The Impact of Binaries on the Stellar Initial Mass Function

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Abstract

The stellar initial mass function (IMF) can be conveniently represented as a canonical two-part power law function and is largely invariant for star formation regions evident in the Local Group of galaxies. The IMF is a “hilfskonstrukt”. It is a mathematical formulation of an idealised population of stars formed together in one star formation event, that is in an embedded cluster. The nature of the IMF – is it a probability density or an optimal sampling distribution function – is raised. Binary stars, if unresolved, have a very significant influence on the counts of low mass stars and need to be corrected for. Especially important is to take care of the changing binary fraction as a result of stellar-dynamical evolution of the embedded clusters which spawn the field populations of galaxies, given that the binary fraction at birth is very high and independent of primary-star mass. At the high mass end, the shape of the IMF is not much affected by unresolved companions, but the high multiplicity fraction amongst massive stars leads to a substantial fraction of these being ejected out of their birth clusters and to massive stars merging. This explains the top-lightness of the IMF in star clusters in M31. In close binaries also the masses of the components can be changed due to mass transfer. Correcting the star counts in R136 in the 30 Dor region for ejected stars, and a stellar-dynamical analysis of globular clusters and of ultra compact dwarf galaxies, together with the most recent star-counts in low-metallicity young massive clusters, all together imply the IMF to become top-heavy with decreasing metallicity and above a star-formation-rate density of about $1 M_\odot/(yr pc^3)$ of the cluster-forming cloud core. This is also indicated through the observed supernova rates in star-bursting galaxies. At the same time, the IMF may be bottom light at low metallicity and bottom-heavy at high metallicity, possibly accounting for the results on elliptical galaxies and ultra-faint dwarf galaxies, respectively.

1.1 Introduction

If the number of stars in the initial-stellar-mass interval $m, m + dm$ is $dN$ then

$$dN = \xi(m) \, dm,$$

(1.1)
where $\xi(m)$ is the stellar initial mass function (IMF), which is, formally, the complete ensemble of stars with their initial masses which form together. Because stars do not form at the same instant in time, the stellar initial mass function (IMF) does not exist as such. Indeed, even if we were able to measure the mass of each star, it is not possible to empirically measure the IMF: at any given time a stellar population is observed, some massive stars have either already evolved or been ejected from the system, the low-mass stars may not have formed yet in entirety and/or some have been lost through stellar dynamical processes, and stellar mergers may have occurred.

The IMF is a mathematical short-cut, a 'hilfskonstrukt', allowing the modelling of stellar populations, the stars of which form in spatially and temporarily correlated star formation events (CSFEs), i.e. in density maxima in molecular clouds which are fed by convergent filamentary gas flows (Kirk et al., 2013; Hacar et al., 2017b; Burkert, 2017). Theory has not been very successful in quantifying how the gas in a galaxy transforms into stars, due to the immense complexities and multitude of physical processes involved, but observations inform that stars form in CSFEs, which for practical purposes can be called embedded clusters (Lada and Lada, 2003; Lada, 2010; Gieles et al., 2012; Megeath et al., 2016; Kroupa et al., 2018). These are typically of sub-pc scale and assemble over a time-scale of a Myr (Marks and Kroupa, 2012), having spatial dimensions comparable to the molecular cloud filaments and the intersection thereof (André et al., 2016; Lu et al., 2018). These embedded clusters appear to form mass-segregated as ALMA and other observations have shown (Kirk and Myers, 2011; Plunkett et al., 2018; Alfaro and Román-Zúñiga, 2018) and may contain from a dozen binaries to many millions of stars, as a result of the large range of gravity-assisted density fluctuations, filaments and inflows in molecular clouds, which themselves are merely momentary condensations of the complex interstellar-medium of a galaxy. Data on globular clusters also indicate these to have formed mass-segregated (Haghi et al., 2015; Zonoozi et al., 2017). The flat birth radius–mass relation (Marks and Kroupa, 2012) and primordial mass segregation may be directly related to the existence of the most-massive-star vs embedded-cluster-stellar-mass ($m_{\text{max}} - M_{\text{ocl}}$) relation (Weidner and Kroupa, 2006).

Star-formation in the embedded clusters is feedback regulated, most likely as a result of the sum of outflows and stellar radiation compensating the depth of the potential of the embedded cluster and individual proto-stars. This is evident in the majority of the gas being expelled as shown by observations (Megeath et al., 2016) and magneto-hydrodynamical simulations (Machida and Matsumoto, 2012; Bate et al., 2014; Federrath et al., 2014; Federrath, 2015, 2016). Noteworthy is that observed CSFEs spanning the range of a few $10^5$ to a few $10^7 M_\odot$ in stars (the Taurus-Auriga embedded clusters, the Orion Nebula Cluster, NGC3603 and R136, all of which have been observed in much detail) are dynamically and physically well reproduced if the star-formation efficiency (SFE) is about 33 per cent, the gas expulsion occurs with about 10 km/s (Whitmore et al., 1999; Zhang et al., 2001; Kroupa, 2005; Smith et al., 2005) and the embedded phase lasts about 0.6 Myr (Kroupa and Bouvier, 2003; Kroupa et al., 2001; Banerjee and Kroupa, 2013, 2014, 2018, 2017). It is an interesting problem to understand which mechanism disperses the gas from these
systems. Observations suggest that even T Tauri associations lose their residual gas on a time scale of about a Myr (Neuhäuser et al., 1998), and Hansen et al. (2012) perform gravo-radiation-hydrodynamics simulations of low-mass star formation in turbulent clouds according to which about 2/3rd of the gas is blown out of the low-mass embedded clusters. The individual embedded clusters therefore should expand significantly within a few Myr (Banerjee and Kroupa, 2017). Direct evidence for this expansion has been documented. Getman et al. (2018) note that the core radii of a large ensemble of very young clusters expand by a factor of about 10 within 1 to 3.5 Myr and and previously Brandner (2008) provided a useful collation of the size changes for very young clusters as a function of their age. Banerjee and Kroupa (2017) show that the expansion can be achieved only via the expulsion of residual gas if SFE $\approx 1/3$ because binary-star heating and mass loss through evolving stars do not suffice, even in unison, to expand the clusters sufficiently within the short time ($\approx 10$ Myr). The gas expulsion unbinds a large fraction of modest-mass embedded clusters (Brinkmann et al., 2017) for which observational evidence has been found (Weidner et al., 2007) with potentially important implications for the structure of galactic disks (Kroupa, 2002b). This leads to an understanding of OB associations as forming from many expanding post-gas-expulsion embedded clusters, all of which formed over a few Myr within a molecular cloud which may itself be expanding or contracting such that the kinematical field of the young stars is complex and may not show an overall expansion of the OB association (e.g. Wright and Mamajek, 2018).

Since the time scales of stellar and galaxy evolution, which much of astrophysics is concerned with, are longer than a few Myr, the stellar populations may, to a good degree of approximation, be described by the IMF, if, for example the evolution of a star cluster or its spectral energy distribution is to be quantified. Because the appearance and evolution of astrophysical systems sensitively depends on the relative fraction of the short-lived massive versus the long-lived low-mass stars, much emphasis has been placed on constraining the detailed shape of the IMF and of the possible variation of this shape with physical conditions of the star-forming gas. Reviews of this topic can be found in Chabrier (2003); Bastian et al. (2010); Kroupa et al. (2013).

### 1.2 The nature of the IMF of stars and in galaxies

Here an overview of the IMF is given in view of recent developments. Before continuing, the important point needs to be stressed that the IMF (normalised to e.g. unit stellar mass) is mathematically strictly identical to the galaxy-wide IMF (gwIMF, the IMF of all stars forming in a galaxy and normalised in the same manner) if the process of star formation is mathematically equivalent to random sampling from an invariant IMF without constraints. Only in this case will many low-mass CSFEs together have the same IMF as one massive embedded cluster with the same number of stars. That is,

$$\text{gwIMF} = \text{IMF}, \quad (1.2)$$
if the invariant IMF is a probability density distribution function (PDF), where invariant means,

$$\text{IMF}(x_1, \rho_1, t_1, T_1, M_{\text{tot,1}}, \ldots) = \text{IMF}(x_2, \rho_2, t_2, T_2, M_{\text{tot,2}}, \ldots),$$

(1.3)

for any parameter \(j, k\). That is, the IMF, which is invariant in any local physical parameter (in one CSFE, i.e. in one embedded cluster), will result in the same gwIMF. Note that this implicitly assumes that massive stars can form in very low density regions.

Thus, by constraining observationally gwIMF, this one fundamentally important concept is tested (Kroupa et al., 2013). Indeed, the Milky-Way-field IMF, extracted from the Galactic field stellar population, has been found to be top-light relative to the canonical IMF (Eq 1.6), as shown by Scalo (1986) and Rybizki and Just (2015). For dwarf late-type galaxies with small star-formation rates (SFRs), it appears to be top-light (lacking massive stars) (Pflamm-Altenburg et al. 2009; Lee et al. 2009; Watts et al. 2018), and for late-type galaxies with high SFRs and elliptical galaxies which formed as major early-starbursts, the galaxy-wide IMF is top-heavy (Matteucci 1994; Gibson and Matteucci 1997; van Dokkum 2008; Gunawardhana et al. 2011; Romano et al. 2017). The survey by Hsu et al. (2012, 2013) of very young stars in the low-density star-forming region of the Orion A cloud south of the dense Orion Nebula Cluster, where only low-mass embedded clusters are found, has revealed significant evidence for a top-light IMF which differs from the IMF found in the Orion Nebula Cluster.

These results suggest that the IMF may not be a probability density distribution function. Progress on this issue has been achieved recently by interpreting the IMF as an optimal sampling distribution function (Kroupa et al., 2013; Schulz et al. 2015; Yan et al. 2017). A variable \(x\) is distributed according to an optimally sampled distribution function if, upon binning and independent of bin size, the Poisson scatter is zero in each bin.

The physical interpretation of optimal sampling being perfect feedback self-regulation of the star-formation process possibly with a high regularity of stellar masses along their hosting filaments and fibres. While optimal sampling is an extreme mathematical assumption, and nature most likely has some randomisation process when embedded clusters form, the lack of variation of the shape of the stellar IMF and the lack of scatter in the \(m_{\text{max}} - M_{\text{ecl}}\) relation indicate that star-formation may be closer to optimal than random sampling (Kroupa et al., 2013).

This is intimately linked to the existence of the \(m_{\text{max}} - M_{\text{ecl}}\) relation, according to which an embedded cluster of stellar mass \(M_{\text{ecl}}\) has a most massive star of mass \(m_{\text{max}}\) (Weidner et al. 2013; Ramirez-Alegria et al. 2016; Megeath et al. 2016; Stephens et al. 2017) that can be potentially physically related to the density of fiber structures in molecular clouds (Hacar et al. 2017a, 2018). Because of this relation, Eq. 1.2 does not hold, because many low-mass CSFEs add only low-mass stars while the few if any massive CFEs do not add enough massive stars to the galaxy if the CSFEs are distributed as a Salpeter-like power-law embedded cluster mass function (Yan et al. 2017). The existence of the \(m_{\text{max}} - M_{\text{ecl}}\) relation may also pose important implications for the existence of multiple
populations/star-bursts in star clusters, as discussed by Bekki et al. (2017) and Kroupa et al. (2018).

1.3 The stellar mass–luminosity relation

Stellar masses cannot be measured directly in most instances, and so the IMF can only be inferred by transforming the luminosity of a star to its mass using the mass–luminosity relation (other techniques such as measuring the gravity at the relevant stellar photosphere are unrealistic for large ensembles of stars). Given the uncertainties involved, this only works reliably for main-sequence stars. Immediately the problem becomes apparent that low-mass stars have not yet reached the main sequence when the massive stars have already evolved away from it, which is why $\xi(m)$ is but a hilfskonstrukt. For an ensemble of single main-sequence stars, which can be created for an observed population by artificially correcting all stars to their zero-age main sequence, we have

$$\xi(m) = \frac{dN}{dm} = -\frac{dN}{dM_x} \frac{dM_x}{dm}, \quad (1.4)$$

where $M_x$ is the absolute magnitude of a star of mass $m$ in the photometric pass- (e.g. V-) band. The $M_x(m)$ function is theoretically uncertain, in particular near $m = 0.3M_\odot$, below which the stars become fully convective and molecular hydrogen becomes an important opacity source and contributor to the mean molecular weight. The theory of the internal constitution of stars remains uncertain due to the complex physics of convection, radiation transport, rotation and magnetic fields. For $m < 0.1M_\odot$ the cores of the stars become electron degenerate, causing the $M_x(m)$ function to become very steep, because a small change in mass does not lead to a corresponding change in the central density. Thus, small changes in $m$ cause large changes in $M_x$, with major uncertainties. Empirical constraints on the $M_x(m)$ function, in connection with theoretical models, have yielded good constraints on the IMF (Kroupa et al., 1993; Kroupa, 2002a; Chabrier, 2003). A noteworthy outcome of this work was the realisation that the function $-\frac{dm}{dM_x}$ has a pronounced maximum near $M_V \approx 11.5 (m \approx 0.3M_\odot)$ (Kroupa et al., 1990, the KTG peak). It is evident in the stellar luminosity function, $\Psi_V = \frac{dN}{dM_V}$, of all resolved stellar populations (Kroupa et al., 2002a, Kroupa and Tout, 1997). The implication is that the IMF does not have a turn-over at this mass. It is noteworthy that just by simply counting stars on the sky to construct $\Psi_V$ their internal constitution is probed.

1.4 Binary stars

Given that the observed maximum in the stellar luminosity function, $\Psi_V(M_x)$, defined as $dN = -\Psi_V dM_x$, of all populations has the KTG peak, the remaining bias affecting the interpretation of $\Psi$ into $\xi$ via Eq. (1.4) is through unresolved multiple stars. The observer can
Figure 1.1 The binary fraction, \( f \), as a function of primary star mass, \( m \). The data (shown by various symbols) demonstrate that for old, main sequence Galactic field stars the binary fraction decreases with decreasing primary mass. Young, i.e. T Tauri stars, however have a binary fraction near unity independently of mass. This is shown as the shaded region termed “initial stellar binary population”. It extends to equal-age massive stars which have a very high multiplicity fraction as well (Sana et al., 2012; Moe and Di Stefano, 2017). The difference for young stars with \( f \approx 1 \) and for brown dwarfs (BDs) with \( f \approx 0.15 \) implies that BDs form with stars but follow their own distribution functions (Marks et al., 2015). It is definitely incorrect to argue that the trend of decreasing \( f \) with decreasing \( m \) implies that BDs form as an extension of the stellar population. An observational approach to test this statement is suggested by Marks et al. (2017). The old main sequence field stellar binary properties can be well understood if all stars form as binaries in embedded clusters with half-mass radii \( r_h \) (Marks and Kroupa, 2012; Belloni et al., 2018) in which the binary systems are dissolved over time as the clusters evolve (“dynamical evolution” arrows). The data are, from top to bottom: De Rosa et al. (2014); Duquennoy and Mayor (1991); Fischer and Marcy (1992); Reid et al. (2008); Kroupa et al. (2003). Adapted from Thies et al. (2015).

only count the number of main-sequence stars as a function of their luminosity, i.e. construct \( \Psi(M_x) \), but typically 50 per cent of all main-sequence stars with about \( m < \) few \( M_\odot \) are binaries with some being also triple and quadruple systems (Goodwin et al., 2007; Duchêne and Kraus, 2013). Note that most stars with mass < few \( M_\odot \) should form as binaries (Goodwin and Kroupa, 2005). Fig. 1.1 illustrates that, when including very young stars of all masses, it transpires that the binary fraction is close to 1 and independent of primary star mass. Only the old, Galactic field main sequence stars show a trend of decreasing binary fraction with decreasing primary mass. This is very well accounted for if all stars form as binaries in embedded clusters (Thies et al., 2015). The birth population of binaries with primaries < few \( M_\odot \) has well defined distribution functions (periods, mass ratios and eccentricities), and is well described by randomly sampling the IMF for the component masses, leading to a flat mass-ratio distribution function (Kroupa, 1995a; Belloni et al. 2015).
As emphasised in the latter reference, when modelling a stellar population it is essential to first draw the desired number of stars from the IMF and then to randomly pair the stars from this ensemble to create the binaries, because a different procedure would affect the IMF.

Detailed calculations and modelling of the Milky Way field population revealed that the deep star counts (reaching stars to distances beyond about 20 pc which rely on the method of photometric parallax to estimate the stellar distances) do not resolve most of the multiple systems, or they miss the companions due to the flux limit or due to glare from the primary. Taking this bias into account, and also the Malmquist and Lutz-Kelker biases, leads to a good reproduction of the various empirical determinations of $\Psi_V$ (Kroupa et al., 1993). Hereby the novel approach used by Kroupa et al. (1993) to arrive at the canonical IMF (for $m < 1 M_\odot$) was to employ the observational constraints on the $M_V(m)$ relation, the deep and the nearby (i.e. parallax-based) star counts simultaneously, to solve for one IMF and for the thickness of the Galactic disk. The approach was to assume a binary population in the Milky Way disk and to match the deep star counts, which do not resolve multiple systems, for the same IMF which also matches the nearby star counts in which multiple systems are resolved. More recent constraints on the IMF from MW disk star count data have not lead to a revision of these results (Bochanski et al., 2010).

Thus, the IMF as derived from the MW disk stellar population can be written as a two-part power-law form

$$\xi(m) = k_i m^{-\alpha_i}$$

where $k_i$ ensure the appropriate normalisation and continuity, and $\alpha_1 = 1.3, 0.08 < m/M_\odot \leq 0.5$ and $\alpha_2 = 2.3, 0.5 < m/M_\odot \leq 1$ being the Salpeter power-law index. A log-normal description is also possible and is indistinguishable from the above simpler form (Kroupa et al., 2013).

Taking care of modelling binary systems is an essential part of arriving at the above result, as neglect of unresolved binary systems leads to different biases in populations with different dynamical histories, see Fig. 1.2. Thus, an observer may readily derive different “IMFs” in two populations which in fact have the same IMF but have different binary populations.

To achieve insights into this problem, the distribution function of the initial binary population needs to be derived, in equivalence to the IMF, in order to then be able to calculate the present-day binary populations for different systems, allowing for the dissolution of the binaries and the ejection of stars through stellar-dynamical encounters. This means mathematically formulating the birth distributions of orbital periods, mass ratios and eccentricities again as “hilfskonstrukts” since they are not observable and do not exist at any instant in time, because, for example, wide binaries may be dissolved in an embedded cluster before other stars have formed. This needs to be tackled to arrive at a full understanding of the Galactic field population and of individual star clusters. For late-type stars, much progress has been achieved but requires the inclusion of highly accurate Nbody modelling currently only possible with the Aarseth direct Nbody codes and the Giersz-MOCCA Monte Carlo
code for massive clusters (Kroupa, 1995a; Belloni et al., 2017). The consistency check of using these birth binary distribution functions, evolving typical birth-CSFEs until they have dissolved to the Galactic field, yields stellar luminosity functions in very good agreement with the observed trigonometrical-parallax-based and photometric-parallax-based luminosity function and also with the observed field binary population (Kroupa, 1995b).

Fig. 1.2 visualises the effect of binaries on the IMF by first drawing a list of stars from the IMF. Each star is given a luminosity and stars weighing $m < 5 M_\odot$ are paired randomly from this list, while more massive primaries obtain a secondary if the mass-ratio lies in the range $0.1 - 1$, both the primary and secondary being taken from this same list, the stars being then removed from the list. This procedure, of only using stars in the list, is important in order to not change the IMF, for further details see Oh et al. (2015) and Oh and Kroupa (2016). The stellar system “masses” are calculated from the combined luminosity of the binaries, and this yields the “system IMF”. It is virtually identical above about $1 M_\odot$ to the stellar IMF but has a very significant deficit of less massive stars. Fig. 1.2 demonstrates the maximal error that can be done when assuming a stellar population has no binaries. Typical stellar populations have a binary fraction near 50 per cent but the bias at the low mass end is still very large, as is shown in Kroupa et al. (2013) for example. Because only a system IMF can be deduced from the observations, unless every binary is resolved, the arrived at IMF would have a turnover in the range $0.3 - 0.5 M_\odot$, which however is not present in reality.

A similar degree of work is not yet available for massive binaries. The observational constraints on the present-day binary properties of massive stars have been quantified well recently (Sana et al., 2012; Moe and Di Stefano, 2017), but these need to be evolved backwards through the dynamical environment of their birth clusters to distill the likely birth distribution functions. While this is a mature procedure for late-type stars (Kroupa, 1995a; Belloni et al., 2017), only the first steps into this direction have been made by Oh et al. (2015) and Oh and Kroupa (2016).

Concerning the massive stars, the seminal work of Massey (2003) showed the observationally constrained IMF to be the canonical invariant Salpeter power-law with $\alpha_3 = 2.3, m > 1 M_\odot$, independent of metallicity and density for very young stellar populations available in the Local Group of galaxies (see Eq. 1.5 for the low-mass stars). Impressive here is that many different teams using different telescopes and observing different clusters and OB associations have shown the IMF to be essentially invariant with the canonical Salpeter-Massey index $\alpha_3 = 2.3, m > 1 M_\odot$ (fig.5 in Kroupa 2002a). That is, the shape of the IMF not showing the expected Poisson scatter, and the $m_{\text{max}} - M_{\text{ej}}$ relation having little or no intrinsic scatter (Weidner et al., 2013), together confirm the IMF to be closer to an optimal density distribution function (Sec. 1.2). Binary and higher-order multiple systems do not affect $\alpha_3$ significantly (Weidner et al., 2009) and Fig. 1.2, although changes in component masses through binary-stellar-evolution affect the power-law index to some degree (Schneider et al., 2015), and the merging of binary components induced in the stellar-dynamically violent environment of massive embedded clusters lead to the appearance of super-canonical ($m > 150 M_\odot$) stars (Banerjee et al., 2012).
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Figure 1.2 To demonstrate the effect of unresolved binaries on IMF estimates from observations, the system IMF is plotted as the thick solid histogram assuming all stars are in binaries. The distribution of stars drawn randomly from the stellar IMF is shown as the solid gray histogram, and the canonical IMF is the dashed line. Stars are paired into binaries as follows: stars more massive than $5 M_\odot$ are assumed to have a mass-ratio distribution which is uniform in the range between 0.1 and 1, as in Oh et al. (2015), while primaries less massive than $5 M_\odot$ have companions drawn randomly from the IMF leading to a flat mass-ratio distribution. Important here is to follow the correct procedure as explained in Oh et al. (2015) and Oh and Kroupa (2016). Note that here the zero-age main sequence luminosities of the stars in a binary are added to provide the luminosity of the unresolved binary system, which is then converted into a mass using the main sequence mass–luminosity relation from Nebojsa (2004) and Salaris and Cassisi (2006) to define the luminosities of stars of mass $m$. The feature around $5 M_\odot$ is caused by this approximate treatment of the binary distribution. The unresolved binaries can significantly affect the low mass end of the IMF if not corrected for appropriately, but have a negligible effect on the massive-star IMF (see also Weidner et al. 2009).

However, given the large internal binding energy of binaries amongst massive stars, massive stars are ejected preferentially from their birth clusters. Noteworthy here is that the canonical IMF is perfectly consistent with the observationally derived IMF in modest M31 star clusters by Weisz et al. (2015), given that massive stars are ejected from these (fig.8 in Oh and Kroupa 2016). When observed, these massive stars are missing, leading to a deficit of massive stars in the young clusters. This has been noted to be the case for the Orion Nebula Cluster (Pflamm-Altenburg and Kroupa 2006). This bias has been corrected for in the star-burst cluster R136 in the Dor 30 star forming region in the Large Magellanic Cloud, showing that this $\approx 10^5 M_\odot$ very young low-metallicity cluster is likely to have been born with a top-heavy IMF (Banerjee and Kroupa 2012). This has been confirmed recently by independent observations (Schneider et al. 2018, see also Kalari et al. 2018 for another similar case).
1.5 The IMF is a systematically varying function

From a theoretical point of view (Larson, 1998; Adams and Fatuzzo, 1996; Adams and Laughlin, 1996; Dib et al., 2007) it has been relatively straightforward to understand that the IMF ought to become top-heavy with decreasing metallicity (less capability for the gas to cool) and increasing density (more coagulations of gas clumps, stronger converging flows). In regions of high star formation rate, cosmic rays produced by the high rate of supernovae penetrate molecular clouds leading to higher ambient temperatures and thus most probably also to top-heavy IMFs (Papadopoulos et al., 2011; Papadopoulos and Thi, 2013). The IMF may become somewhat bottom-heavy in high-metallicity clouds and bottom-light at low metallicities for the same reasons. Essentially, the above theoretical framework largely rests on star-formation depending on the local Jeans mass and/or being self-regulated through the various feedback processes that act once proto-stars appear, whereby photons have a larger interaction cross section with higher-metallicity gas, while it is modulated by the gravitational potential which, if deep enough, may cause protostellar cores to merge before individual stars can form in them. On the other hand, the theory based on gravo-turbulent molecular clouds (Padoan et al., 2007; Hennebelle and Chabrier, 2008; Hopkins, 2013) appears to be challenged by recent and rather surprising observations according to which stars from in fine, phase-space coherent fibres and filaments (Hacar et al., 2017a, 2018; Bresnahan et al., 2018), which can only appear when the cloud has stopped being turbulent on the relevant scales. A strongly turbulent cloud can also not lead to a bottom heavy IMF as suggested by Chabrier et al. (2014), because the shocks destroy low-mass proto-stellar cores before they can collapse (Bertelli Motta et al., 2016; Liptai et al., 2017). Given the immensely complex physical processes and boundary conditions acting during star formation, it is not surprising that it has until now not been possible to arrive at a convincing theoretical description of the properties of the IMF such that it is consistent with observed stellar and brown dwarf populations.

Rather than relying on theoretical arguments, the line of thought followed here is that the properties of the stellar IMF are constrained from observed simple stellar populations (containing stars of the same metallicity and age) in order to extract rules according to which it changes with conditions. Such an approach allows star formation theory to be tested and, independently of how successful star formation theory may be, it ensures that the IMF is consistent with resolved stellar populations. It allows larger systems such as galaxies to be described as being composed of many simple populations. A embedded, open or globular cluster is typically composed of a simple population.

The above alluded to top-heaviness has been confirmed by direct star-counts in the 30 Dor region (Schneider et al., 2018). Other direct evidence for a top-heavy IMF in a massive low-metallicity star cluster has also recently been published (Kalari et al., 2018). An elaborate analysis of the evolution of Milky Way globular clusters (GCs) and of ultra compact dwarf galaxies (UCDs) has previously (Dabringhausen et al., 2009, 2012; Marks et al., 2012) allowed a quantification of the dependency of the shape of the IMF on metallicity and
density of the embedded-cluster forming cloud core,

$$\alpha_{1,2,3} = fn([\text{Fe/H}], \rho_{\text{ecl}}),$$  \hspace{1cm} (1.6)

where [Fe/H] is the iron abundance relative to the Solar value and $\rho_{\text{ecl}}$ is the mass-volume-density (stellar plus gas mass) of the embedded cluster prior to gas expulsion (eq. 12, 14 and 15 with 0.87 replaced by $-0.87$ in Marks et al. 2012). According to these results the IMF becomes increasingly top-heavy above a star-formation-rate density of about $0.1 M_\odot/(\text{yr pc}^3)$ within the embedded-cluster-forming cloud core on a pc scale (Marks et al., 2012; Kroupa et al., 2013). Further evidence for this systematic variation of the stellar IMF with metallicity and density comes from the mass-to-light ratio of star clusters in the Andromeda galaxy (Hasani Zonoozi et al., 2016; Haghi et al., 2017). The high rate of core-collapse supernovae in the central UCD-type objects in the star-bursting galaxy Arp 220 (Dabringhausen et al., 2012), the larger rates of type Ib and IIb relative to 'normal' type II supernovae in Arp 299 (Anderson et al., 2011) as well as the different ratios of supernova types in star-forming (metal-poor) dwarf relative to (metal-rich) giant galaxies found in the Palomar Transient Factory (Arcavi et al., 2010) all suggest the above systematic IMF variation.

This variation of the IMF is visualised in Fig. 1.3, noting that the bottom-lightness at low metallicity may be related to the bottom-light trend with decreasing metallicity found by Gennaro et al. (2018) for ultra-faint dwarf galaxies (Jěrábková et al., 2018). The top-heaviness at low metallicity and high density may well be relevant for the emergence of multiple populations of stars in globular clusters (Prantzos and Charbonnel, 2006; Bekki et al., 2017).

With this we now have, for the first time, a mathematical formulation of a systematically varying IMF which is consistent with resolved nearby very young and open star clusters, GCs and UCDs and, it appears, also whole galaxies (Kroupa and Weidner, 2003; Kroupa et al., 2013; Recchi and Kroupa, 2015; Yan et al., 2017; Watts et al., 2018; Jěrábková et al., 2018). Elliptical galaxies, which formed with star formation rates larger than a few thousand $M_\odot$/yr, will have enriched with metals rapidly, as already inferred by Matteucci (1994) and Gibson and Matteucci (1997), leading, in their innermost super-solar abundance regions, to stellar IMFs which are bottom-heavy (Conroy and van Dokkum, 2012), since the high-metallicity individual star-burst embedded clusters forming in the innermost region of such systems will have had bottom-heavy IMFs (eq. 12 in Marks et al. 2012). The application of Eq. 1.6 to galaxies, by adding all IMFs in all forming embedded clusters, resolves the H$\alpha$ radial cutoff vs the UV-extended galactic-disk problem (Pflamm-Altenburg and Kroupa, 2008), implies all galaxies, independent of mass, to consume their gas on an about 3Gyr timescale, solving the stellar-mass-build-up time problem of dwarf galaxies (Pflamm-Altenburg and Kroupa, 2009) and leads to the observed mass–metallicity relation of galaxies (Köppen et al., 2007; Fontanot et al., 2017).

An application of Eq. 1.6 to the early Universe suggests that the very young and very massive GC and UCD progenitors must have appeared quasar-like with immense lumi-
Figure 1.3 The variable IMF in comparison to the canonical IMF shown as the dashed line. There is significant observational evidence that the IMF is not universal, that is, that it depends on environment, see Eq. 1.6. Based on Marks et al. (2012), it is shown here how the IMF can vary with density and metallicity. In each panel the metallicity and density-dependent IMF is shown as a solid line of thickness as given by the key in the panel. Left panel: low-density case, corresponding to an embedded star cluster with a stellar mass of $M_{\text{ecl}} = 100 M_\odot$. The vertical line demonstrates the expected high mass star cut-off based on the $m_{\text{max}} - M_{\text{ecl}}$ relation (Weidner et al., 2013), that is, such an embedded cluster would not contain stars more massive than $m_{\text{max}}$ unless a binary merges. Right panel: High-density case, corresponding a $10^8 M_\odot$ star cluster in which $m_{\text{max}} \approx 150 M_\odot$. The density, $\rho_{\text{ecl}}$, is given in terms of the mass in gas and stars within the embedded cluster, as defined in eq. 7 in Yan et al. (2017). All IMFs are normalised to the same stellar mass.

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