loss (see also Elmegreen & Hunter 2006). Lee et al. conclude that stochasticity, SFH, and ionizing photon losses all contribute to the offset in the correct sense, but none alone is likely to produce a strong enough trend to match the observations. Hunter, Elmegreen & Ludka, by contrast, favor a scenario where many ionizing photons from OB stars leak out of small galaxies, which causes an underestimation of the emission measure. [In many small galaxies, the Strömgren radius around a single O-star can be larger than the gaseous galactic scale height, hence, leakage of ionizing photons is expected (Melena et al. 2009).] Finally, Boselli et al. (2009) similarly demonstrated that derived Hα-to-UV ratios are very sensitive to the adopted extinction corrections and microstar-formation history (from a few to tens of millions of years). Analyzing a restricted sample of "normal" (that is, low inclination, non-AGN, nonstarburst) galaxies, Boselli et al. find Hα-to-UV ratios consistent with Kroupa-/Chabrier-type high-mass IMFs and limit potential high-mass ($M > 2\,M_{\odot}$) IMF variations to $\Gamma = 1.35$ for massive galaxies and $\Gamma = 1.6$ for low-luminosity systems.

It remains to be seen if the Hα deficiency noted above is truly indicative of a correlation between the shape of the IMF and SFR. Future resolved color-magnitude studies of these galaxies, along with deep Hα imaging of their halos, will be necessary to settle this issue.

In a similar vein, Gogarten et al. (2009, see also Dong et al. 2008) have studied individual UV-bright regions in the outer disk of the spiral galaxy M81 using high-resolution HST imaging that can resolve massive stars. They found that regions lacking Hα also lack high-mass stars, but that this is consistent with expectations of evolutionary fading, that is, as a stellar population ages the high-mass stars that drive Hα emission die first, leaving the region UV bright but Hα faint. Hence, this particular ratio is highly sensitive to the SFH of a region. If each region is formed in an instantaneous burst, and assuming that the number of regions formed per unit time is roughly constant, population models can be constructed to predict the number of UV-bright regions that will be Hα bright or faint. Zaritsky & Christlien (2007) have made such a model and found that this ratio is approximately the ratio between the lifetimes of stars that can produce Hα and those that produce UV, that is, 16 Myr/100 Myr. Large studies of UV-bright regions in the outer disks of galaxies are necessary to confirm the predicted statistics.

Following on the Gogarten et al. result, Goddard, Kennicutt & Ryan-Weber (2010) have studied star-forming regions in a sample of 21 galaxies, focusing on HII regions well beyond the optical radius of the galaxy. Based on the Hα/UV ratio and statistical properties of the HII regions, they do not find any evidence for variations in the IMF at the high-mass end, once stochasticity is taken into account.

These Hα/UV diagnostics appear sufficiently sensitive to a galaxy's recent SFH and/or radiative transfer effects that we do not yet consider them to be strong evidence for IMF variations. Detailed studies of the selection effects inherent in the sample and the SFHs of the deviant galaxies using resolved stellar population studies, along with deep Hα imaging of their halos, are needed to confirm that the IGIMF and IMF are truly different. If confirmed, this would most likely indicate that the ratio of intermediate- to high-mass stars can vary with environment.

Finally, though the low-mass end of the IMF does not significantly contribute the IR spectral energy distribution of starburst galaxies, it does influence the absolute value of the SFR derived from, e.g., emission lines (Section 1.3). Emission line luminosities imply a specific number of high-mass stars, but converting this measurement into an estimate of the total stellar mass in a galaxy requires accounting for lower mass stars by adopting and integrating over a normalized IMF. An IMF with many low-mass stars will imply a larger SFR for a given emission line luminosity than an IMF with fewer low-mass stars. For a given reservoir of gas, these different SFRs also imply distinct gas consumption timescales: IMFs with more low-mass stars (and thus higher SFRs) imply shorter gas depletion timescales. Goldader et al. (1997) have compared the derived SFRs with the gas consumption timescale in a sample of 12 ultraluminous IR galaxies. They found that a Salpeter (or steeper) IMF that continues down to 0.1 $M_{\odot}$ results in gas consumption timescales that are shorter than the mean age of the stellar population (derived from near-IR spectroscopy). IMFs that turnover below 1 $M_{\odot}$ (such as Kroupa/Chabrier types) and have a Salpeter slope above this value are consistent with their observations.

3.2.4. Ultraviolet spectral diagnostics. The UV spectra of high-mass stars ($> 15\,M_\odot$) possess broad emission and absorption lines formed in the winds these stars drive. One approach is to study the line profiles of C IV 1,550 Å and Si IV 1,400 Å, which are heavily influenced by the shape of the high-mass stellar IMF, in spectra of unresolved stellar populations. This method is, however, completely insensitive to variations in the low-mass regime. The benefit of this technique is that it allows for a direct comparison of the upper end of the IMF in different environments, as it can be applied to objects as disparate as local starburst galaxies, quiescent resolved and semiresolved star-forming regions in the Galaxy and LMC/SMC, and even to high redshift galaxies. The latter is discussed in Section 4.1.1, and a series of studies applying this diagnostic to giant H II regions in M33 was presented earlier in Section 3.1.2. These studies found that the observations of M33 were consistent with a Salpeter IMF in the high-mass end, but that stochastic sampling was important to take into account. This caveat should have a much smaller effect on studies of strongly star-forming regions or full galaxies that are expected to have fully sampled IMFs. An additional concern is that UV spectral diagnostics depend on the assumed SFH of the region. Most studies of full galaxies assume a constant SFH for >20 Myr, whereas UV studies of stellar clusters assume an instantaneous burst.

In one of the first studies using UV line profile diagnostics, Conti, Leitherer & Vacca (1996) obtained HST STIS (Space Telescope Imaging Spectrograph) spectroscopy of the starburst galaxy NGC 1741. Comparing the profiles of C IV and Si IV, they concluded that the high-mass IMF in this galaxy is consistent with a Salpeter slope. These and additional UV spectral diagnostics have been extensively modeled for starburst galaxies (starburst galaxies are dominated by young stellar populations so that the SFH is less uncertain) using population synthesis, and their dependence on the burst history and metallicity is now relatively well known (e.g., González Delgado, Leitherer & Heckman 1997; Leitherer et al. 1999; Maraston et al. 2009). Nearby starburst galaxies also have UV spectral diagnostics that are consistent with a Salpeter distribution of high-mass stars (see reviews Pellerin & Robert 2007 and Leitherer 2009).

Tremonti et al. (2001) have studied the UV spectral properties across the actively star-forming galaxy NGC 5253, focusing mainly on the difference between the spectra of "clusters" and "the field." Although this distinction was somewhat arbitrary (based on surface brightness), the cluster spectra were consistent with a Salpeter IMF extending up to $\sim 100\,M_\odot$, whereas the field appeared to be deficient in stars with masses above $\sim 30\,M_\odot$. One interpretation is that the IMF in these environments is different. Instead, these researchers suggest that the lack of high-mass spectral features in the field is due to an age difference between the young clusters and the field (cf. Massey 2002). Stars will diffuse out from their natal unbound associations into the field over some timescale that depends on their initial velocity dispersion (e.g., Goodwin & Bastian 2006), but it is thought to be on the order of several million years. The most massive stars will therefore end their lives as supernovae before they reach the field. Chandar et al. (2005) have repeated this analysis for 12 local starburst galaxies and come to similar conclusions.

3.2.5. Dynamics of galaxies. The L_V/M_{dyn} diagnostic introduced earlier as a constraint on the IMF of YMCs (see Section 3.2.1) is also useful in the study of whole galaxies. As discussed above, this diagnostic cannot probe the shape of the IMF in detail; rather, it provides a single L_V/M_{dyn} value that can be compared to predictions of stellar population models generated by adopting distinctly different underlying IMFs. The complications of using this method for galaxies rather than star clusters are (*a*) that galaxies are not simple stellar populations, so one needs to work out their SFHs and often account for differential extinction; and (*b*) the presence of additional dynamical components, namely gas and dark matter.

M82 is a nearby prototypical starburst galaxy and, as such, has often been used for IMF studies. Unfortunately, due to its dusty nature and edge-on orientation, extinction effects can be particularly troublesome. Rieke et al. (1993) modeled M82 and found that the galaxy's K-band luminosity, Type II supernovae rate, CO index, and kinematic mass were best reproduced by models that were deficient in low-mass stars relative to the local IMF [compared to those found by Miller & Scalo (1979) and Scalo (1986)]. Subsequent studies by Satyapal et al. (1995), however, concluded that the inner regions of M82 are fainter than previously derived as they adopt lower values for the extinction. Based on these observations, Satyapal et al. concluded that a normal (that is, Salpeter or Kroupa-/Chabrier-type) IMF is consistent with the data for M82. More recently, detailed modeling of near to mid-IR spatially resolved spectra indicates that the IMF may indeed flatten below a few solar masses (Förster Schreiber et al. 2003), that is, the characteristic mass of the IMF would be 1–3 $M_{\odot}$, hence, still suggestive of IMF variations, but less extreme than previous studies. As discussed in Section 3.2.1, dynamical measurements of massive star clusters in M82 indicate normal IMFs for some, although M82F appears to be deficient in low-mass stars.

For a fixed dynamical mass, the ratio of high- to low-mass stars can be inferred from estimates of the ionizing flux from high-mass stars. It is worth noting that the Miller & Scalo (1979) and Scalo (1986) IMFs are, in fact, bottom heavy with respect to a Salpeter or Kroupa/Chabrier IMF due to the steepness of the former at the highest masses. Thus, readers are encouraged to examine quantitatively results from the literature to determine whether a region is top heavy, bottom heavy, or even bottom light with respect to modern estimates of the field star IMF.

In a study similar to that of M82, Doyon, Joseph & Wright (1994) constructed models of the interacting starburst galaxy NGC 3256 in order to constrain the IMF. By adopting different forms of the IMF and different SFHs (constant, bursts, and declining), they matched their models against five observables (the strength of the CO bandhead, the equivalent width of Brγ, the fraction of Lyman continuum photons to IR luminosity, emission line ratios, and total K-band luminosity). The best fit models were deficient in low-mass stars; however, the IMF was found to be degenerate with the SFH and also the assumed mass of the burst. Salpeter distributions in the high-mass regime that turn over at lower masses (that is, Kroupa-/Chabrier-type IMFs) were broadly consistent with the data.

Bell & de Jong (2001) also used dynamical diagnostics to investigate possible IMF variations in spiral galaxies. For a galaxy with a given color and rotation curve, a maximal disk L_V/M_{dyn} ratio can be calculated by assuming that baryons make up as much of the mass of the disk as possible, and thereby minimizing the disk's dark component. Comparing these maximal disk L/M ratios to those predicted by spectrophotometric spiral galaxy evolution models, Bell & de Jong found that a Salpeter IMF overestimates the number of low-mass stars in their disk galaxy sample, whereas a Kroupa IMF fits the data well. They further use the scatter observed in the Tully-Fisher relation to place strict constraints on IMF variations between spiral galaxies. Assuming that all of the scatter is due to IMF variations (that is, assuming zero measurement error or variations in the SFH of the galaxies) implies a scatter in the stellar mass associated with a given luminosity less than a factor of two (see also McGaugh 2005).

Along similar lines, Cappellari et al. (2006) used a sample of 25 E/S0 galaxies with 2D integral field spectroscopy from the SAURON (Spectroscopic Areal Unit for Research on Optical Nebulae) project to estimate the mass-to-light ratio of each galaxy (where the mass has been determined dynamically) and then compare this to the expected mass-to-light ratio of the stellar populations, as derived through spectral fitting. They conclude that a Kroupa IMF is consistent with the data and that there is no evidence for a varying IMF within these galaxies. Their sample (shown as *open black circles* in **Figure 4**) comprises galaxies with luminosity-weighted ages between 2 and 17 Gyr, suggesting that the IMF does not vary with cosmic age. Note, however, that due to the large mass in stellar remnants in old (>10 Gyr) stellar populations, it is difficult to unambiguously differentiate between bottom-light and normal IMFs in these systems (see van Dokkum 2008). We return to this point in Section 4.

3.2.6. Chemical evolution of galaxies. One of the long-lasting effects of the shape of the IMF on the observed properties of galaxies lies in the abundances of elements in stars. Because different elements are thought to be produced by stars of differing masses, chemical evolution models developed to understand the abundance ratios and gradients in galaxies can also place constraints on the IMF. The basic model parameters are stellar yields (outlining which elements are produced by stars of different masses, and in what amounts), gas inflow and outflow (the inflow of "primordial" material into the galaxy, and the loss of metal-enriched material into the IGM), the SFH of the galaxy, and finally, the IMF. These models can then be compared to the abundance and color gradients observed in actual galaxies. The limiting factor for the accuracy of these models is the prescription adopted to describe stellar yields (including supernovae and supernovae rates), for which models can vary widely (e.g., Chiappini, Matteucci & Meynet 2003).

α-elements (such as O, Mg, Ca, and Ti) are thought to be produced by core collapse supernovae (SNe) at the end of a massive star's life. Iron, on the other hand, is also produced in large amounts in Type Ia SNe, hence, there is a delay between the star-forming event and when Fe is released. Because the α-elements are thought to be produced in different amounts in a supernova, depending on the initial mass of the star, any variance in their ratios suggests a change in the IMF (Nissen et al. 1994). The halo of the Galaxy exhibits a plateau at low metallicities in terms of the abundance ratios of α-elements compared to iron below [Fe/H] ~ -1.8 (e.g., García Pérez et al. 2006); above this metallicity the [α/Fe] abundance falls due to the production of Fe in Type Ia SNe. The existence of this plateau suggests that these stars were formed out of material that was well mixed and of a similar composition. This in turn suggests that the IMF of the stars in the generation before the observed halo stars did not vary significantly.

Because the α-element ratios appear to be constant down to the lowest metallicities probed, this suggests that the high-mass end of the IMF has been invariant since a redshift of $z \sim 3$–5. This is supported by α-element abundances measured in high redshift damped Lyman-α systems (Molaro et al. 2001, Pettini et al. 2008) and in absorption systems along quasar sight lines (Becker et al. 2006), both of which are consistent with yields expected from a Salpeter IMF at the high-mass end. One caveat to this analysis is that it assumes that the gas that formed stars was enriched with homogeneously mixed elements produced in SNe. Small systems, such as dwarf galaxies may have only experienced a handful of SNe at early times, so their α-element abundances may be different than that seen in the Galactic halo (Venn & Hill 2008; although see also Frebel, Kirby & Simon 2010).

One can combine the relatively straightforward models above with different SFHs and stellar yields in order to model full galaxies. Models of elliptical galaxies have been performed that can reproduce their photochemical properties (metallicity, gradients, etc.) using a Salpeter IMF, which continues down to 0.1 $M_\odot$ (e.g., Pipino & Matteucci 2004; Calura, Pipino & Matteucci 2008). These same models indicate that in disk galaxies, and in the Solar Neighborhood, a Salpeter IMF overestimates the metal production (Romano et al. 2005), implying an environmental-dependent form of the IMF. Similar models carried out by Nagashima et al. (2005), however, directly conflict with these results and suggest that only extreme top-heavy IMFs can explain the properties of elliptical galaxies.

Ballero, Kroupa & Matteucci (2007) applied chemical evolution models to explain the metallicity distribution of stars in the Galactic bulge and M31, and concluded that the bulge IMF must have been different from the Galactic disk IMF. These evolutionary models are subject to uncertainties related to the specifics of galaxy formation (e.g., Pipino & Matteucii 2008) and the detailed treatment of gas inflow and outflow, both of which are not precisely known at the present time. These uncertainties make it difficult to draw strong conclusions, particularly in the face of conflicting results based on direct star counts (e.g., Zoccali et al. 2000, and discussed in Section 4.2.2).

Avoiding the complications of inflow and outflow, Renzini (2005) reports that the metal content of galaxy clusters (a combination of the IGM material and galaxies) is well reproduced by a Salpeter IMF between 1 and 25 $M_{\odot}$. Conversely, Portinari et al. (2004) have argued that all standard IMFs above 1 $M_{\odot}$ (e.g., Salpeter or Kroupa/Chabrier) fail to reproduce the metal content of the IGM once metals "locked up" in low-mass stars are taken into account.

Although chemical evolution models have obtained notable success in explaining many abundance ratios, gradients, and age-metallicity relations, significant uncertainties remain, and they provide conflicting constraints on galactic IMFs. To our knowledge, no study has turned the argument around; assuming an invariant IMF, what constraints can be placed on the stellar yields, SFH of galaxies, galaxy build-up, and the progenitors of Type Ia and II supernovae?

There is observational evidence for a high-mass-biased IMF of primordial stars, in the form of the metallicity distribution function of stars in the Galactic halo. The lack of many extremely metal-poor stars, [Fe/H] < -4, indicates that extremely low-metallicity stars had lifetimes shorter than the current age of the Universe, implying that no low-mass ($<1\,M_{\odot}$) primordial stars were formed (e.g., Tumlinson 2006). For a review of the observations of very low-metallicity stars, we refer the reader to Beers & Christlieb (2005).

A lasting effect of the first generation of stars is their production and distribution into the early Universe of heavy elements. Which elements are produced and at what ratios depend on the initial masses of the primordial stars; if the stars are more massive than $\sim 300\,M_{\odot}$, however, the entire core collapses into a black hole and no heavy elements are ejected (Heger & Woosely 2002). Hence, it is possible to place constraints on the primordial IMF from abundance patterns observed in low-metallicity stars. Tumlinson, Venkatesan & Shull (2004) attempt such a study and conclude that the first generation of stars need not be extremely massive (hundreds of solar masses), but could instead lie within the 8–40 $M_{\odot}$ regime, with few or no low-mass stars. It does appear, however, that the stellar IMF was significantly more top heavy in the early Universe relative to the present day. The exact transition period from high-mass-biased to the current form remains elusive, although models, such as those presented in Smith et al. (2009), are beginning to make detailed predictions of when and where this transition takes place.

4. COSMOLOGICAL INITIAL MASS FUNCTION VARIATIONS

A flurry of work in recent years has attempted to constrain variations in the stellar IMF over cosmological timescales and distances. Although most diagnostics are necessarily indirect, some offer intriguing evidence for variations, whereas others favor the standard, or universal IMF. In this Section, we analyze the evidence for and against IMF variations from studies aimed at medium to high redshifts. Additionally, we examine local stellar structures (e.g., GCs and dwarf spheroidal galaxies) that formed at high redshifts, as this "near-field cosmology" gives us the most direct handle on IMF variations, at least in the low-mass regime.

There are theoretical reasons to expect that the IMF may vary cosmologically. If the turnover in the IMF, observed to be $\sim 0.1 - 0.3\,M_{\odot}$ today, is related to the minimum temperature $T_{\rm min}$ of molecular clouds (as might be expected if star formation is linked to dust temperature), then the point of the turnover may vary because $T_{\rm min}$ is linked to the cosmic microwave background temperature (Larson 2005). The reason why such a link may exist is that collapsing gas is only able to fragment as long as the temperature can continue to decrease when the density increases.

The minimum achievable fragmentation mass is then given by the Jeans mass that corresponds to the density and temperature at which the temperature minimum occurs. Below this mass the gas begins to reheat as the collapse continues. Alternatively, Elmegreen, Klessen & Wilson (2008) have stressed that temperature and density are needed to define a characteristic mass (that is, the turnover mass) and that the density was likely higher in the past too. If $T_{\rm min} \propto (1+z)$ and $\rho \propto (1+z)^3$, then the thermal Jeans mass is independent of redshift: $T_{\rm min}^{3/2}/\rho^{1/2}$ = constant.

The possibility of a cosmologically varying IMF is intriguing, as locally (see above sections) the characteristic mass of the IMF does not appear to depend strongly on environmental conditions. Davé (2008) notes that while no conclusive evidence for a cosmologically varying IMF exists, whenever detections are reported, they invariably point to the IMF being more top heavy in the past than at present times. However, some caution should be exerted, as summed up by the "Davé theorem" (R. Davé, priv. comm.): "All problems in extragalactic astrophysics can be solved by an appropriate choice of the IMF."

4.1. The Distant Universe

4.1.1. Rest-frame ultraviolet spectroscopy. The most direct way to determine the shape of the IMF for high-mass stars in high redshift galaxies is to use the rest-frame UV spectral features introduced in Section 3.2.4; the use of this diagnostic in both redshift regimes allows a valuable direct comparison of the high-mass IMF in the nearby and high redshift Universe. As noted earlier, however, this diagnostic is somewhat sensitive to a galaxy's recent SFH, in addition to the slope of its IMF.

Although high redshift galaxies are intrinsically faint, they are within reach of 8–10-m-class telescopes if they are gravitationally lensed. Two such galaxies have been heavily observed, MS 1512-cB58 at a redshift of $Z = 2.7276$ and "The Cosmic Horseshoe" at $Z = 2.38115$. Using the observed C IV P-Cygni profile, which is sensitive to the slope of the IMF above $\sim$10 $M_\odot$, and the presence of stars above 50 $M_\odot$, Pettini et al. (2000) conclude that high-mass slope of the IMF in MS 1512-cB58 is consistent with the Salpeter value. Quider et al. (2009) come to the same conclusion for The Cosmic Horseshoe. Steidel et al. (2004) used similar techniques on a somewhat closer galaxy, at $Z = 1.411$, and also conclude that the slope of the IMF is consistent with the Salpeter value for high-mass stars.

With the next generation of extremely large telescopes, detailed studies of the rest-frame UV in a large variety (from starburst to quiescent) of galaxies out to high redshifts should become possible. This may prove to be a rich line of investigation to see if and where the IMF may be different.

4.1.2. Galaxy-scaling relations and dynamics. By comparing the rest-frame color evolution of galaxies in clusters to their luminosity evolution, van Dokkum (2008) argued for an IMF that evolves with redshift, with the IMF being much more top heavy at higher redshift. This work is based on the Coma galaxy cluster and seven other galaxy clusters at redshifts between 0.176 and 0.837, where accurate photometry and dynamical masses are available. By examining changes with redshift in the relationship between a galaxy's rest-frame UV colors and mass, it is clear that early-type (that is, elliptical) galaxies become bluer with increasing redshift. This result agrees with what is predicted if early-type galaxies formed at high redshift and have been evolving (more or less) passively ever since. However, the exact rate at which they are evolving in color appears to be inconsistent with completely passive evolution if the underlying IMF follows a Salpeter distribution near $\sim$1 $M_\odot$. The observations can be brought into agreement with the passive evolution scenario if the IMF is allowed to vary near $\sim$1 $M_\odot$.

Using the characteristic mass of a Chabrier IMF as a parameterization (M_c), van Dokkum (2008) found that M_c varies by a factor of 20, between today and a redshift of 4. This drastic IMF variation will leave an imprint on older stellar populations (such as GCs and dwarf spheroidal galaxies) and appears to be at odds with observations. We return to this point in Section 4.2. The assumptions underlying this work are that the slope of the mass-color relation observed in Coma also applies to higher redshifts and does not vary between clusters, that the simple stellar population models are known to the required accuracy, and that the epoch of galaxy formation is known to sufficient accuracy.

For large samples of galaxies, there exists a relatively tight relationship between a galaxy's stellar mass (M_*) and its SFR. As discussed in Section 1.3, the SFR inferred from Hα, UV, or IR observations is heavily dependent on the IMF assumed; the M_*-SFR relation is therefore implicitly or explicitly dependent upon an assumed IMF. The observed trend of M_*-SFR is well reproduced by simulations of galaxy formation (largely independent of modeling parameters); however, the offset of this relationship (that is, the zero point) in the observations and models differ, with models overpredicting the total amount of mass formed for a given SFR over time. The magnitude of this difference grows with increasing redshift, which led Davé (2008) to speculate that the characteristic mass, M_c, of the IMF may vary with redshift. In order to reconcile the models with observations, he proposed that $M_c = 0.5(1+z)^2$, similar to that independently proposed by van Dokkum (2008). This implies a characteristic mass of 2, 4.5, and 8 $M_\odot$ at redshifts of 1, 2, and 3, respectively. As is discussed in Section 4.2, this is inconsistent with observations of GCs and nearby dwarf galaxies, which have formation epochs between $z = 3$–5. Hence, either GCs and dwarf galaxies are not representative of the typical star-forming event at these redshifts or systematics are at play in comparing the observed-to-modeled M_*-SFR relation.

Such an evolution also seems at odds with dynamical measurements of individual galaxies at $z \sim 2$. Similar to studies described in Section 3.2.5, Cappellari et al. (2009) compared the mass derived for nine galaxies at a redshift of $\sim$2 using Jeans dynamical modeling, virial estimates, and stellar population models. As the mass estimate based on stellar populations is largely dependent on the IMF adopted (see also Section 2.4.1), this method can be used to test for a cosmologically varying IMF. These researchers find good agreement between the three mass estimates and conclude that the IMF in these galaxies is bottom light (in their terminology), meaning consistent with a Kroupa-/Chabrier-type distribution. Galaxies from their sample are shown as filled green triangles in **Figure 4**. These conclusions are consistent with those presented by Cappellari et al. (2006), discussed in Section 3.2.5, where early-type galaxies in the local Universe were found to be consistent with Kroupa-/Chabrier-type IMFs. Because these galaxies formed at high redshift ($z > 3$, e.g., Renzini 2006), this argues against a cosmologically varying IMF. Additionally, because the SFRs within these forming elliptical galaxies are expected to have been extremely high (e.g., Genzel et al. 2003), this also argues against an IMF that correlates with SFR.

Direct measurements of the L/M of high redshift submillimeter galaxies, which include measurements of the total stellar (through modeling of the observed spectral energy distribution) and gaseous mass (through CO measurements), are becoming possible (Tacconi et al. 2008). Tacconi et al. compare the mass derived in stars and gas to that derived dynamically, through velocity dispersion/rotation measurements. After correcting for the AGN component in the observed spectral energy distributions, Tacconi et al. find that the submillimeter galaxies in their sample are all consistent with a Chabrier IMF, assuming a fairly conservative CO-to-H2 conversion factor. These points are shown as filled blue circles in **Figure 4**.

Elliptical galaxies exhibit a tight relationship between their central velocity dispersion, effective radius, and central surface brightness (Djorgovski & Davis 1987, Faber et al. 1987), which is known as the fundamental plane. Although the first two components (effective radius and central velocity dispersion) are structural properties, the central surface brightness depends on the luminosity of the galaxy, which in turn is dependent on the stellar population properties (age, IMF, etc.). If the IMF varies as a function of galaxy mass, then the fundamental plane will be affected, in particular it will "twist" when different redshifts are probed (see Renzini 2006 for a review). This is because the IMF controls the rate of luminosity evolution, so if the IMF depended on galaxy mass, the fundamental plane would evolve at different rates for different high-/low-mass galaxies (Renzini & Ciotti 1993). Renzini (2006) has searched for such an effect by comparing the fundamental plane of the Coma cluster in the local Universe to galaxy clusters at redshifts of $z = 0.58$ and $z = 0.83$. He finds no systematic twist indicating that high- and low-mass elliptical galaxies have approximately the same IMF.

4.1.3. Integrated global properties. Hopkins & Beacom (2006) and Wilkins, Trentham & Hopkins (2008) have compared the stellar mass density observed at a given redshift to the integral of the SFH of the Universe up to that time. These researchers find that the integral of the SFH predicts higher stellar mass densities than observed. By changing the slope of the IMF in the high-mass star range (that is, making it top heavy), the total mass formed from extrapolating an instantaneous indicator (like Hα) can be adjusted in order to bring the two measurements into agreement. However, it should be noted that even at $z = 0$ they require a nonstandard index for the IMF to explain their observations and that a more or less constant shift separates all data points (regardless of redshift) from the integrated SFH models, suggesting that systematics may be at play. If an IMF is adopted that allows concordance at low redshifts, a cosmologically varying IMF must be invoked to explain observations for $z > 0.7$ (Wilkins et al. 2008).

The results above depend on the accuracy with which we know the mass and SFR density of the Universe at various redshifts. These parameters are measured from galaxy LFs, which are truncated by detection limits. This truncation makes it necessary to extrapolate the galaxy LF to low luminosities before integrating to obtain the total mass and SFR densities; the shape assumed for the LF below the detection limit strongly affects the results of the integration. Using a large UV survey of Lyman Break Galaxies in the redshift range $z = 2$–3, Reddy & Steidel (2009) find a much steeper LF than earlier measurements, meaning that low-luminosity galaxies make up a larger fraction of the mass density of the Universe at high redshift than previously assumed. Taking into account the low-luminosity end of the UV galaxy distribution, the researchers find that there is no need to invoke a varying or nonstandard IMF to bring the integral of the SFH of the Universe into agreement with the observed stellar mass density.

4.1.4. Galaxy number counts. Submillimeter galaxies, detected in large numbers by the SCUBA (Submillimetre Common-User Bolometer Array) detector on the JCMT (James Clerk Maxwell Telescope), are thought to be massive starbursting galaxies, somewhat akin to local ultraluminous IR galaxies (e.g., Chapman et al. 2005). Due to their brightness, large samples of submillimeter galaxies are being assembled for comparison with semianalytic ΛCDM simulations.

In order to bring the predicted numbers of faint submillimeter galaxies from semianalytic ΛCDM simulations into agreement with observations, Baugh et al. (2005) needed to assume an extremely top-heavy IMF ($\Gamma = 0$). In their models, such an IMF both increases the total UV luminosity for a given mass and increases the metal yield, which in turn produces more dust. This additional dust can absorb more UV photons and emit them at IR wavelengths, subsequently increasing the number of observable submillimeter galaxies. Alternative models, which do not require top-heavy IMFs, have also been put forward to explain the submillimeter galaxy counts (Granato et al. 2004).

These semianalytic models have a rather large number of free or semiconstrained variables, hence, it appears premature to claim strong IMF variations before alternatives are investigated.

Using constraints on the total extragalactic background light, cosmic SFH, and the present K-band luminosity density, Fardal et al. (2007) conclude that a Salpeter IMF above 1 $M_\odot$ cannot be fit to all three constraints. These researchers favor an evolving IMF, in particular a "paunchy IMF" that is one with an excess of intermediate-mass stars (1.5–4 $M_\odot$). Whether the cosmic SFH is known to the necessary degree (see Section 4.1.3), other contaminating sources (e.g., AGN) can be accurately accounted for, and short bright stellar evolutionary stages (e.g., thermally pulsing asymptotic giant branch stars) are known precisely enough in order to place strict constraints on the IMF, and its evolution is questionable at the present time.

4.2. Near-Field Cosmology

Although the most massive stars dominate the light that we see in star-forming galaxies at high redshift, it is the low-mass stars that remain for many gigayears, bearing the imprint of their IMF. Locally, there are abundant examples of the remnants of star formation from the early Universe ($z \geq 3$), namely GCs, the Galactic bulge/halo, and dwarf spheroidal galaxies.

4.2.1. Globular clusters. Globular clusters are thought to be, by and large, made up of a single population of stars with a common age and metallicity (although the discovery of composite populations in many GCs suggests a possibly more complicated formation process; c.f. Bedin et al. 2004). GCs are some of the oldest objects in the Universe (e.g., Brodie & Strader 2006), although GC-like objects continue to form in the present day (see Section 2.4.1). Due to the proximity of Galactic GCs, many studies of their mass functions have been carried out using deep HST and ground-based imaging. Fitting their mass functions leads to characteristic masses (adopting the Chabrier form) of $M_c = 0.33$ (Paresce & de Marchi 2000). This is similar, although slightly higher than that found, for young clusters in the Milky Way disk ($M_c = 0.1$–0.3, see Section 2). However, as pointed out by van Dokkum (2008), this is clearly much lower than predicted by the results of van Dokkum (2008) and Davé (2008), which expect $M_c > 4\,M_\odot$ for the cluster formation epoch ($z = 3$–5). Additionally, intermediate-age (4.5 Gyr, $z_{\rm form} \sim 0.4$) clusters in the SMC also appear to have mass functions consistent with GCs and young clusters (Rochau et al. 2007).

The similarity between the IMF of young clusters and GCs is shown in **Figure 3**. Fitting tapered power laws to the young and old clusters results in a consistent picture, where the stars in both young and old clusters formed from the same underlying IMF (G. de Marchi, F. Paresce, and S. Portegies Zwart, submitted). However, the characteristic mass in older clusters does appear to be systematically larger than in young clusters and in the field (see Section 2.1).

Due to internal dynamical effects, GCs are expected to have their mass functions evolve with time. This has been observed in a relationship between the slope of the PDMF between 0.3–0.8 $M_\odot$ and the concentration (that is, compactness) of a cluster (de Marchi, Paresce & Pulone 2007). The evolution of the stellar mass function within GCs in a tidal field has been studied through detailed N-body modeling by Baumgardt, de Marchi & Kroupa (2008; see also Kruijssen 2009), who found that all of the GCs with well-determined PDMFs could be explained with a Kroupa (2002) IMF and subsequent dynamical evolution. Their models show that M_c increases with age (specifically with time until disruption), hence, the current value of M_c for GCs is in fact an upper limit for their initial values.

Thus, if M_c was significantly different at a redshift of 3–5 than the present, then GCs are not representative of the average star formation at that epoch, as their stellar mass functions appear nearly identical to those measured today in young star-forming regions in the Galaxy (see **Figure 3**). An important caveat to the above analysis is that GCs with top-heavy stellar IMFs (that is, those with large values of M_c) would not have survived to the present time, as they would have long since dissolved (for a Kroupa- or Salpeter-type IMF, the low-mass stars provide most of the gravitational potential of the cluster). Hence, it is possible that the current GCs in the Galaxy may not represent the average star-forming event at high redshifts. There are some chemical peculiarities, in particular the fraction of C-rich stars, in the halo which indicate that this may have been the case (Tumlinson 2007).

Following on the discussion in Section 2.4.1, we can also use the L_V/M_{dyn} ratio of GCs to test the stellar mass function within them. In **Figure 4**, we show the ratio for a sample of GCs of observed dynamical mass, M_{dyn}, to the mass derived by measuring the luminosity and apply a mass-to-light ratio from IMF-dependent simple stellar population models, M_{pop}. The sample shown consists of GCs in the Galaxy (McLaughlin & van der Marel 2005, Kruijssen & Mieske 2009) and NGC 5128 (Rejkuba et al. 2007, Kruijssen 2008). Both samples are consistent with SSP model predictions for a Kroupa IMF, with the small offsets likely due to internal dynamical effects (Kruijssen 2009).

4.2.2. The Galactic bulge and halo. The Galactic bulge is a largely coeval, old, and metal-rich stellar population that appears to be very similar in stellar content to other spiral bulges and elliptical galaxies (for a review see Renzini 1999). Hence, the bulge represents a unique chance to study these populations through resolving individual stars. Using HST NICMOS imaging of a region of the bulge, Zoccali et al. (2000) demonstrate that the LF of stars is in agreement with that observed for disk stars and GCs that appear not to have undergone large amounts of dynamical evolution, down to 0.15 $M_\odot$.

Gravitational microlensing studies also place constraints on the bulge mass function, primarily from observations of the distribution of event durations. Alcock et al. (2000a) describe the results of difference image analysis from the MACHO data and conclude that the observations are consistent with the PDMF of Scalo (1986) with no evidence for a large population of brown dwarfs. Other microlensing studies toward the LMC probe the mass function of compact objects in the halo of the Milky Way. Tisserand et al. (2007) and Wyrzykowski et al. (2009) conclude that less than 10% of the mass of Galactic halo could be in the form of compact objects with likely masses between 0.15 and 0.9 $M_\odot$. The suggestion that these might be very old white dwarfs (e.g., Oppenheimer et al. 2001) would imply a mass function for halo stars peaked at masses several times higher than found for the galactic disk. However, Reid (2005) argues strongly that there is no convincing evidence for an anomalous population of white dwarfs that could contribute significantly to the dark halo mass. Like the GCs, no constraints can be placed on the high-mass end of the IMF, but below a few solar masses, the IMF of old stellar systems and young star-forming regions appears consistent.

4.2.3. Nearby dwarf galaxies. Dwarf spheroidal galaxies provide excellent laboratories in which to study the IMF while avoiding the dynamical evolution encountered by GCs. These galaxies have similar ages and SFHs as GCs; however, their stellar densities are orders of magnitude lower, so they experience correspondingly less dynamical evolution. Wyse et al. (2002) used HST data to construct a LF of stars in Ursa Major, an old, local group dwarf spheroidal galaxy. To avoid the complication of transforming observed luminosities to stellar mass, the researchers directly compare the Ursa Major LF to that characterizing GCs of similar metallicity. They find that the LFs are indistinguishable down to $\sim$0.3 $M_\odot$ and conclude that the IMF must be independent of density and the presence of dark matter into at least the subsolar mass regime.

5. CONCLUSIONS

It was impossible to thoroughly review all observational results that bear on whether the IMF is universal or not in the space (and time) available to us. As mentioned in Section 1, we have set out to review claims concerning variations in the IMF in order to see whether other reasonable explanations of the results could be invoked without resorting to a nonuniversal IMF. We do not find overwhelming evidence for large systematic variations in the IMF as a function of the initial conditions of star formation. We believe most reports of nonstandard/varying IMFs have other plausible explanations, but we have highlighted measurements that deserve significant follow-up to confirm their findings. In this Section we summarize the main points of the review and conclude with an outlook for future work.

5.1. Synthesis of the Results Presented

In the more than 50 years since Edwin Salpeter published his seminal work, it is remarkable that the "best fit" value for the functional form of the stellar IMF above $1\,M_{\odot}$ remains $\Gamma \simeq 1.3$. Since that time, there has been tremendous work, especially on the subsolar regime, and it appears that some consensus is arising within the community. The general picture is that the high-mass end is well approximated by a power law with an index of ~ -1.35 (with an upper limit of $\simeq 150\,M_{\odot}$) that continues down to $\sim 0.5-2\,M_{\odot}$. At lower masses, the system IMF can be approximated as a log-normal distribution, with a peak at $\sim 0.2-0.3\,M_{\odot}$ and a dispersion of $\sim 0.5-0.6\,M_{\odot}$, or a series of broken power laws with similar shape. The IMF in the substellar regime is still rather uncertain, although many recent studies suggest that it is consistent with a $\Gamma \lesssim -0.5$ power law and the extrapolation of the log-normal distribution to lower masses. It remains to be seen whether a power-law departure of the IMF is required at the lowest masses and whether there exists a lower mass cutoff. Below, we summarize important conclusions from each section of this review.

5.1.1. Local clusters, associations, and the field. Locally, there does not appear to be any strong systematic variation in the IMF. Studies of many of the Galactic regions suffer from low number statistics, and as such, the tools to study them have been necessarily rather coarse. However, when larger numbers of high-mass stars do exist, a Salpeter form in the high-mass end is often found. At subsolar masses, the remarkable similarity of the IMFs found in the field, dense massive clusters, and more diffuse low-density star-forming regions argues for a universal IMF above the hydrogen burning limit. Some nearby regions, in particular Taurus, exhibit stellar IMFs that appear to be inconsistent with those observed in other regions (e.g., Orion, IC 348, Cham I). In a handful of other nearby regions (e.g., highlighted in the text), the most recent studies suggest deviations from the nominal IMF (Kroupa-/Chabrier-type); however, detailed follow-up observations are needed to confirm these reports.

5.1.2. The low-mass end. We are only just beginning to peer into the stellar/substellar boundary of the IMF and large uncertainties remain. There is some evidence that the characteristic mass of a log-normal IMF in the Upper Sco region is significantly lower than that found in the field or other regions. If confirmed, Upper Sco would contain more brown dwarfs than other regions (like Orion). Although there are some intriguing hints, current observations have not conclusively addressed whether there is a lower limit to the IMF, and if so, whether it might vary.

5.1.3. Extreme Galactic star-forming sites. Large telescopes and advanced instrumentation allow us to probe the stellar content in some of the most extreme places of star formation in the

Galaxy. Young massive clusters, like Westerlund 1, have power-law slopes that are consistent with the Salpeter value down to a few solar masses. The Arches cluster, Quintuplet, and NGC 3603 appear to have somewhat shallower indices; however, the presence of mass segregation in these dense clusters complicates the analysis. The global IMF within these dense clusters appears to be largely consistent with a universal distribution. The Galactic center has been extensively studied as the strong tidal field is (theoretically) expected to influence the IMF. Studies have reported a range of IMFs in the region. The detailed history of the stars found in the very center of the Galaxy (formed in situ or having spiraled into their present locations) and the strong dynamical evolution both complicate the analysis. Hints that the IMF may vary in these extreme environments require additional high-resolution imaging and spectroscopy (which will be within reach with the next generation of telescopes) in order to be confirmed.

5.1.4. Nearby galaxies. The LMC and SMC provide a larger baseline to study the effects of environment on the IMF and their proximity allows the direct study of stars with masses above $\sim$1 $M_\odot$. Studies of LMC/SMC clusters have been able to rule out strong variations of the IMF (above 1 $M_\odot$) as a function of density (over three orders of magnitude in the cluster central density) and metallicity (between 0.2 $Z_\odot$ and 1 $Z_\odot$). Similar results have been presented for M33. Integrated measurements (e.g., UV spectral diagnostics) of these regions will provide excellent templates in order to study starburst galaxies at mid-to-high redshift in order to directly compare the high-mass end of the IMF.

5.1.5. Starburst galaxies. Studies of nearby (tens of millions of parsecs) starburst galaxies and the star clusters within them have also led to a consensus that the IMF is similar to that observed in nearby star-forming regions. This is particularly interesting for the stellar clusters, as their stellar densities (and SFR densities) can vary over many orders of magnitude, implying that the IMF is not strongly influenced by the local environment. The massive cluster, M82F, is still the best candidate to host a strongly deviant (top-heavy) IMF.

5.1.6. Integrated galactic initial mass function (IGIMF). The sum of the IMFs of all clusters, groups, and associations (clusters for short hand) that are forming within a galaxy (the IGIMF) may not be statistically equivalent to the IMF of an individual region if the most massive star that can form in a cluster is dependent on the total mass of the cluster. This has led to the development of different sampling algorithms for the build up of stars within clusters. Some algorithms give a direct dependence of maximum stellar mass with group size, hence, large populations of low-mass clusters will never be able to form the highest mass stars. If the mass distribution of clusters is known/assumed, models of the IGIMF and its properties can be developed. If the cluster mass function is characterized by a power law with index -2 (currently favored by observations), then the IGIMF and IMF are very similar for any sampling algorithm used. For steeper cluster mass functions, the difference between the scenarios becomes more pronounced.

5.1.7. The integrated galactic initial mass function and galactic properties. Observations of low SFR galaxies in the local Universe show a diverging trend in their integrated Hα to UV luminosity ratios. Because Hα and UV emission are due to stars of different masses, one interpretation of these results has been that the IMF is different in these galaxies, being deficient in high-mass stars in small galaxies relative to massive galaxies. However, an alternative hypothesis is that the Hα flux is low within these galaxies because many of the ionizing photons from massive stars escape the galaxy without being absorbed by the ISM. Additionally, sample selection and "bursty" SFHs can also explain the observed trends without resorting to IMF variations. Resolved stellar color-magnitude diagrams for these galaxies are required in order to definitively test which scenario is correct. We note that the plateau in metallicity observed for the very lowest mass stars is consistent with theories describing the very first generation of star formation in the Universe. These theories predict that the first generation of stars should consist primarily of intermediate- and high-mass stars, with a radically different IMF than the standard IMFs discussed here (see Bromm & Larson 2004).

5.1.8. Cosmological studies. Recent studies have also found evidence for a varying IMF with cosmological time, being weighted toward heavier characteristic masses at higher redshift. Due to necessity, these analyses are indirect and, hence, are a ripe avenue for future research. These reports have come from the evolution of the mass-color relation in galaxy clusters, the stellar mass–SFR relationship observed in large samples of galaxies, and in number counts of specific galaxies with respect to model predictions. Each study has its own uncertainties and caveats, with some being dependent on model parameters. Elemental abundances in high redshift star-forming galaxies, in damped Lyman-α systems, and along quasar lines of sight all point indirectly to a Salpeter-type IMF, at least for the massive stars. Additionally, dynamical mass estimates of individual systems, along with stellar mass estimates from photometric modeling, appear to rule out strong IMF variations, with the handful of results published to date being consistent with a Kroupa-/Chabrier-type IMF. Reports that the stellar mass density did not equal the integral of the SFH of the Universe, hence suggesting that SFR indicators are not accurate at high redshift, seem to have been resolved through pushing deeper into the galaxy LF (that is, the SFR had been underestimated by counting galaxies and extrapolating to lower galaxy luminosities).

5.1.9. Near-field cosmology. We do have direct access to local environments that formed at high redshifts, namely GCs, the Galactic bulge/halo, and local dwarf spheroidal galaxies. In these stellar systems, the resolved stellar mass function appears to be consistent (at least in the low-mass end) with that observed in the local field population as well as in forming young clusters. This argues against a cosmologically varying IMF.

5.2. Future Avenues of Study

Future developments in instrumentation will enable more detailed probes of IMF variations than presently possible. Although large variations seem to be ruled out, more subtle systematic changes with initial conditions could lead to better constraints on theories of star formation.

For resolved stellar populations, large complete (or representative) samples of stars from well-defined stellar populations in a range of environments are needed in order to test for potential IMF variations. Current observations of star clusters in local group galaxies are confusion rather than sensitivity limited. As such, the time to complete an observation (at a fixed signal-to-noise ratio) goes as the diameter of the telescope to the power of six (in the diffraction- and background-limited regime). Ground-based AO on 6–10-m telescopes as well as the new capabilities of WF3 on HST will continue to improve studies of the IMF in crowded fields for years to come, but future facilities will provide great advances. The 6.5-m James Webb Space Telescope, scheduled for launch in 2014, will conduct diffraction-limited observations in space from 1–25 μm, obtaining sensitivity to 1 $M_{Jupiter}$ mass objects in the nearest, youngest star-forming regions. The next generation of AO-assisted extremely large telescopes (ELTs) will be able to resolve individual stars within star-forming regions less than 1.0 $M_{\odot}$ out to 1 Mpc in the local group. They will also allow us to push well into the substellar regime in the inner and outer Milky Way as well as in the Magellanic Clouds.

Although crowding is not a concern for nearby stars, identification of nearby multiple systems will depend on continued advances in high spatial resolution, high-contrast imaging. Surveys of nearby stars sensitive to faint, close companions will enable a more complete characterization of multiplicity properties as a function of primary star mass, companion mass, and orbital separation for comparison to the system IMF (Goodwin & Kouwenhoven 2009). Detailed follow-up of newly identified multiple systems will also greatly improve empirical calibrations of the transformation between observables and theoretical estimates of mass (e.g., dynamical mass measurements).

Aside from multiplicity surveys, studies of the Galactic field population will benefit most from advances in sensitivity and areal coverage. A major breakthrough in understanding the field population of brown dwarfs over the lifetime of the Milky Way will come with the *Wide-Field Infrared Survey Explorer* (WISE) satellite, launched in late 2009. This all-sky mid-IR survey should be able to detect the elusive "Y dwarfs," which represent the oldest, coldest substellar objects in the Milky Way with temperatures below 400 K. With an exquisitely sensitive sample of nearby, ultracool brown dwarfs, WISE will constrain the galactic field IMF well below the hydrogen burning limit for a large fraction of the age of the galaxy (Wright 2008). The SkyMapper survey will address the historical incompleteness in the nearby star sample at southern declinations, and synoptic surveys such as Pan-STARRS, the LSST, and the astrometric ESA GAIA mission will revolutionize kinematic studies of stellar populations throughout the galaxy. We will be able to obtain parallaxes for stars and warm brown dwarfs to 100 pc or more, find complete samples of stars in young clusters and associations from their dynamics down to very low masses, and pinpoint the formation sites of massive (OB) stars across the Milky Way. Do all high-mass stars form in clusters? This observation will be critical to test the IGIMF scenario.

Continued development of long-wavelength observational capabilities promise to shed more light on the stages of star formation from which the IMF arises. The *Spitzer Space Telescope* has helped to uncover hidden star formation in the densest molecular cloud cores, and future missions such as ESA's *Herschel Space Observatory* as well as millimeter interferometers, such as SMA (Submillimeter Array), CARMA (Combined Array for Research in Millimeter-Wave Astronomy), PdBI (Plateau de Bure Interferometer), and ALMA (Atacama Large Millimeter Array), allow us to peer into molecular cores of individual protostars, refining our understanding of how the molecular cloud core mass function is transformed into the IMF of stars and substellar objects (e.g., Myers 2009).

Finally, the next generation of ELTs will also open up the high redshift universe to detailed studies. Dynamical measurements of SSCs out to hundreds of millions of parsecs and full galaxies spanning a large range in SFRs beyond $z \sim 2$ will become possible, providing a more direct handle on IMF variations. Spatially resolved rest-frame UV spectroscopic diagnostics of star-forming regions in high redshift galaxies will be in reach, which will allow a direct comparison with local templates; the recent revival of STIS and installation of the Cosmic Origins Spectrograph (COS) on HST will also enable more UV-based investigations of the high-mass IMF in nearby galaxies and clusters.

Realizing the promise of these technical advances, however, will require a similar advance in the statistical analysis of IMF measurements. As we enter this new era, we advocate a shift in the means used to characterize and search for variations in the IMFs of resolved stellar populations. Specifically, we recommend that future IMF studies publish their derived space densities, such that IMF variations can be tested by using a direct statistical comparison of two measured IMFs, such as with a Kolmogorov-Smirnov test, rather than by comparing the parameters of the analytic fit adopted to characterize these increasingly rich datasets. If a functional form is fit to a IMF measurement, we suggest that statistical tools such as the F-test can provide quantitative guidance as to the most appropriate functional form to adopt and that the uncertainties associated with the derived parameters be clearly reported. By providing a more statistically sound basis for IMF comparisons, we will be better poised to uncover IMF variations where they do exist and to quantify the limits on IMF variations imposed by measurements consistent with a universal IMF.

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LITERATURE CITED

Adams FC, Fatuzzo M. 1996. *Ap. J.* 464:256
Alcock C, Allsman RA, Alves DR, Axelrod TS, Becker AC, et al. 2000a. *Ap. J.* 542:281
Allen PR, Koerner DW, Reid IN, Trilling DE. 2005. *Ap. J.* 625:385
Allison RJ, Goodwin SP, Parker RJ, de Grijs R, Portegies Zwart SF, Kouwenhoven MBN. 2009. *Ap. J. L.* 700:L99
Anders P, Fritze-v. Alvensleben U. 2003. *Astron. Astrophys.* 401:1063
Andersen M, Meyer MR, Greissl J, Aversa A. 2008. *Ap. J. L.* 683:L183
Andersen M, Meyer MR, Oppenheimer B, Dougados C, Carpenter J. 2006. *Astron. J.* 132:2296
Andersen M, Zinnecker H, Moneti A, McCaughrean MJ, Brandl B, et al. 2009. *Ap. J.* 707:1347
Ascenso J, Alves J, Lago MTVT. 2009. *Astron. Astrophys.* 495:147
Ballero SK, Kroupa P, Matteucci F. 2007. *Astron. Astrophys.* 467:117
Baraffe I, Chabrier G, Gallardo J. 2009. *Ap. J. L.* 702:L27
Barrado y Navascues D, Bouvier J, Stauffer JR, Lodieu N, McCaughrean MJ. 2002. *Astron. Astrophys.* 395:813
Barrado y Navascues D, Stauffer JR, Bouvier J, Martín EL. 2001. *Ap. J.* 546:1006
Bartko H, Martins F, Fritz TK, Genzel R, Levin Y, et al. 2009. *Ap. J.* 697:1741
Bartko H, Martins F, Trippe S, Fritz TK, Genzel R, et al. 2010. *Ap. J.* 708:834
Bastian N, Gieles M, Goodwin SP, Trancho G, Smith LJ, et al. 2008. *MNRAS* 389:223
Bastian N, Goodwin SP. 2006. *MNRAS* 369:L9
Bastian N, Konstantopoulos I, Smith LJ, Trancho G, Westmoquette MS, Gallagher JS. 2007. *MNRAS* 379:1333
Bastian N, Saglia RP, Goudfrooij P, Kissler-Patig M, Maraston C, et al. 2006. *Astron. Astrophys.* 448:881
Baugh CM, Lacey CG, Frenk CS, Granato GL, Silva L, et al. 2005. *MNRAS* 356:1191
Baumgardt H, de Marchi G, Kroupa P. 2008. *Ap. J.* 685:247
Becker GD, Sargent WLW, Rauch M, Simcoe RA. 2006. *Ap. J.* 640:69
Bedin LR, Piotto G, Anderson J, Cassisi S, King IR, et al. 2004. *Ap. J. L.* 605:L125
Beers TC, Christlieb N. 2005. *Annu. Rev. Astron. Astrophys.* 43:531
Béjar VJS, Martin EL, Zapatero Osorio MR, Rebolo R, Barrado y Navascués D, et al. 2001. *Ap. J.* 556:830
Bell EF, de Jong RS. 2001. *Ap. J.* 550:212

Bessell MS, Stringfellow GS. 1993. *Annu. Rev. Astron. Astrophys.* 31:433
Bihain G, Rebolo R, Béjar VJS, Caballero JA, Bailer-Jones CAL, et al. 2006. *Astron. Astrophys.* 458:805
Binney J, Tremaine S. 1987. *Galactic Dynamics*. Princeton, NJ: Princeton Univ. Press. 747 pp.
Bochanski JJ, Hawley SL, Reid IN, Covey KR, West AA, et al. 2010. *Astron. J.* In press
Bonatto C, Bica E. 2007. *MNRAS* 377:1301
Bonnell IA, Davies MB. 1998. *MNRAS* 295:691
Boss AP. 2001. *Ap. J. L.* 551:L167
Boselli A, Boissier S, Cortese L, Buat V, Hughes TM, Gavazzi G. 2009. *Ap. J.* 706:1527
Boudreault S, Bailer-Jones CAL, Goldman B, Henning T, Caballero JA. 2010. *Astron. Astrophys.* 510:27
Bouvier J, Kendall T, Meeus G, Testi L, Moraux E, et al. 2008. *Astron. Astrophys.* 481:661
Bouvier J, Stauffer JR, Martin EL, Barrado y Navascues D, Wallace B, Bejar VJS. 1998. *Astron. Astrophys.* 336:490
Bouy H, Brandner W, Martín EL, Delfosse X, Allard F, Basri G. 2003. *Astron. J.* 126:1526
Brandl B, Sams BJ, Bertoldi F, Eckart A, Genzel R, et al. 1996. *Ap. J.* 466:254
Brandner W, Clark JS, Stolte A, Waters R, Negueruela I, Goodwin SP. 2008. *Astron. Astrophys.* 478:137
Briceño C, Luhman KL, Hartmann L, Stauffer JR, Kirkpatrick JD. 2002. *Ap. J.* 580:317
Brodie JP, Strader J. 2006. *Annu. Rev. Astron. Astrophys.* 44:193
Bromm V, Larson RB. 2004. *Annu. Rev. Astron. Astrophys.* 42:79
Bruzual G, Charlot S. 2003. *MNRAS* 344:1000
Burgasser AJ, Reid IN, Siegler N, Close L, Allen P, et al. 2007. See Reipurth, Jewitt & Keil 2007, p. 427
Caballero JA, Bejar VJS, Rebolo R, Eisloeffel J, Zapatero Osorio MR, et al. 2007. *Astron. Astrophys.* 470:903
Calura F, Pipino A, Matteucci F. 2008. *Astron. Astrophys.* 479:669
Cappellari M, Bacon R, Bureau M, Damen MC, Davies RL, et al. 2006. *MNRAS* 366:1126
Cappellari M, di Serego Alighieri S, Cimatti A, Daddi E, Renzini A, et al. 2009. *Ap. J. L.* 704:L34
Cara M, Lister ML. 2008. *Ap. J.* 686:148
Carraro G, Baume G, Piotto G, Méndez RA, Schmidtobreick L. 2005. *Astron. Astrophys.* 436:527
Casewell SL, Dobbie PD, Hodgkin ST, Moraux E, Jameson RF, et al. 2007. *MNRAS* 378:1131
Chabrier G. 2003. *Publ. Astron. Soc. Pac.* 115:763
Chabrier G. 2005. See Corbelli, Palla & Zinnecker 2005, p. 41
Chandar R, Leitherer C, Tremonti CA, Calzetti D, Aloisi A, et al. 2005. *Ap. J.* 628:210
Chapman SC, Blain AW, Smail I, Ivison RJ. 2005. *Ap. J.* 622:772
Chiappini C, Matteucci F, Meynet G. 2003. *Astron. Astrophys.* 410:257
Clarke CJ. 2009. *Ap. Space Sci.* 324:121–28
Conti PS, Leitherer C, Vacca WD. 1996. *Ap. J. L.* 461:L87
Corbelli E, Palla F, Zinnecker H, eds. 2005. *The Initial Mass Function 50 Years Later*, *Ap. Space Sci. Libr. 327*. Dordrecht, Netherlands: Springer
Covey KR, Hawley SL, Bochanski JJ, West AA, Reid IN, et al. 2008. *Astron. J.* 136:1778
Dabringhausen J, Hilker M, Kroupa P. 2008. *MNRAS* 386:864
Da Rio N, Gouliermis DA, Henning T. 2009. *Ap. J.* 696:528
Davé R. 2008. *MNRAS* 385:147
Deacon NR, Nelemans G, Hambly NC. 2008. *Astron. Astrophys.* 486:283
de Grijs R, Anders P, Bastian N, Lynds R, Lamers HJGLM, O'Neil EJ. 2003. *MNRAS* 343:1285
de Grijs R, Gilmore GF, Johnson RA, Mackey AD. 2002. *MNRAS* 331:245
Delfosse X, Beuzit J-L, Marchal L, Bonfils X, Perrier C, et al. 2004. In *Spectroscopically Spatially Resolving the Components Close Binary Stars*, *ASP Conf. Ser. 318*, ed. RW Hilditch, H Hensberge, K Pavlovski, p. 166. San Francisco: ASP
de Marchi G, Paresce F, Portegies Zwart S. 2005. See Corbelli, Palla & Zinnecker 2005, p. 77
de Marchi G, Paresce F, Pulone L. 2007. *Ap. J.* 656:L65
de Wit WJ, Bouvier J, Palla F, Cuillandre J-C, James DJ, et al. 2006. *Astron. Astrophys.* 448:189
Djorgovski S, Davis M. 1987. *Ap. J.* 313:59
Dong H, Calzetti D, Regan M, Thilker D, Bianchi L. 2008. *Astron. J.* 136:479
Doyon R, Joseph RD, Wright GS. 1994. *Ap. J.* 421:101
Duquennoy A, Mayor M. 1991. *Astron. Astrophys.* 248:485

Duquennoy A, Mayor M, Halbwachs J-L. 1991. *Astron. Astrophys. Suppl.* 88:281
Elmegreen BG. 1999. *Ap. J.* 515:323
Elmegreen BG. 2006. *Ap. J.* 648:572
Elmegreen BG. 2009. In *The Evolving ISM in the Milky Way and Nearby Galaxies, The 4th Spitzer Science Center Conference, ed. K Sheth, A Noriega-Crespo, J Ingalls, R. Paladini*, p. 14. Pasadena: Spitzer Science Center. Available online at **http://ssc.spitzer.caltech.edu/spitzermission/reportsandproceedings/meetings/ismevol/**
Elmegreen BG, Hunter DA. 2006. *Ap. J.* 636:712
Elmegreen BG, Klessen RS, Wilson CD. 2008. *Ap. J.* 681:365
Elmegreen BG, Scalo J. 2006. *Ap. J.* 636:149
Espinoza P, Selman FJ, Melnick J. 2009. *Astron. Astrophys.* 501:563
Faber SM, Dressler A, Davies RL, Burstein D, Lynden-Bell D. 1987. In *Nearly Normal Galaxies, from the Planck Time to the Present*, ed. SM Faber, p. 175. New York: Springer
Fardal MA, Katz N, Weinberg DH, Davé R. 2007. *MNRAS* 379:985
Figer DF, Kim SS, Morris M, Serabyn E, Rich RM, McLean IS. 1999. *Ap. J.* 525:750
Figuerêdo E, Blum RD, Damineli A, Conti PS. 2002. *Astron. J.* 124:2739
Fischer DA, Marcy GW. 1992. *Ap. J.* 396:178
Flynn C, Gould A, Bahcall JN. 1996. *Ap. J. L.* 466:L55
Förster Schreiber NM, Genzel R, Lutz D, Sternberg A. 2003. *Ap. J.* 599:193
Frebel A, Kirby E, Simon JD. 2010. *Nature* 464:72
García Pérez AE, Asplund M, Primas F, Nissen PE, Gustafsson B. 2006. *Astron. Astrophys.* 451:621
Genzel R, Baker AJ, Tacconi LJ, Lutz D, Cox P, et al. 2003. *Ap. J.* 584:633
Ghez AM, Duchêne G, Matthews K, Hornstein SD, Tanner A, et al. 2003. *Ap. J. L.* 586:L127
Gieles M, Sana H, Portegies Zwart SF. 2010. *MNRAS* 402:1750
Gilmore G. 2001. In *Starburst Galaxies: Near and Far*, ed. L Tacconi, D Lutz, p. 34. Heidelberg: Springer
Gliese W, Jahreiß H. 1991. On *The Astronomical Data Center CD-ROM: Selected Astronomical Catalogs*, Vol. I, ed. LE Brotzmann, SE Gesser. Greenbelt, MD: NASA/Astron. Data Cent., Goddard Space Flight Cent.
Glover S. 2005. *Space Sci. Rev.* 117:445
Goddard QE, Kennicutt R, Ryan-Weber E. 2010. *MNRAS* In press (arXiv 1003.2520)
Gogarten SM, Dalcanton JJ, Williams BF, Seth AC, Dolphin A, et al. 2009. *Ap. J.* 691:115
Goldader JD, Joseph RD, Doyon R, Sanders DB. 1997. *Ap. J.* 474:104
González Delgado RM, Leitherer C, Heckman T. 1997. *Ap. J.* 489:601
González Delgado RM, Pérez E. 2000. *MNRAS* 317:64
Goodwin SP, Bastian N. 2006. *MNRAS* 373:752
Goodwin SP, Kouwenhoven MBN. 2009. *MNRAS* 397:L36
Gould A, Bahcall JN, Flynn C. 1997. *Ap. J.* 482:913
Gouliermis D, Brandner W, Henning T. 2006. *Ap. J.* 641:838
Graff DS, Freese K. 1996. *Ap. J. L.* 467:L65
Granato GL, De Zotti G, Silva L, Bressan A, Danese L. 2004. *Ap. J.* 600:580
Greissl J, Meyer MR, Christopher M, Scoville N. 2010. *Ap. J.* 710:1746
Greissl J, Meyer MR, Wilking BA, Fanetti T, Schneider G, et al. 2007. *Astron. J.* 133:1321
Güdel M, Briggs KR, Arzner K, Audard M, Bouvier J, et al. 2007. *Astron. Astrophys.* 468:353
Guieu S, Dougados C, Monin J-L, Magnier E, Martín EL. 2006. *Astron. Astrophys.* 446:485
Haas MR, Anders P. 2010. *Astron. Astrophys.* 512:79
Harayama Y, Eisenhauer F, Martins F. 2008. *Ap. J.* 675:1319
Hartmann L, Cassen P, Kenyon SJ. 1997. *Ap. J.* 475:770
Heger A, Woosley SE. 2002. *Ap. J.* 567:532
Henry TJ, Jao W-C, Subasavage JP, Beaulieu TD, Ianna PA, et al. 2006. *Astron. J.* 132:2360
Hillenbrand LA. 1997. *Astron. J.* 113:1733
Hillenbrand LA. 2009. *IAU Symp.* 258:81
Hillenbrand LA, Carpenter JM. 2000. *Ap. J.* 540:236
Hillenbrand LA, Hartmann LW. 1998. *Ap. J.* 492:540
Hillenbrand LA, White RJ. 2004. *Ap. J.* 604:741

Ho LC, Filippenko AV. 1996. *Ap. J.* 472:600
Holtzman JA, Faber SM, Shaya TR, Lauer TJ, Groth EJ, et al. 1992. *Astron. J.* 103:691
Homeier NL, Alves J. 2005. *Astron. Astrophys.* 430:481
Hong JS, van den Berg M, Grindlay JE, Laycock S. 2009. *Ap. J.* 706:223
Hopkins AM, Beacom JF. 2006. *Ap. J.* 651:142
Hoversten EA, Glazebrook K. 2008. *Ap. J.* 675:163
Hunter DA, Baum WA, O'Neil EJ Jr, Lynds R. 1996. *Ap. J.* 456:174
Hunter DA, Elmegreen BG, Ludka BC. 2010. *Astron. J.* 139:447
Hunter DA, Light RM, Holtzman JA, Lynds R, O'Neil EJ Jr, Grillmair CJ. 1997. *Ap. J.* 478:124
Jamet L, Pérez E, Cerviño M, Stasińska G, González Delgado RM, Vílchez JM. 2004. *Astron. Astrophys.* 426:399
Jeffries RD, Naylor T, Devey CR, Totten EJ. 2004. *MNRAS* 351:1401
Kalirai JS, Fahlman GG, Richer HB, Ventura P. 2003. *Astron. J.* 126:1402
Kennicutt RC Jr. 1983. *Ap. J.* 272:54
Kennicutt RC Jr. 1998. *Annu. Rev. Astron. Astrophys.* 36:189
Kenyon SJ, Gómez M, Whitney BA. 2008. See Reipurth 2008, p. 405
Kerber LO, Santiago BX. 2006. *Astron. Astrophys.* 452:155
Kim SS, Figer DF, Kudritzki RP, Najarro F. 2006. *Ap. J. L.* 653:L113
Knödlseder J. 2000. *Astron. Astrophys.* 360:539
Kouwenhoven MBN, de Grijs R. 2008. *Astron. Astrophys.* 480:103
Krabbe A, Genzel R, Eckart A, Najarro F, Lutz D, et al. 1995. *Ap. J. L.* 447:L95
Kraus AL, Hillenbrand LA. 2007. *Astron. J.* 134:2340
Kroupa P. 2001. *MNRAS* 322:231
Kroupa P. 2002. *Science* 295:82
Kroupa P, Tout CA, Gilmore G. 1993. *MNRAS* 262:545
Kroupa P, Weidner C. 2003. *Ap. J.* 598:1076
Kruijssen JMD. 2008. *Astron. Astrophys.* 486:L21
Kruijssen JMD. 2009. *Astron. Astrophys.* 507:1409
Kruijssen JMD, Mieske S. 2009. *Astron. Astrophys.* 500:785
Lada CJ. 2006. *Ap. J. L.* 640:L63
Lada CJ, Lada EA. 2003. *Annu. Rev. Astron. Astrophys.* 41:57
Larsen SS. 2006. In *Planets to Cosmology: Essential Science in Hubble's Final Years*, ed. M Livio. STScI, May 2006, Series: Space Telescope Science Institute, p. 35. Cambridge University Press, Cambridge (astro-ph/0408201)
Larsen SS, Brodie JP, Hunter DA. 2004. *Astron. J.* 128:2295
Larson RB. 1973. *MNRAS* 161:133
Larson RB. 2005. *MNRAS* 359:211
Lee JC, Gil de Paz A, Tremonti C, Kennicutt RC Jr, Salim S, et al. 2009. *Ap. J.* 706:599
Leinert C, Henry T, Glindemann A, McCarthy DW Jr. 1997. *Astron. Astrophys.* 325:159
Leitherer C. 2009. *AIP Conf. Ser.* 1111:175 In *Probing Stellar Populations Out To the Distant Universe*, ed. G Giobbi, A Tornambe, G Raimondo, M Limongi, LA Antonelli, N Menci, E Brocato. New York, Springer (arXiv:0812.5113)
Leitherer C, Schaerer D, Goldader JD, Delgado RMG, Robert C, et al. 1999. *Ap. J. Suppl.* 123:3
Lepine S, Thorstensen JR, Shara MM, Rich RM. 2009. *Astron. J.* 137:4109
Levine JL, Steinhauer A, Elston RJ, Lada EA. 2006. *Ap. J.* 646:1215
Lodieu N, Dobbie PD, Deacon NR, Hodgkin ST, Hambly NC, Jameson RF. 2007a. *MNRAS* 380:712
Lodieu N, Hambly NC, Jameson RF. 2006. *MNRAS* 373:95
Lodieu N, Hambly NC, Jameson RF, Hodgkin ST, Carraro G, Kendall TR. 2007b. *MNRAS* 374:372
Lodieu N, Zapatero Osorio MR, Rebolo R, Martín EL, Hambly NC. 2009. *Astron. Astrophys.* 505:1115
Loeckmann U, Baumgardt H, Kroupa P. 2010. *MNRAS* 402:519
Low C, Lynden-Bell D. 1976. *MNRAS* 176:367
Lucas PW, Roche PF, Tamura M. 2005. *MNRAS* 361:211
Luhman KL. 2004. *Ap. J.* 617:1216

Luhman KL. 2007. *Ap. J. Suppl.* 173:104
Luhman KL, Briceño C, Stauffer JR, Hartmann L, Barrado y Navascués D, Caldwell N. 2003a. *Ap. J.* 590:348
Luhman KL, Joergens V, Lada C, Muzerolle J, Pascucci I, White R. 2007. See Reipurth, Jewitt & Keil 2007, p. 443
Luhman KL, Mamajek EE, Allen PR, Cruz KL. 2009. *Ap. J.* 703:399
Luhman KL, Rieke GH, Young ET, Cotera AS, Chen H, et al. 2000. *Ap. J.* 540:1016
Luhman KL, Stauffer JR, Muench AA, Rieke GH, Lada EA, et al. 2003b. *Ap. J.* 593:1093
Lyo A-R, Song I, Lawson WA, Bessell MS, Zuckerman B. 2006. *MNRAS* 368:1451
Maciejewski G, Niedzielski A. 2007. *Astron. Astrophys.* 467:1065
Maciel WJ, Rocha-Pinto HJ. 1998. *MNRAS* 299:889
Mackey AD, Gilmore GF. 2003. *MNRAS* 338:85
Maíz Apellániz J. 2008. *Ap. J.* 677:1278
Maíz Apellániz J, Úbeda L. 2005. *Ap. J.* 629:873
Malumuth EM, Waller WH, Parker JW. 1996. *Astron. J.* 111:1128
Maness H, Martins F, Trippe S, Genzel R, Graham JR, et al. 2007. *Ap. J.* 669:1024
Maraston C. 2005. *MNRAS* 362:799
Maraston C, Bastian N, Saglia RP, Kissler-Patig M, Schweizer F, Goudfrooij P. 2004. *Astron. Astrophys.* 416:467
Maraston C, Nieves Colmenárez L, Bender R, Thomas D. 2009. *Astron. Astrophys.* 493:425
Martini P, Osmer PS. 1998. *Astron. J.* 116:2513
Maschberger T, Clarke CJ. 2008. *MNRAS* 391:711
Maschberger T, Kroupa P. 2009. *MNRAS* 395:931
Mason BD, Hartkopf WI, Gies DR, Henry TJ, Helsel JW. 2009. *Astron. J.* 137:3358
Massey P. 2002. *Ap. J. Suppl.* 141:81
Massey P. 2003. *Annu. Rev. Astron. Astrophys.* 41:15
Massey P, Hunter DA. 1998. *Ap. J.* 493:180
Massey P, Johnson KE, Degioia-Eastwood K. 1995. *Ap. J.* 454:151
Massey P, Lang CC, Degioia-Eastwood K, Garmany CD. 1995. *Ap. J.* 438:188
McCrady N, Gilbert AM, Graham JR. 2003. *Ap. J.* 596:240
McCrady N, Graham JR, Vacca WD. 2005. *Ap. J.* 621:278
McGaugh SS. 2005. *Ap. J.* 632:859
McKee CF, Ostriker EC. 2007. *Annu. Rev. Astron. Astrophys.* 45:565
McLaughlin DE, van der Marel RP. 2005. *Ap. J. Suppl.* 161:304
McMillan SLW, Vesperini E, Portegies Zwart SF. 2007. *Ap. J.* 655:L45
Melena NW, Elmegreen BG, Hunter DA, Zernow L. 2009. *Astron. J.* 138:1203
Mengel S, Lehnert MD, Thatte N, Genzel R. 2002. *Astron. Astrophys.* 383:137
Metchev SA, Hillenbrand LA. 2009. *Ap. J. Suppl.* 181:62
Metchev SA, Kirkpatrick JD, Berriman GB, Looper D. 2008. *Ap. J.* 676:1281
Meurer GR, Wong OI, Kim JH, Hanish DJ, Hockman TM, et al. 2009. *Ap. J.* 695:765
Meyer MR, Adams FC, Hillenbrand LA, Carpenter JM, Larson RB. 2000. In *Protostars and Planets IV*, ed. V Mannings, AP Boss, SS Russell, p. 121. Tucson: Univ. Ariz. Press
Meyer MR, Greissl J. 2005. *Ap. J. L.* 630:L177
Miller GE, Scalo JM. 1979. *Ap. J. Suppl.* 41:513
Moeckel N, Bonnell IA. 2009. *MNRAS* 400:657
Molaro P, Levshakov SA, D'Odorico S, Bonifacio P, Centurión M. 2001. *Ap. J.* 549:90
Moraux E, Bouvier J, Stauffer JR, Barrado y Navascués D, Cuillandre J-C. 2007. *Astron. Astrophys.* 471:499
Moraux E, Bouvier J, Stauffer JR, Cuillandre J-C. 2003. *Astron. Astrophys.* 400:891
Moraux E, Lawson WA, Clarke C. 2007. *Astron. Astrophys.* 473:163
Morris M. 1993. *Ap. J.* 408:496
Muench A, Getman K, Hillenbrand L, Preibisch T. 2008. See Reipurth 2008, p. 483
Muench AA, Lada EA, Lada CJ. 2000. *Ap. J.* 533:358
Muench AA, Lada EA, Lada CJ, Alves J. 2002. *Ap. J.* 573:366
Myers PC. 2009. *Ap. J.* 700:1609

Nagashima M, Lacey CG, Okamoto T, Baugh CM, Frenk CS, Cole S. 2005. *MNRAS* 363:L31
Nayakshin S, Sunyaev R. 2005. *MNRAS* 364:L23
Nissen PE, Gustafsson B, Edvardsson B, Gilmore G. 1994. *Astron. Astrophys.* 285:440
Norman ML. 2008. In *Proc. First Stars III, AIP Conf. Ser.* 990, ed. BW O'Shea, A Heger, T Abel, pp. 3–15. New York: Springer
Nürnberger DEA, Petr-Gotzens MG. 2002. *Astron. Astrophys.* 382:537
Oppenheimer BR, Hambly NC, Digby AP, Hodgkin ST, Saumon D. 2001. *Science* 292:698
Pandey AK, Upadhyay K, Ogura K, Sagar R, Mohan V, et al. 2005. *MNRAS* 358:1290
Paresce F, de Marchi G. 2000. *Ap. J.* 534:870
Parker JW, Hill JK, Cornett RH, Hollis J, Zamkoff E, et al. 1998. *Astron. J.* 116:180
Parker RJ, Goodwin SP. 2007. *MNRAS* 380:1271
Paumard T, Genzel R, Martins F, Nayakshin S, Beloborodov AM, et al. 2006. *Ap. J.* 643:1011
Pellerin A. 2006. *Astron. J.* 131:849
Pellerin A, Robert C. 2007. *MNRAS* 381:228
Pettini M, Steidel CC, Adelberger KL, Dickinson M, Giavalisco M. 2000. *Ap. J.* 528:96
Pettini M, Zych BJ, Steidel CC, Chaffee FH. 2008. *MNRAS* 385:2011
Pflamm-Altenburg J, Weidner C, Kroupa P. 2007. *Ap. J.* 671:1550
Pflamm-Altenburg J, Weidner C, Kroupa P. 2009. *MNRAS* 395:394
Phelps RL, Janes KA. 1993. *Astron. J.* 106:1870
Pinfield DJ, Burningham B, Tamura M, Leggett SK, Lodieu N, et al. 2008. *MNRAS* 390:304
Pipino A, Matteucci F. 2004. *MNRAS* 347:968
Pipino A, Matteucci F. 2008. *Astron. Astrophys.* 486:763
Portegies Zwart SF, McMillan SLW, Gieles M. 2010. *Annu. Rev. Astron. Astrophys.* 48:431–93
Portinari L, Moretti A, Chiosi C, Sommer-Larsen J. 2004. *Ap. J.* 604:579
Preibisch T, Balega Y, Hofmann K-H, Weigelt G, Zinnecker H. 1999. *New Astron.* 4:531
Prisinzano L, Micela G, Sciortino S, Favata F. 2003. *Astron. Astrophys.* 404:927
Proszkow E-M, Adams FC. 2009. *Ap. J. Suppl.* 185:486
Quider AM, Pettini M, Shapley AE, Steidel CC. 2009. *MNRAS* 398:1263
Rana NC, Basu S. 1992. *Astron. Astrophys.* 265:499
Rebull LM, et al. 2010. *Ap. J. Suppl. Ser.* 186:259
Reddy NA, Steidel CC. 2009. *Ap. J.* 692:778
Rees MJ. 1976. *MNRAS* 176:483
Reid IN. 2005. *Annu. Rev. Astron. Astrophys.* 43:247
Reid IN, Cruz KL, Laurie SP, Liebert J, Dahn CC, et al. 2003. *Astron. J.* 125:354
Reid IN, Gizis JE. 1997. *Astron. J.* 113:2246
Reid IN, Gizis JE, Hawley SL. 2002. *Astron. J.* 124:2721
Reid IN, Hawley SL. 2005. *New Light on Dark Stars: Red Dwarfs, Low-Mass Stars, Brown Stars* (*Springer-Praxis Ser. Astron. Astrophys.*), pp. 301–85. Chichester, UK: Praxis
Reid IN, Kirkpatrick JD, Liebert J, Burrows A, Gizis JE, et al. 1999. *Ap. J.* 521:613
Reipurth B, ed. 2008. *Handbook of Star Forming Regions*: Vol. I. *The Northern Sky*. San Francisco: ASP
Reipurth B, Jewitt D, Keil K, eds. 2007. *Protostars and Planets V*. Tucson: Univ. Ariz. Press
Rejkuba M, Dubath P, Minniti D, Meylan G. 2007. *Astron. Astrophys.* 469:147
Renzini A. 1999. In *The Formation of Galactic Bulges*, ed. CM Carollo, HC Ferguson, R Wyse, p. 9. Cambridge, UK: Cambridge Univ. Press
Renzini A. 2005. See Corbelli, Palla & Zinnecker 2005, p. 221
Renzini A. 2006. *Annu. Rev. Astron. Astrophys.* 44:141
Renzini A, Ciotti L. 1993. *Ap. J. L.* 416:L49
Reyle C, Robin AC. 2001. *Astron. Astrophys.* 373:886
Reyle C, Scholz R-D, Schultheis M, Robin AC, Irwin M. 2006. *MNRAS* 373:705
Rieke GH, Loken K, Rieke MJ, Tamblyn P. 1993. *Ap. J.* 412:99
Robin AC, Rich RM, Aussel H, Capak P, Tasca LAM, et al. 2007. *Ap. J. Suppl.* 172:545
Rocha-Pinto HJ, Maciel WJ. 1997. *MNRAS* 289:882
Rochau B, Gouliermis DA, Brandner W, Dolphin AE, Henning T. 2007. *Ap. J.* 664:322

Romano D, Chiappini C, Matteucci F, Tosi M. 2005. *Astron. Astrophys.* 430:491
Sabbi E, Sirianni M, Nota A, Tosi M, Gallagher J, et al. 2008. *Astron. J.* 135:173
Sagar R. 2002. In *Extragalactic Star Clusters, IAU Symp. 207*, ed. D Geisler, EK Grebel, D Minniti, p. 515. San Francisco: ASP
Salpeter EE. 1955. *Ap. J.* 121:161
Sanner J, Geffert M. 2001. *Astron. Astrophys.* 370:87
Sanner J, Geffert M, Brunzendorf J, Schmoll J. 1999. *Astron. Astrophys.* 349:448
Santos JFC Jr, Bonatto C, Bica E. 2005. *Astron. Astrophys.* 442:201
Satyapal S, Watson DM, Pipher JL, Forrest WJ, Coppenbarger D, et al. 1995. *Ap. J.* 448:611
Scalo J. 1998. In *The Stellar Initial Mass Function, 38th Herstmonceux Conf.*, Vol. 142, ed. G Gilmore, D Howell, p. 201. San Francisco: ASP
Scalo J. 2005. See Corbelli, Palla & Zinnecker 2005, p. 23
Scalo JM. 1986. *Fundam. Cosmic Phys.* 11:1
Schmalzl M, Gouliermis DA, Dolphin AE, Henning T. 2008. *Ap. J.* 681:290
Schmidt SJ, West AA, Burgasser AJ, Bochanski JJ, Hawley SL. 2010. *Astron. J.* 139:1045
Schödel R, Ott T, Genzel R, Eckart A, Mouawad N, Alexander T. 2003. *Ap. J.* 596:1015
Scholz A, Geers V, Jayawardhana R, Fissel L, Lee E, et al. 2009. *Ap. J.* 702:805
Scholz R-D, Lo Curto G, Méndez RA, Hambaryan V, Costa E, et al. 2005. *Astron. Astrophys.* 439:1127
Schröder K-P, Pagel BEJ. 2003. *MNRAS* 343:1231
Schultheis M, Robin AC, Reylé C, McCracken HJ, Bertin E, et al. 2006. *Astron. Astrophys.* 447:185
Selman FJ, Melnick J. 2005. *Astron. Astrophys.* 443:851
Sherry WH, Walter FM, Wolk SJ. 2004. *Astron. J.* 128:2316
Sirianni M, Nota A, de Marchi G, Leitherer C, Clampin M. 2002. *Ap. J.* 579:275
Sirianni M, Nota A, Leitherer C, de Marchi G, Clampin M. 2000. *Ap. J.* 533:203
Slesnick CL, Hillenbrand LA, Carpenter JM. 2004. *Ap. J.* 610:1045
Slesnick CL, Hillenbrand LA, Carpenter JM. 2008. *Ap. J.* 688:377
Slesnick CL, Hillenbrand LA, Massey P. 2002. *Ap. J.* 576:880
Smith BD, Turk MJ, Sigurdsson S, O'Shea BW, Norman ML. 2009. *Ap. J.* 691:441
Smith LJ, Gallagher JS. 2001. *MNRAS* 326:1027
Soderblom DR, Duncan DK, Johnson DRH. 1991. *Ap. J.* 375:722
Spitzer L. 1978. *Physical Processes in the Interstellar Medium*. New York: Wiley-Intersci. 333 pp.
Steidel CC, Shapley AE, Pettini M, Adelberger KL, Erb DK, et al. 2004. *Ap. J.* 604:534
Sternberg A. 1998. *Ap. J.* 506:721
Stolte A, Brandner W, Brandl B, Zinnecker H. 2006. *Astron. J.* 132:253
Stolte A, Brandner W, Brandl B, Zinnecker H, Grebel EK. 2004. *Astron. J.* 128:765
Stolte A, Grebel EK, Brandner W, Figer DF. 2002. *Astron. Astrophys.* 394:459
Sung H, Bessell MS. 2004. *Astron. J.* 127:1014
Tacconi LJ, Genzel R, Smail I, Neri R, Chapman SC, et al. 2008. *Ap. J.* 680:246
Tisserand P, Le Guillou L, Afonso C, Albert JN, Andersen J, et al. 2007 *Astron. Astrophys.* 469:387
Tremonti CA, Calzetti D, Leitherer C, Heckman TM. 2001. *Ap. J.* 555:322
Tumlinson J. 2006. *Ap. J.* 641:1
Tumlinson J. 2007. *Ap. J. L.* 664:L63
Tumlinson J, Venkatesan A, Shull JM. 2004. *Ap. J.* 612:602
Vallenari A, Pasetto S, Bertelli G, Chiosi C, Spagna A, Lattanzi M. 2006. *Astron. Astrophys.* 451:125
Vanbeveren D. 1982. *Astron. Astrophys.* 115:65
van de Kamp P. 1971. *Annu. Rev. Astron. Astrophys.* 9:103
van Dokkum PG. 2008. *Ap. J.* 674:29
Venn KA, Hill VM. 2008. *The Messenger* 134:23
Wang QD, Dong H, Lang C. 2006. *MNRAS* 371:38
Weidner C, Kroupa P. 2005. *Ap. J.* 625:754
Weidner C, Kroupa P. 2006. *MNRAS* 365:1333
Weidner C, Kroupa P, Bonnell IAD. 2010. *MNRAS* 401:275
Weights DJ, Lucas PW, Roche PF, Pinfield DJ, Riddick F. 2009. *MNRAS* 392:817

Whitworth A, Bate MR, Nordlund Å, Reipurth B, Zinnecker H. 2007. See Reipurth, Jewitt & Keil 2007, p. 459
Wild V, Walcher CJ, Johansson PH, Tresse L, Charlot S, et al. 2009. *MNRAS* 395:144
Wilking BA, Meyer MR, Greene TP, Mikhail A, Carlson G. 2004. *Astron. J.* 127:1131
Wilkins SM, Hopkins AM, Trentham N, Tojeiro R. 2008. *MNRAS* 391:363
Wilkins SM, Trentham N, Hopkins AM. 2008. *MNRAS* 385:687
Wright EL. 2008. *EAS Publ. Ser.* 33:57
Wright NJ, Drake JJ, Drew JE, Vink JS. 2010. *Ap. J.* 713:871
Wyrzykowski L, Kozlowski S, Skowron J, Belokurov V, Smith MC, et al. 2009. *MNRAS* 397:1228
Wyse RFG, Gilmore G, Houdashelt ML, Feltzing S, Hebb L, et al. 2002. *New Astron.* 7:395
Zaritsky D, Christlein D. 2007. *Astron. J.* 134:135
Zheng Z, Flynn C, Gould A, Bahcall JN, Salim S. 2001. *Ap. J.* 555:393
Zinnecker H. 1984. *MNRAS* 210:43
Zinnecker H, Yorke HW. 2007. *Annu. Rev. Astron. Astrophys.* 45:481
Zoccali M, Cassisi S, Frogel JA, Gould A, Ortolani S, et al. 2000. *Ap. J.* 530:418

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