VARIATIONS OF THE IMF

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Abstract The stellar IMF has been found to be essentially invariant. That means, any detailed observational scrutiny of well resolved populations of very young stars appears to show the IMF to be of more or less the same shape independent of the metallicity and density of the star-forming region. While some apparent differences are seen, the uncertainties inherent to this game do not allow a firm conclusion to be made that the IMF varies systematically with conditions. The IMF integrated over entire galaxies, however, is another matter. Chemical and photometric properties of various galaxies do hint at galaxial IMFs being steeper than the stellar IMF, as is also deduced from direct star-count analysis in the MW. These results are however sensitive to the modelling of stellar populations and to corrections for stellar evolution, and are thus also uncertain. However, by realising that galaxies are made from dissolving star clusters, star clusters being viewed as the fundamental building blocks of galaxies, the result is found that galaxial IMFs must be significantly steeper than the stellar IMF, because the former results from a folding of the latter with the star-cluster mass function. Furthermore, this notion leads to the important insight that galaxial IMFs must vary with galaxy mass, and that the galaxial IMF is a strongly varying function of the star-formation history for galaxies that have assembled only a small mass in stars. Cosmological implications of this are that the number of SNII per low-mass star is significantly depressed and that chemical enrichment proceeds much slower in all types of galaxies, and particularly slowly in galaxies with a low average star-formation rate over what is expected for an invariant Salpeter IMF. Using an invariant Salpeter IMF also leads to wrong M/L ratios for galaxies. The detailed implications need to be studied in the future.

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1. The shape of the stellar IMF

The number of stars in the mass interval $m, m + dm$ is $dN \equiv \xi(m) \, dm$, where $\xi(m)$ is the stellar initial mass function (IMF). The logarithmic slope is $\Gamma(\log_{10} m) = d \log_{10} \xi_{L}(\log_{10} m)/d \log_{10} m$ such that $\log_{10} \xi(m) = \log_{10} k - \alpha \log_{10} m$ for the power-law form, $\xi(m) = km^{-\alpha}$, and $\alpha(m) = -d \log_{10} \xi(m)/d \log_{10} m = 1 - \Gamma(m)$. The logarithmic IMF is $\xi_{L}(m) = m \ln(10) \xi(m)$, which is useful when counting stars in logarithmic mass intervals.

The stellar IMF is the distribution of stellar masses that results from a single star-formation burst. Because essentially all stars form in clusters (Lada & Lada 2003) we expect to measure the stellar IMF in young star clusters before they disperse to the field of a galaxy.

The stellar IMF is one of the most fundamental distribution functions of astrophysics, and consequently a huge effort has been invested into constraining its shape since its first formulation in 1954 by Salpeter (1955) (at the Australian National University in Canberra) as a single power-law with $\alpha = 2.35$ for $0.4 < m/M_{\odot} < 10$, based on an early analysis of star-counts in the solar neighbourhood. A further milestone in this remarkable scientific enterprise is given by Miller & Scalo (1979) who made a large effort in constraining the IMF to mass ranges outside the Salpeter limits and who deduced that the stellar IMF flattens below $0.5 M_{\odot}$. Scalo (1986) re-considered this problem in what today remains the most significant piece of work in this topic by studying all of the then available observational constraints on local star counts, the shape of the stellar luminosity function, the mass-luminosity relation, stellar evolution for early-type stars and the vertical structure of the Milky Way (MW), and suggested the IMF to turn-down below about $0.4 M_{\odot}$, which had important implications in trying to understand the nature and occurrence of unseen matter in the disk of the MW. An important improvement in understanding the shape of the IMF for low-mass stars was contributed by Kroupa, Tout & Gilmore (1993 and two prior papers) who proposed that the strong maximum near $M_{V} \approx 12$ in the luminosity function of solar-neighbourhood stars stems from an inflection in the mass–luminosity relation, which in turn results from the association of $H_{2}$ molecules and the onset of full convection below about $0.4 M_{\odot}$. This revised the IMF to be essentially flat below $0.4 M_{\odot}$, but the inclusion of corrections for unresolved multiple systems and detailed modelling of star-counts with Malmquist bias and galactic-disk structure solved the disagreement between local and deep star counts and thereby increased the slope of the IMF below $0.5 M_{\odot}$. The resulting form of the two-part power-law IMF for late-type stars ($\alpha_{1} \approx 1.3 : 0.08 < m/M_{\odot} < 0.5; \alpha_{2} \approx$...
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2.3 : $0.5 < m/M_\odot < 1$) has been verified by Reid, Gizis & Hawley (2002) using revised local star-counts that incorporate HIPPARCOS distances. For $m > 1 M_\odot$ the IMF is proposed by Reid et al. to have $\alpha_3 = 2.5 - 2.8$, while Scalo (1986) derived $\alpha_3 \approx 2.7$, which is supported by the work of Yuan (1992). Written out,

$$
\xi(m) = k \begin{cases} 
\left( \frac{m}{m_H} \right)^{-\alpha_0}, & m_{\text{low}} \leq m < m_H, \\
\left( \frac{m}{m_H} \right)^{-\alpha_1} \left( \frac{m}{m_0} \right)^{-\alpha_2}, & m_H \leq m < m_0, \\
\left( \frac{m}{m_0} \right)^{-\alpha_1} \left( \frac{m}{m_1} \right)^{-\alpha_2} \left( \frac{m}{m_1} \right)^{-\alpha_3}, & m_0 \leq m < m_1, \\
\left( \frac{m}{m_1} \right)^{-\alpha_1} \left( \frac{m}{m_{\text{max}}} \right)^{-\alpha_2} \left( \frac{m}{m_{\text{max}}} \right)^{-\alpha_3}, & m_1 \leq m < m_{\text{max}},
\end{cases} 
$$

with exponents

$$
\alpha_0 = +0.3 \pm 0.7, \quad 0.01 \leq m/M_\odot < 0.08, \\
\alpha_1 = +1.3 \pm 0.5, \quad 0.08 \leq m/M_\odot < 0.50, \\
\alpha_2 = +2.3 \pm 0.3, \quad 0.50 \leq m/M_\odot < 1.00, \\
\alpha_3 = +2.7 \pm 0.7, \quad 1.00 \leq m/M_\odot,
$$

is the KTG93 IMF after extension to the sub-stellar mass range (Kroupa 2001; 2002). This IMF is the galaxial IMF as it is derived from galactic field stars, and, as we will see further below, differs from the stellar IMF. The multi-power-law description is used merely for convenience, as it allows us to leave the low-mass part of the IMF unchanged while experimenting with different slopes above, say, $1 M_\odot$. Other functional forms have been suggested (Miller & Scalo 1978; Larson 1998; Chabrier 2001), but these bear the disadvantage that the whole functional form reacts to changes in the parameters. Such parametrisations are useful for studying possible changes of the stellar IMF with cosmological epoch.

To constrain the stellar IMF we need detailed observations of young populations in star clusters and OB associations. The hope is that young clusters are not yet dynamically evolved so that the initial stellar population becomes evident. However, as dynamical modelling of young clusters containing O stars shows, significant dynamical evolution is already well established at an age of 1 Myr as a result of (i) the dense conditions before gas removal such that the binary-star population changes significantly away from its primordial properties, and (ii) rapid cluster expansion as a result of violent gas expulsion (Kroupa, Aarseth & Hurley 2001). This would lead to a systematic biasing of the observed stellar IMF against low-mass members if the cluster was significantly mass-segregated prior to gas expulsion (Moraux, Kroupa & Bouvier 2004). In addition to these difficulties come obscuration by natal gas and dust and the large uncertainties in deriving ages and masses given inadequate theoretical models of stars that are still relaxing from their accretion history, rotating rapidly, are variable and active, and have circum-stellar material.
The task of inferring the stellar IMF is thus terribly involved and uncertain. Nevertheless, substantial progress has been achieved. Given that there are many star clusters and OB associations, a large body of literature has been amassing over the decades, and Scalo (1998) compiled the then available IMF slope vs mass data.

An updated form of this plot is shown in Fig. 1, and as can be seen, the stellar IMF essentially follows the above galaxial IMF below $1 M_\odot$ (after correcting the observations for unresolved multiple systems), whilst having a Salpeter slope above $1 M_\odot$. Striking is that Large and Small Magellanic Cloud data (solid triangles) are not systematically different to the more metal rich MW data (solid circles). A systematic difference between dense clusters and sparse OB associations is also not evident (Massey 1998). Notable is that the scatter is large above $1 M_\odot$ but constant and that it can be fitted by a Gauss distribution of $\alpha$ values centred on the Salpeter index (Kroupa 2002). The scatter can be understood to result from statistical fluctuations and stellar-dynamical evolution of the clusters and the dynamically evolved OB associations (Elmegreen 1999; Kroupa 2001). These observations on the $\alpha$-plot thus point to a remarkable uniformity of the stellar IMF, which can thus be summarised by the multi-power-law form of eq. 2 but with

$$\alpha_3 = 2.3.$$  \hfill (3)

Some apparently significant deviations from this standard or canonical IMF do occur though (Fig. 2), and it will be the aim of observers and modellers alike to try to understand why the two clusters of similar age, the Pleiades (Hambly et al. 1999) and M35 (Barrado y Navascués et al. 2001), appear to have such different mass functions below $0.5 M_\odot$.

The existence of a universal canonical stellar IMF is therefore supported by the majority of data. It has a Salpeter index above about $0.5 M_\odot$. But this result uncovers a possibly unsettling discrepancy between this stellar IMF (eq. 3) and the galaxial IMF (eq. 2) which was found to be steeper for $m > 1 M_\odot$.

2. The galaxial IMF

The distribution of stellar masses in an entire galaxy results from the addition of all star-forming events ever to have occurred,

$$\xi_{\text{IGIMF}}(m) = \int_{M_{\text{ecl,min}}}^{M_{\text{ecl,max}}} \xi(m \leq m_{\text{max}}) \xi_{\text{ecl}}(M_{\text{ecl}}) \, dM_{\text{ecl}}.$$  \hfill (4)

This is the integrated galaxial IMF (IGIMF), i.e. the IMF integrated over space and time. Here $\xi_{\text{ecl}}$ is the MF of embedded clusters, and
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Figure 1. The alpha plot compiles measurements of the power-law index, $\alpha$, as a function of the logarithmic stellar mass and so measures the shape of the MF. The canonical IMF (eq. 3) is represented by the thick short-dashed horizontal lines, and other functional forms are shown using other line-types (MS indicates the Miller & Scalo (1979) log-normal form; and the thin short- and long-dashed lines are from Larson (1998), while the thick short-dash-dotted curve is the Chabrier (2001) form labelled by Ch). Shaded regions indicate mass-ranges over which derivation of the MF is particularly hard. For details see Kroupa (2002).

Figure 2. The measured logarithmic stellar mass functions, $\xi$, in the Orion Nebula Cluster [ONC, solid circles], the Pleiades [triangles] and the cluster M35 [lower solid circles]. The average Galactic field single star-star IMF (eq. 2) is shown as the solid line with the associated uncertainty range. For details see Kroupa (2002).

$$M_{\text{el, min}} = 5 M_\odot, M_{\text{el, max}} \lesssim 10^6 M_\odot$$

$M_{\text{el, min}} = 5 M_\odot, M_{\text{el, max}} \lesssim 10^6 M_\odot$ are the minimum and maximum cluster masses, respectively. Note that the IGIMF becomes indistinguishable to the field-star IMF in galaxies in which presently on-going star-formation contributes insignificantly to the already present stellar population, and also that $\xi_{\text{IGIMF}}$ does not correspond to the shining matter distribution for $m \gtrsim 1 M_\odot$. To evaluate this we need to consider only the recently formed stars.
Within each cluster stars are formed following the canonical IMF. However, small star-forming cloud cores, similar to the individual groups containing a dozen \( M_\odot \) in gas seen in Taurus–Auriga, for example, can never form O stars. Since the stellar IMF has been found to be essentially invariant, even when comparing the small groups of dozens of pre-main sequence stars in Taurus–Auriga with the rich Orion Nebula Cluster (Kroupa et al. 2003), constructing a young cluster population is mathematically equivalent to randomly sampling the canonical IMF. However, sampling without a mass constraint would in principle allow small star-forming regions to form very massive stars, which would be in violation to the observations according to which massive stars are formed in rich clusters. We therefore choose stars randomly from the canonical IMF but impose a mass-limit on the mass in stars that can form from a molecular cloud core with mass \( M_{\text{core}} = M_{\text{ecl}}/\epsilon \), where \( \epsilon \gtrsim 0.4 \) is the star-formation efficiency (Lada & Lada 2003),

\[
M_{\text{ecl}} = \int_{m_{\text{low}}}^{m_{\text{max}}} m \cdot \xi(m) \, dm,
\]

where \( m_{\text{low}} = 0.01 M_\odot \). In each cluster there is one single most-massive star with mass \( m_{\text{max}} \),

\[
1 = \int_{m_{\text{max}}}^{m_{\text{max}*}} \xi(m) \, dm,
\]

where \( m_{\text{max}} \approx 150 M_\odot \) is the fundamental upper stellar mass limit (Weidner & Kroupa 2004a). This set of two equations needs to be solved numerically to obtain \( m_{\text{max}} = m_{\text{max}}(M_{\text{ecl}}) \) that enters eq. 4. We note that our usage of an \( m_{\text{max}}(M_{\text{ecl}}) \) correlation disagrees with Elmegreen’s (2004) conjecture that no such relation exists. This problem is dealt with further by Weidner & Kroupa (2004b).

The slope, \( \beta \), of the star cluster IMF, \( \xi_{\text{ecl}} \propto M_{\text{ecl}}^{-\beta} \), is constrained by observations:

- \( 20 \leq M_{\text{ecl}}/M_\odot \leq 1100: \beta \approx 2 \) locally (Lada & Lada 2003);
- \( 10^3 \leq M_{\text{ecl}}/M_\odot \leq 10^4: \beta \approx 2.2 \) for LMC and SMC (Hunter et al. 2003)
- \( 10^4 \leq M_{\text{ecl}}/M_\odot \leq 10^6: \beta \approx 2 \pm 0.08 \) for Antennae clusters (Zhang & Fall 1999).

Assuming \( \beta \approx 2.2 \) and the canonical IMF slope \( \alpha \equiv \alpha_3 = 2.35 \) for stars above \( 1 M_\odot \) we get the resulting IGIMF shown in Fig. 3 which is considerably steeper than the Salpeter IMF (see Kroupa & Weidner 2003 for more details).
Figure 3. The dotted line is the canonical stellar IMF, $\xi(m)$, in logarithmic units and given by the standard four-part power-law form (eq. 3). The dashed line is $\xi_{\text{IGIMF}}(m)$ for $\beta = 2.2$. The IMFs are scaled to have the same number of objects in the mass interval $0.01 - 1.0\,M_\odot$. Note the turn down near $m_{\text{max}} = 150\,M_\odot$ which comes from taking the fundamental upper mass limit explicitly into account (Weidner & Kroupa 2004; 2004a). Two lines with slopes $\alpha_{\text{line}} = 2.35$ and $\alpha_{\text{line}} = 2.77$ are indicated.

Figure 4. The IGIMF power-law index $\alpha_{\text{IGIMF}}(m > 1\,M_\odot)$ as a function of the star-cluster MF power-law index $\beta$ for $\alpha = 2.35, 2.7, 3.2$.

In Fig. 4 the slope of the IGIMF, $\alpha_{\text{IGIMF}}$ for $m > 1\,M_\odot$, is studied for various values of $\beta$ and $\alpha$. The effect is more pronounced the steeper (larger $\beta$) the cluster mass function is.

This has a profound impact on the evolution of galaxies as can be deduced from Fig. 5. In the upper panel is shown the number of white dwarfs per star relative to the Salpeter IMF. For $\beta$ values above 2 it drops considerably, and in the lower panel, where the number of supernovae of type II (SNII) per star is plotted, the effect is even stronger. For $\alpha = 2.35$ and $\beta = 2.2$ there are 89% of white dwarfs but only 35% of SNII compared to a Salpeter IMF.
3. Variations among galaxies

The star-formation rate (SFR) of a galaxy is given by

\[ SFR = \frac{M_{\text{tot}}}{\delta t}, \]

where \( M_{\text{tot}} = \int_{M_{\text{cl,min}}}^{M_{\text{cl,max}}} M_{\text{cl}} \xi_{\text{cl}}(M_{\text{cl}}) dM_{\text{cl}} \) is the mass in clusters assembled in time interval \( \delta t \). Let's assume for the moment that the cluster IMF, \( \xi_{\text{cl}} \), is also invariant, and that \( M_{\text{cl,min}} = 5 M_\odot \) is fixed while \( M_{\text{cl,max}} \) may vary. Then the \( M_{\text{cl,max}} \) vs \( SFR \) relation can be calculated for different \( \delta t \). A comparison of this simple theory with empirical data is provided in Fig. 7. The figure plots empirical maximum star-cluster masses vs galaxial global SFRs, and a fit to these data yields

\[ \log_{10}(M_{\text{cl,max}}) = \log_{10}(k_{\text{ML}}) + (0.75(\pm0.03) \cdot \log_{10} SFR) + 6.77(\pm0.02), \]

where \( k_{\text{ML}} \) is the mass-to-light ratio. Fig. 6 shows this relation. Interestingly, the theory is nicely consistent with the data for \( \beta \approx 2.2 \) and
$\delta t \approx 10$ Myr, which suggests that the cluster IMF may indeed be quite invariant, and that a galaxy is able to assemble complete star-cluster systems within typically 10 Myr independent of the SFR (Weidner, Kroupa & Larsen 2004).

With the use of eq. 8 the time-dependent IGIMF of galaxies of different types can be calculated: On specifying a SFR, $M_{\text{ecl, max}}$ follows (eq. 8) and from eq. 4 the galaxial IMF can be computed in dependence of the star-formation history by adding up all galaxial IMFs generated in each multiple-$\delta t$-epoch until the present. As a straight-forward result we expect the galaxial IMF to be steeper (larger $\alpha_{\text{IGIMF}}$) for low-mass galaxies than for massive galaxies because the average SFR is lower for the former. We also expect a dependence of the galaxial IMF on the star-formation history (SFH) of a galaxy.

These expectations are born out. The final IGIMF of a dwarf or low-surface brightness galaxy with a stellar mass of $M_{\text{gal}} = 10^7 M_{\odot}$ assuming a stellar IMF slope $\alpha = 2.35$ is shown in Fig. 7, and in Fig. 8 for $\alpha = 2.70$. In the case with $\alpha = 2.35$ three SFHs are considered. A single burst of star-formation followed by no further formation (solid line), an episodic SFR with 100 Myr long peaks every 900 Myr (long-dashed line) and a constant SFR over 14 Gyr (dotted line). The influence of the SFH on the IGIMF is significant for galaxies with a small mass in stars. For a steeper input IMF (Fig. 8) this effect is even more pronounced. Such a steep IMF slope may possibly be the true value if the observationally derived stellar IMFs for massive stars are corrected for unresolved binaries (Sagar & Richtler 1991). In galaxies with a large stellar mass, $M_{\text{gal}} = 10^{10} M_{\odot}$ (Fig. 9), the sensitivity of $\alpha_{\text{IGIMF}}$ on the SFH becomes negligible because the average SFR is always large enough to sample the star-cluster IMF to the fundamental stellar upper mass limit. In summary, the IGIMF slope, $\alpha_{\text{IGIMF}}$, is shown as a function of $M_{\text{gal}}$ in Fig. 10. The differently shaded regions are for single burst, episodic and a constant SFR, respectively.

What implications beyond a reduction of the number of SNII do these findings have? The observed diversity of metallicities in different dwarf galaxies of rather similar mass (Mateo 1998; Garnett 2004) may be explained by this effect without invoking individually fitted effective yields as are needed in chemo-dynamical models with ’standard’ IMFs (Lanfranchi & Matteucci 2004). On the other hand, our models indicate that massive spirals and ellipticals should show less variations in the IGIMF and thus metallicity due to their high average SFR which is actually what is observed in nearby galaxies (fig. 9 in Garnett 2004). Current available models for the chemical evolution of galaxies have difficulties to reproduce the chemical abundances in disc galaxies with a standard galaxial Salpeter IMF, as it produces too many metals (Portinari et al.)
This problem may be resolvable by the model presented here but detailed chemo-dynamical calculations incorporating our approach need to be computed. Finally, the mass-to-light ratio of galaxies are too low for models that assume invariant galaxial Salpeter IMFs; the real $M/L$ ratio are larger.

**Figure 6.** Maximum cluster mass versus global star-formation rate (SFR), both in logarithmic units. Filled dots are observations by Larsen (2001; 2002) with error estimates and the linear regression fit is the solid line (eq. 8). The other curves are theoretical relations (eq. 7) which assume the entire young-cluster population forms in $\delta t = 1, 10$ and 100 Myr (bottom to top). The cluster IMF has $\beta = 2$ (dotted curves) or $\beta = 2.35$ (dashed curves).

**Figure 7.** IGIMFs for three dwarf or low-surface brightness galaxies with a final stellar mass of $10^7 \, M_\odot$ but different SFHs. The solid curve results from a single initial 100 Myr long burst of star formation. The dashed curve assumes a periodic SFH with 14 peaks each 100 Myr long and 900 Myr quiescent periods in between. The thick dotted curve assumes a constant SFR over 14 Gyr. For all cases the canonical power-law slope above $1 \, M_\odot$ ($\alpha = 2.35$) is used and the cluster IMF slope is $\beta = 2.35$. The straight solid line above $0.5 \, M_\odot$ shows the canonical input IMF for comparison. The thin dotted line is a Salpeter IMF extended to low masses. Note the downturn of the IGIMFs at high masses. It results from the inclusion of a limiting maximum mass, $m_{\text{max}} \leq m_{\text{max}^*}$, into our formalism.
4. Conclusions

1. IGIMFs are steeper than the stellar IMF.

2. Therefore there are significantly fewer SNII per G-type star per galaxy.

3. Chemical enrichment and $M/L$ ratios of galaxies calculated with an invariant Salpeter IMF are wrong.

3. The IGIMFs vary from galaxy to galaxy.

4. Dwarf galaxies show the largest variations: $3.1 \lesssim \alpha_{\text{IGIMF}} \lesssim 3.6$ for $\alpha_{3,\text{true}} = 2.35$ (Salpeter) and $\beta = 2.35$.

5. The sensitivity of the IGIMF on the SFH increases with $\alpha_3$. The true value of $\alpha_{3,\text{true}}$ for the stellar IMF may actually be significantly larger than 2.35.

6. Understanding the corrections for unresolved multiples on the derivation of the high-mass part of the stellar IMF is of fundamental importance!
Figure 10. The resulting IGIMF slopes above $1 M_\odot$ are shown in dependence of stellar galaxy mass for different models, as indicated. The lower bounds of the shaded areas are for an initial star formation burst forming the entire stellar galaxy while the upper bounds are derived for a continuous SFR. The various symbols correspond to calculated models. Symbols lying within the shades area correspond to models with an episodic SFH.

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