THE STELLAR INITIAL MASS FUNCTION IN LOCAL DWARF GALAXIES

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Abstract

The stellar initial mass function (IMF) for dwarf galaxies in the local universe is reviewed. These galaxies are at distances between 50 kpc (LMC) and tens of Mpc. This distance range allows IMF determinations from star counts in conjunction with photometry/spectroscopy, color-magnitude diagrams, and integrated spectral energy distributions. There is no observational evidence for a significant IMF variation among local dwarf galaxies. Small variations, however, could be hidden by systematic and experimental uncertainties. Environment and metallicity in particular have little observable effect on the IMF. The high-mass end of the IMF above $\sim$10 $M_\odot$ follows a power-law slope with a Salpeter exponent. At intermediate masses between 3 and 10 $M_\odot$ the slope is close to Salpeter, or somewhat steeper (richer in less massive stars). This trend is reversed at lower masses where a flattening of the IMF or even a truncation may occur, somewhat similar to the solar neighborhood case. Extrapolating the Salpeter slope to the hydrogen-burning limit of $\sim$0.1 $M_\odot$ would lead to an overestimate of the star-formation rate by a factor of several. A power-law fit with a Salpeter slope truncated at 1 and 100 $M_\odot$ is an acceptable approximation for the IMF and gives reasonable star-formation rates.

1 Introduction

The shape of the stellar initial mass function (IMF) and its theoretical interpretation are fundamental to our understanding of the star-formation process. Yet, more than 40 years after the influential paper on the solar neighborhood IMF by [51] we are still lacking a concise theory, and observational studies are subject to substantial uncertainties. Rather than repeating the current state of the IMF in this review, I refer the reader to the comprehensive articles written by [45], [54], [56], and [11]. The goals I have set for this paper are (i) to highlight the challenges of deriving the IMF in local dwarf galaxies, (ii) to present a consensus view of the IMF shape (if there exists one), and (iii) to make a recommendation for the choice of the IMF in dwarf galaxies at cosmological distances.

2 Relevant parameters

Figure 1 shows the “classical” solar neighborhood field star IMF of [54]. A few more recent IMF studies over the full mass range have become available since then. A complete literature survey is in [56]. Since few of these investigations have revised the basic functional behavior of the IMF (at least not to a degree that would affect the interpretation of the IMF in dwarf galaxies), I will use Figure 1 for a qualitative discussion of the main relevant issues.

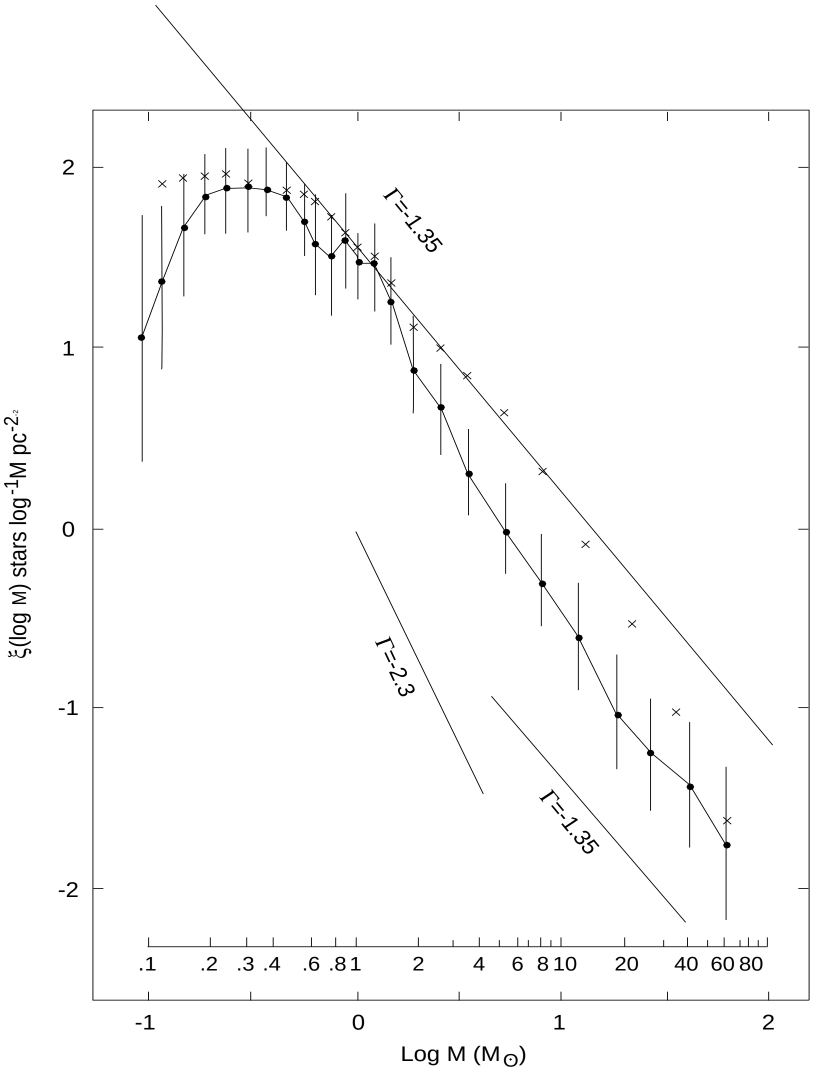

Figure 1: Field star IMF in the solar neighborhood. Plotted are star numbers per logarithmic mass interval. Crosses: solar-neighborhood IMF of [45]; points with error bars: revised field star IMF of [54]. The straight lines indicate slopes of –1.35 (Salpeter slope), and –2.3 (power-law approximation to the high-mass end of the Miller-Scalo IMF) at arbitrary normalization. The extrapolation of the Salpeter IMF to 0.1 $M_\odot$ highlights the difference between this IMF and a more realistic IMF with a flattening at low masses.

The solar neighborhood IMF can be approximated by a power-law with an exponent close to Salpeter's value of $\Gamma = -1.35$ for masses higher than $\sim$10 $M_\odot$. The IMF becomes steeper towards lower masses but can still be reasonably well approximated by a power-law exponent down to $\sim$2 $M_\odot$. The IMF is scale-free over 1 to 2 orders of magnitude in mass. Below about 2 $M_\odot$, the IMF flattens, or may even turn over — although this is under debate (see [25]). Uncertainties become prohibitive at the lowest masses but it may well be (and is plausible) that the trend in Figure 1 continues, and the IMF over the full mass range is symmetric with respect to the maximum at $\sim$0.3 $M_\odot$. This would suggest a preferred mass of $\sim$0.3 $M_\odot$, and the mass range accessible to observations would merely be the tip of the iceberg.

It is worth recalling that even if the IMF is truncated close to 1 $M_\odot$, most of the mass of a stellar population is locked in low-mass stars. For a Salpeter IMF, stars with masses between 1 and 10 $M_\odot$ contribute six times more mass to the total mass than all stars above 40 $M_\odot$. Conversely, most of the stellar light is provided by the most massive stars due to the steep stellar mass-luminosity relation.

Is the IMF of Figure 1 universal? There are suggestions that this is not the case. The slope of the IMF could vary with environment, with a steeper IMF found in more metal-rich star-formation regions (e.g., [42]). There could also be a metallicity dependent upper mass limit $M_{\rm up}$ to the IMF, in particular in dust-enshrouded starbursts (e.g., [27]). Or low-mass stars could be deficient or completely absent. A mass cut-off around $M_{\rm low} \approx 5$ M$_\odot$ was derived for M82 by [50]. An IMF with a deficit of intermediate and low-mass stars was suggested by [32] to account for the large amount of oxygen observed in galaxy clusters.

In order to illustrate the effect of even a moderate variation of the IMF, I took the models of [29] to make predictions for a few key quantities related to dwarf galaxies. I assumed a "standard" IMF ($\Gamma = -1.35$ between 1 and 100 M$_\odot$) for this exercise and considered three variants whose normalization leaves the total star-formation rate unchanged:

- $\Gamma = -2.3$: The non-thermal luminosity of stellar winds and supernovae at 10 Myr would be reduced by a factor of 10, thereby reducing the energization of dwarf galaxy superbubbles and outflows (e.g., [37]). The output of ionizing photons at 3 Myr would be down by a factor of 20, and so would be the [O II] line flux (e.g., [12], [24]).
- $M_{\rm up} = 30$ M$_\odot$. If most Wolf-Rayet stars are the evolved descendants of very massive stars, such an IMF would predict very few Wolf-Rayet galaxies (cf. [26], [7]). Along the same argument, the O3 star cluster in the center of R136 ([38]) could not have formed in a galaxy with $M_{\rm up} = 30$ M$_\odot$.
- $M_{\rm low} = 5$ M$_\odot$. The mass converted into stars would be reduced by a factor of 3. Galaxies would consume only a small fraction of their gas supply over a Hubble time at their currently observed star-formation rates ([52]). Starbursts with a truncated IMF would become invisible after about 100 Myr without ongoing star formation (cf. [46] and could remain undetected in galaxy number counts.

These examples should be motivation enough to seriously investigate the evidence for deviations from the solar neighborhood IMF in local dwarf galaxies.

3 Results for the Large Magellanic Cloud

The proximity of the Large Magellanic Cloud (LMC) allows IMF determinations whose precision is often comparable to those obtained in the Galaxy. Therefore I will review selected LMC results to have a baseline for comparison with more distant dwarf galaxies. I will begin with a discussion of the field population at low and high masses and then move on to the IMF in clusters.

The LMC populations were reviewed by [41]. Ground-based work, as pushed to the limits by [61], is restricted to main-sequence turn-off masses >1 M$_\odot$. Recent deep WFPC2 imagery of an outer LMC field by [18] reaches $V \approx 28$, with a completeness limit of $V = 26$. The corresponding main-sequence mass limit is 0.6 M$_\odot$. The luminosity function provides constraints on the star-formation history and the IMF between 0.6 and 3 M$_\odot$. The data favor an IMF with a Salpeter or somewhat steeper slope. However, disentangling IMF and star-formation history is far from trivial. The look-back times corresponding to the sampled masses are a few Gyr, and significant variations in the star-formation history of the LMC have occurred over that period (e.g., [1]).

Most of the work on the high-mass end of the *field* IMF was done by P. Massey and collaborators (e.g., [40]). The IMF for masses above ~40 M$_\odot$ is clearly steeper than Salpeter,

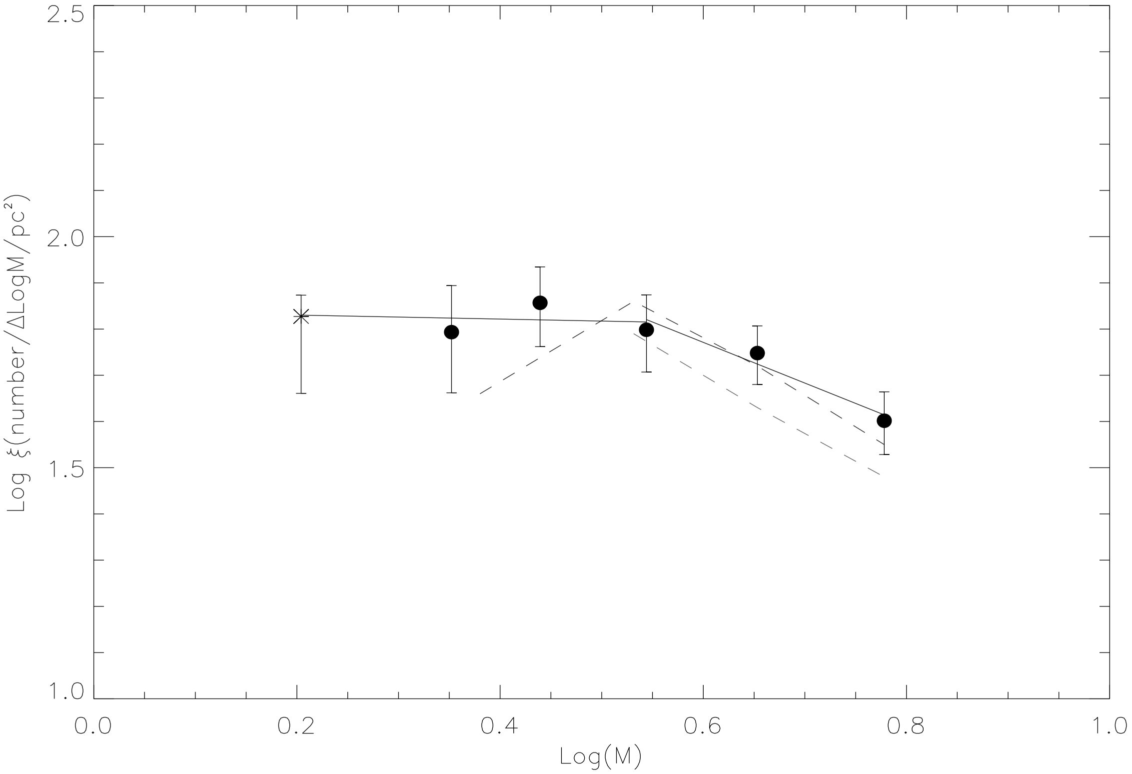

Figure 2: Low-mass end of the IMF in the central R136 region derived from deep HST WFPC2 V and I imagery ([58]). The dashed lines are the results of [20] and [19], based on less deep photometry. The data point at $\log M = 0.2$ is the average over the mass interval $0.1 < \log M < 0.3$. The completeness level for all mass intervals is >50%.

a trend found in the Milky Way and the SMC as well. Most likely, this is the result of an increasing concentration of O stars with earlier spectral type in clusters and associations ([14]). The earliest types (which correspond to the most massive stars) are predominantly observed in clusters due to their short lifetimes, whereas older stars are commonly found in the field, presumably after becoming gravitationally unbound. Note that the earliest O stars do not contribute significantly to the integrated light of a galaxy, even at 2200 Å. Therefore the fact that these stars are almost exclusively found in clusters is not in conflict with the result of [43] that clusters do not account for the bulk of the UV light in starburst galaxies.

Star clusters form quasi-instantaneously in comparison with stellar evolutionary lifetimes. Therefore star-formation histories are generally not an issue when converting luminosity functions (and, for the most extreme masses, spectral types) into an IMF. An abundance of cluster work is available in the literature (see [56]). I will concentrate on R136, the central cluster of the 30 Doradus region ([63]) because (i) the cluster is massive enough ($\sim 10^5$ $M_\odot$) that the high-mass end of the IMF is well populated and (ii) recent deep HST imagery sheds light on the top-heavy IMF controversy in starburst galaxies.

[48] derived the IMF above ~ 20 $M_\odot$ by matching spectral types to stellar evolutionary models. Indications for spatial variations of the IMF slope were found, but uncertainties are large. The mean IMF slope is $\Gamma = -1.5 \pm 0.2$, similar to the Salpeter value. Deep HST imaging and crowded-field photometry are complementary: the lack of spectroscopic information prevents mass determinations of the most massive stars due to the color degeneracy ([40]) but photometric analysis of fainter, less massive stars becomes possible. [35], using HST UBV photometry,

compared the properties of 30 Dor within and outside R136. They find a flatter IMF in the central region of R136. The positions of massive stars can either reflect the initial condition at the cluster's birth or they can result from mass segregation due to dynamical evolution. It is not clear what applies to R136 but models for the Orion Trapezium cluster indicate that the timescale for significant mass segregation due to dynamical evolution is longer than the cluster age ([2]). A near-infrared view of R136 was presented by [3] who used adaptive optics to achieve diffraction limited H- and K-photometry. Their results confirm an average IMF slope of –1.6 and a flatter IMF towards the center of R136. The census of R136 at the high-mass end was recently completed by [38] who detected about 40 previously unknown O3 stars in the very center. Combining their detections with other existing spectroscopy indicates a power-law IMF with $\Gamma = -1.35$ between 100 and 10 $M_\odot$.

HST is needed for spatially resolved photometry of intermediate- and low-mass stars. [20] and [19] detected stars down to $V \approx 25$ within the central pc of R136. Comparison with stellar evolution models leads to an IMF slope consistent with results at higher masses: stars form with a power-law IMF down to the detection limit of ∼3 $M_\odot$. This limit could be pushed further down to about 1 $M_\odot$ by [58] (see Figure 2). R136 is clearly forming stars in this mass range but not at the rate observed at higher masses: the IMF is flattening around 2 to 3 $M_\odot$. Extrapolation of a Salpeter IMF down to and beyond this mass range would lead to a significant overestimate of the number of low-mass stars and the total cluster mass. In the future, deep near-infrared imaging with HST's NICMOS camera allows a search for pre-main-sequence stars which are still embedded in dust and therefore not included in the optical census. Measuring individual stellar velocities could independently verify the total cluster mass — if virial equilibrium applies. Such a program is underway (R. Terlevich, private communication).

Similar (but less detailed) results are available for the intermediate- and high-mass star content of other Local Group galaxies. There are few observationally significant variations of the IMF, and the average slope tends to cluster around the Salpeter value (see also Figure 5 of [56]). The surveyed regions cover more than one order of magnitude in metallicity.

4 A biased sample of local dwarf galaxies

Space limitations preclude a systematic review of the available literature. An excellent overview can be found in the conference volume edited by [15]. I will instead present my own view of the most important issues by choosing a "biased" sample of five local dwarf galaxies with relevant observational data. The galaxies are in Table 1. They are ordered in terms of increasing distance from 2 to 50 Mpc and cover a broad range of luminosity and metallicity. Each of the five galaxies is particularly suited to address the issues quoted in column 5 of Table 1.

Table 1. Sample galaxies.

Galaxy	d (Mpc)	$\log L_{\rm IR}$ ($L_\odot$)	Z ($Z_\odot$)	IMF Aspect
NGC 1569	2.2	9.2	1/4	clusters versus field stars
M 82	3.2	10.5	1/3	IMF in dusty, metal-rich environments
NGC 5253	4.1	8.9	1/6	low-mass stars and cluster evolution
I Zw 18	10	8.1	1/50	IMF at extremely low metallicity
NGC 1741	50	10.3	1/4	IMF from integrated light analysis

4.1 NGC 1569: clusters and field stars

The dwarf irregular NGC 1569 is the closest example of a starburst galaxy. Most of its field population of stars with masses higher than a few $\mathrm{M}_\odot$ was formed during a global star-formation episode beginning more than 100 Myr ago, and ending as recently as $\sim$10 Myr ago ([16]). The IMF in this mass range is a power law somewhat steeper than Salpeter, and the associated star-formation rate over the whole galaxy is about 1 $\mathrm{M}_\odot$ yr^{-1} if the mass is distributed between 1 and 100 $\mathrm{M}_\odot$. While this value may not sound too impressive (it is comparable to the total star-formation rate of the Milky Way), the *normalized* star-formation rate per unit surface reveals the extraordinary nature of this object. NGC 1569 forms stars at a rate of a few $\mathrm{M}_\odot$ yr^{-1} kpc^{-2}, which is three orders of magnitude higher than in our Galaxy and a factor of 100 above the highest rates measured in dwarf irregular galaxies of the Local Group ([36], [60], [13]).

The low-mass end of the IMF in the NGC 1569 field is inaccessible to direct observations, even with HST. An innovative study of the low-mass regime was done by [17]. NGC 1569 hosts several "super star clusters" ([47]), highly concentrated (half-light radius of a few pc), gravitationally bound stellar clusters which rival entire dwarf galaxies in luminosity ($M_\mathrm{B} = -14$). Faint red supergiant features were detected and resolved with Keck spectroscopy. The velocity dispersion of $\sigma = 15.7$ km s^{-1} suggests a mass of 3×10^5 $\mathrm{M}_\odot$ for the super star cluster. This mass and the mass-to-light ratio are consistent with a single stellar population formed about 10 Myr ago if the IMF has a Salpeter slope with stars forming down to 1 – 2 $\mathrm{M}_\odot$ (cf. Figure 9 of [29]). A similar result was found for the super star cluster in NGC 1705. If the simple dynamical model is correct, the IMF extends down to 1 – 2 $\mathrm{M}_\odot$ but there is no dynamical evidence for less massive stars.

4.2 M 82: a case for a top-heavy IMF

M 82 is the prototype of a dusty starbursting dwarf galaxy. The terminology of a "top-heavy IMF" for this galaxy was coined in an influential paper by [50]. Top-heavy indicates a higher proportion of red supergiants over giants and dwarfs than expected for a normal IMF. In terms of mass, a top-heavy IMF has an excess of stars in the mass range 10 – 20 $\mathrm{M}_\odot$ over stars of 5 $\mathrm{M}_\odot$ and less. Observational evidence for a top-heavy IMF in M 82 comes from the relatively high K-band luminosity of the nucleus, together with its relatively low dynamical mass. This results in a low M/L ratio which can only be understood if red giants and dwarfs (which produce mass) are deficient with respect to supergiants (which produce near-IR light). Low-mass cut-offs around 3 – 5 $\mathrm{M}_\odot$ are required. Additional support for a top-heavy IMF has been found in some other galaxies as well, although the case is far from settled (see [55]).

Whether the M 82 IMF is indeed top-heavy is critically dependent on the adopted dynamical mass, the extinction correction, and the star-formation history. If the starburst is not condensed in a central cluster but rather spread out over a few hundred pc as a result of sequential star formation, all observational constraints can be satisfied with a standard Salpeter IMF extending to 0.1 $\mathrm{M}_\odot$ ([53]). However, such a model would use up 30% of the total dynamical mass. This is an uncomfortably large percentage since it is unlikely that the starburst accounts for most of even the stellar mass due to the presence of an older pre-existing population.

The obvious alternative would be an IMF with a somewhat larger value of M_low, closer to the original top-heavy IMF concept. Although quantitative modeling has yet to be done, my feeling is that the low-mass IMF in R136 of [58] may be consistent with all constraints in M 82 as well. If so, the starburst IMF is indeed mildly top-heavy.

4.3 NGC 5253: age gradients from clusters

Star clusters may provide useful constraints on the low-mass IMF even if a dynamical mass determination is not available. NGC 5253, a dwarf galaxy in the Centaurus group serves as an example ([4]). Star formation in this galaxy is concentrated in numerous star clusters whose properties are very similar to those in NGC 1569 or NGC 1705. [4] studied the six brightest clusters and found ages ranging between a few to 60 Myr. Older clusters may exist but are beyond the detection limit. The properties of the *cluster population* can (at least in principle) give constraints in the IMF.

The maximum cluster age of 60 Myr corresponds to a main-sequence turn-off mass of $\sim$7 $M_{\odot}$. This immediately suggests that the IMF extends to at least $M_{\rm low} \approx 7$ $M_{\odot}$. If the IMF were truncated at this mass, the cluster color should turn very red: when the turn-off mass reaches $M_{\rm low}$, the cluster becomes unusually red since a "naked" red giant population is observed in the absence of a bluer main-sequence population ([6]). If clusters with ages of more than a few hundred Myr are found, a stability argument can be made in favor of a large cluster mass, or equivalently, for the presence of low-mass stars. Otherwise the cluster evaporation timescales are shorter than the observed ages (cf. [59]). The underlying assumption of all these arguments is of course that the clusters themselves form nearly instantaneous, with little subsequent star formation. Observations of individual clusters in the Galaxy and the Magellanic Clouds generally support this assumption ([39]).

4.4 I Zw 18: formation of Wolf-Rayet stars

I will now turn to the high-mass end of the IMF. Wolf-Rayet stars are a particularly sensitive tracer since they are considered the evolved descendants of the most massive O stars ([34]). Wolf-Rayet stars form out of more massive progenitors by stellar mass loss via radiatively driven winds. The mass-loss efficiency scales with the far-ultraviolet radiation field so that the most luminous, and therefore the most massive stars have the strongest winds and are the most important evolutionary channel for Wolf-Rayet formation. Wolf-Rayet features have been detected in some fraction of H II galaxies. Their strength requires a massive star population following a Salpeter (or even slightly flatter) IMF ([34], [44], [57]).

I Zw 18 is still the most metal-poor galaxy known ([22]). The recent detection of Wolf-Rayet stars in I Zw 18 ([28], [21], [10]) imposes rather stringent limits on the upper end of the IMF. Mass loss becomes less and less efficient at lower metallicity due to the weakening of the driving spectral lines. Therefore only the most massive main-sequence stars evolve into Wolf-Rayet stars at low metallicity. As a caveat, the assumption is made that Wolf-Rayet stars originate predominantly from single stars. If binaries are important, this argument would be weakened ([62]). Quantitative modeling by [10] suggests that the observed Wolf-Rayet population in I Zw 18 evolved from progenitor stars with masses of at least 100 $M_{\odot}$. These masses are similar to those derived for individual hot stars in the R136 cluster by [9], indicating a similar IMF at the high-mass end.

4.5 NGC 1741: high-redshift analog (?)

NGC 1741 is a luminous ($L \approx L^{\star}$) Magellanic-type irregular at a distance of 50 Mpc. The spatial morphology is dominated by two main starburst centers, each being about 100 times as luminous as 30 Doradus. Both starburst centers are composed of several intense knots of recent star formation. The starburst region NGC 1741B1 was observed in the ultraviolet with HST's GHRS and analyzed by [8] and [23]. A section of the ultraviolet spectrum is shown in

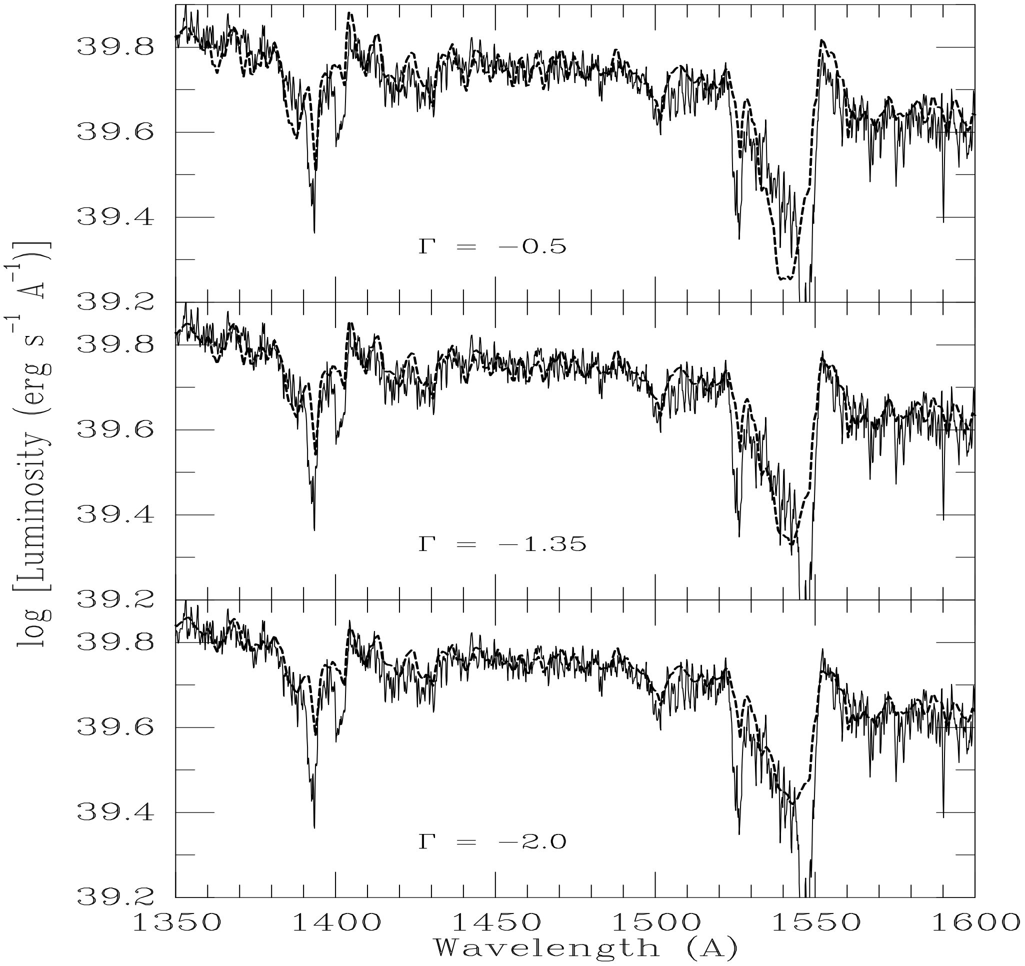

Figure 3: Comparison between the observed spectrum of NGC 1741B1 around Si IV $\lambda1400$ and C IV $\lambda1550$ (full lines) and synthetic spectra for three IMF slopes (dashed lines). Upper panel: $\Gamma = -0.5$; middle: $\Gamma = -1.35$ (Salpeter slope); lower: $\Gamma = -2.0$. Other parameters of the synthetic spectra are: continuous star formation, $t = 5$ Myr, $Z = \mathrm{Z}_\odot$, $M_{\mathrm{low}} = 1$ M$_\odot$, $M_{\mathrm{up}} = 100$ M$_\odot$ (from [23]).

Figure 3. The most prominent lines are C IV $\lambda1550$ and Si IV $\lambda1400$. These lines have broad absorptions and/or emissions due to their origin in stellar winds from hot stars. They can be used to constrain the IMF of the underlying stellar population ([30], [31]): the profiles contain information on the wind momentum flux, and since radiation pressure is the driving force, on the stellar luminosity. Evolution models predict a stellar mass-luminosity relation so that the line profiles are eventually tied to the stellar mass. Evolutionary synthesis modeling leads to a prediction for the ultraviolet spectrum of a population of massive stars.

The purpose of Figure 3 is to illustrate how an IMF can be derived from the analysis of integrated light but also to raise the awareness for the limits of this method. The general trend in the figure is easy to understand: the larger the fraction of early-O stars (responsible for the stellar-wind lines) relative to late-O/early-B stars (responsible for the continuum), the more pronounced the observed P Cygni profiles. A larger fraction of early-O stars translates into a flatter IMF. The C IV $\lambda1550$ and Si IV $\lambda1400$ profiles indicate a standard IMF with a Salpeter slope ($\Gamma = -1.35$) in the mass range between 15 and 100 M$_\odot$. A much flatter IMF produces an excess of blueshifted wind absorption whereas a much steeper IMF underpredicts the wind emission. Note that the narrow absorptions at rest wavelength are interstellar and therefore not included in the wind modeling. The conclusion from Figure 3 is that it is difficult to constrain the IMF exponent to better than ±0.5.

NGC 1741 has become the favorite local analog of star-forming dwarf galaxies at high redshift (e.g., [33]) whose restframe ultraviolet spectra are quite similar to that of NGC 1741B1. The lensed star-forming galaxy cB58 at a redshift of $z = 2.723$ has been discussed, e.g., by [65] and [49]. A quantitative comparison with NGC 1741 should be taken cum grano salis due to the metallicity difference but it is safe to conclude that a young population with stellar masses above $\sim$30 $M_\odot$ and age of 10 Myr or less is present. Otherwise the observed stellar lines could not be understood. Nothing is known about the low-mass star content but if local starbursts are taken as analogs, there should be few recently formed stars below $\sim$1 $M_\odot$. Star-formation rates derived from an extrapolation of the IMF below $\sim$1 $M_\odot$ would likely be an overestimate.

5 Conclusions and recommendations to "IMF users"

The IMF in local dwarf galaxies has been derived using several independent observational techniques. The accessible stellar masses are between 100 $M_\odot$, where stochastic effects due to small-number statistics set in, and 1 $M_\odot$, where the observational sensitivity limit is reached. Additional constraints on the IMF can be obtained from the galactic chemical composition and its time evolution (e.g., [64], [5]). This field is reviewed elsewhere in this conference.

A major source of uncertainty is stellar evolutionary theory, which enters in essentially all IMF determinations: at the high-mass end for O supergiants and Wolf-Rayet stars, at intermediate masses for red supergiants and red giants, and at the lowest masses for pre-main-sequence stars. Other areas of concern are stellar atmospheres and cluster dynamics.

Most studies suggest a rather uniform IMF in dwarf galaxies. Considering the very different observational techniques used and the prevailing theoretical uncertainties, this result appears to have some significance. In general, the IMF in dwarf galaxies is not too different from the IMF in the solar neighborhood, except perhaps for the lowest masses. In the absence of tighter observational constraints, and since observers have a preference for power laws, I will use a power-law approximation for the derived IMF. Note, however, that this may detract from the actual astrophysical meaning of the initial mass function.

- At the high-mass end (> 10 $M_\odot$), the average IMF has a slope of $\Gamma \approx -1.35 \pm 0.5$, where the range is due to the measurement uncertainties. Correlations with environmental parameters have been searched for, but none have been found.

- There is a trend for a somewhat steeper IMF ($\Gamma \approx -1.6$) at lower masses between 3 and 10 $M_\odot$, although the effect is barely significant. This value is similar to that of the solar neighborhood found by [54].

- The low-mass end below 3 $M_\odot$ is most controversial. Observational methods are too crude and results too sparse to quote an average IMF. There appears to be a deficit stars which could be due to a low-mass cut-off, or more likely, a flattening of the IMF.

Although the IMF is the major link between the theory of the star-formation process and galaxy evolution, it is often only needed by observers as a parameter to model the energy output of a galaxy, such as the spectrum, the metal production, or the supernova rate. A power-law approximation with a slope of $\Gamma = -1.35$ between 1 and 100 $M_\odot$ should be adequate for this purpose. This IMF reproduces the distribution of those stars which are the most important contributors to the observed spectrum. It also mimics the total mass and therefore the star-formation rate by neglecting both the IMF steepening between 3 and 10 $M_\odot$ and the flattening or cut-off at lower masses. For comparison, the commonly used extrapolation of a Salpeter IMF to 0.1 $M_\odot$ would overestimate the star-formation rate by a factor of 2.5.

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References

[1] Bertelli, G., Mateo, M., Chiosi, C., & Bressan, A. 1992, *Astrophys. J.* **388**, 400

[2] Bonnell, I. A., & Davies, M. B. 1998, *MNRAS* **295**, 691

[3] Brandl, B., Sams, B. J., Bertoldi, F., Eckart, A., Genzel, R., Drapatz, S., Hofmann, R., Löwe, M., & Quirrenbach, A. 1996, *Astrophys. J.* **466**, 254

[4] Calzetti, D., Meurer, G. R., Bohlin, R. C., Garnett, D. R., Kinney, A. L., Leitherer, C., & Storchi-Bergmann, T. 1997, *Astron. J.* **114**, 1834

[5] Carigi, L., Colín, P., Peimbert, M., & Sarmiento, A. 1995, *Astrophys. J.* **445**, 98

[6] Charlot, S., Ferrari, F., Mathews, G. J., & Silk, J. 1993, *Astrophys. J.* **419**, L57

[7] Conti, P. S. 1991, *Astrophys. J.* **377**, 115

[8] Conti, P. S., Leitherer, C., & Vacca, W. D. 1996, *Astrophys. J.* **461**, L87

[9] de Koter, A., Heap, S. R., & Hubeny, I. 1997, *Astrophys. J.* **477**, 792

[10] de Mello, D. F., Schaerer, D., Heldmann, J., & Leitherer, C. 1998, *Astrophys. J.*, submitted

[11] Elmegreen, B. G. 1999, in *Unsolved Problems in Stellar Evolution*, ed. M. Livio (Cambridge: CUP), in press

[12] Gallagher, J. S., Bushouse, H., & Hunter, D. A. 1989, *Astron. J.* **97**, 700

[13] Gallart, C., Aparicio, A., Bertelli, B., & Chiosi, C. 1996, *Astron. J.* **112**, 1950

[14] Garmany, C. D. 1990, in *Properties of Hot Luminous Stars*, ed. C. D. Garmany (San Francisco: ASP), 16

[15] Gilmore, G., Parry, I., & Ryan, S. 1998, *38th Herstmonceux Conference, The Stellar Initial Mass Function* (San Francisco: ASP), in press

[16] Greggio, L., Tosi, M., Clampin, M., De Marchi, G., Leitherer, C., Nota, A., & Sirianni, M. 1998, *Astrophys. J.*, in press

[17] Ho, L. C., & Filippenko, A. V. 1996, *Astrophys. J.* **466**, L83

[18] Holtzman, J. A., et al. 1997, *Astron. J.* **113**, 656

[19] Hunter, D. A., O'Neil, E. J., Lynds, R., Shaya, E. J., Groth, E. J., & Holtzman, J. A. 1996, *Astrophys. J.* **459**, 27

[20] Hunter, D. A., Shaya, E. J., Holtzman, J. A., Light, R. M., O'Neil, Jr., E. J., & Lynds, R. 1995, *Astrophys. J.* **448**, 179

[21] Izotov, Y. I., Foltz, C. B, Green, R. F., Guseva, N. G., & Thuan, T. X. 1997, *Astrophys. J.* **487**, L37

[22] Izotov, Y. I., & Thuan, T. X. 1998, *Astrophys. J.* **497**, 227

[23] Johnson, K., Vacca, W. D., Leitherer, C., & Conti, P. S. 1998, *Astrophys. J.*, submitted

[24] Kennicutt, R. C. 1992, *Astrophys. J.* **388**, 310

[25] Kroupa, P. 1995, *Astrophys. J.* **453**, 358

[26] Kunth, D., & Joubert, M. 1985, *Astr. Astrophys.* **142**, 411

[27] Lançon, A., & Rocca-Volmerange, B. 1996, *New Astron.* **1**, 215

[28] Legrand, F., Kunth, D., Roy, J.-R., Mas-Hesse, J. M., & Walsh, J. R. 1997, *Astr. Astrophys.* **326**, L17

[29] Leitherer, C., & Heckman, T. M. 1995, *Astrophys. J. Suppl. Ser.* **96**, 9

[30] Leitherer, C., Robert, C., & Heckman, T. M. 1995, *Astrophys. J. Suppl. Ser.* **99**, 173

[31] Leitherer, C., Vacca, W. D., Conti, P. S., Filippenko, A. V., Robert, C., & Sargent, W. L. W. 1996, *Astrophys. J.* **465**, 717

[32] Loewenstein, M., & Mushotzky, R. F. 1996, *Astrophys. J.* **466**, 695

[33] Lowenthal, J. D., Koo, D. C., Guzmán, R., Gallego, J., Phillips, A. C., Faber, S. M., Vogt, N. P., Illingworth, G. D., & Gronwall, C. 1997, *Astrophys. J.* **481**, 673

[34] Maeder, A., & Conti, P. S. 1994, *Ann. Rev. Astr. Astrophys.* **32**, 227

[35] Malumuth, E. M., & Heap, S. R. 1994, *Astron. J.* **107**, 1054

[36] Marconi, G., Tosi, M., Greggio, L., & Focardi, P. 1995, *Astron. J.* **109**, 173

[37] Martin, C. L. 1996, *Astrophys. J.* **465**, 680

[38] Massey, P., & Hunter, D. A. 1998, *Astrophys. J.* **493**, 180

[39] Massey, P., Johnson, K. E., & DeGioia-Eastwood, K. 1995, *Astrophys. J.* **454**, 151

[40] Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995, *Astrophys. J.* **438**, 188

[41] Mateo, M. 1992, in *IAU Symp. 149, The Stellar Populations of Galaxies*, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 147

[42] Melnick, J. 1992, in *Star Formation in Stellar Systems*, ed. G. Tenorio-Tagle, M. Prieto, & F. Sánchez (Cambridge: CUP), 253

[43] Meurer, G. R., Heckman, T. M., Leitherer, C., Robert, C., Kinney, A., & Garnett, D. 1995, *Astron. J.* **110**, 2665

[44] Meynet, G. 1995, *Astr. Astrophys.* **298**, 767

[45] Miller, G. E., & Scalo, J. M. 1979, *Astrophys. J. Suppl. Ser.* **41**, 513

[46] Norman, C. A. 1991, in *Massive Stars in Starbursts*, ed. C. Leitherer, N. R. Walborn, T. M. Heckman, & C. A. Norman (Cambridge: CUP), 271

[47] O'Connell, R. W., Gallagher, J. S., & Hunter, D. A. 1994, *Astrophys. J.* **433**, 65

[48] Parker, W., & Garmany, C. D. 1993, *Astron. J.* **106**, 1471

[49] Pettini, M., Steidel, C. C., Dickinson, M., Kellogg, M., Giavalisco, M., & Adelberger, K. L. 1997, in *The Ultraviolet Universe at Low and High Redshift*, ed. W. H. Waller, M. N. Fanelli, J. E. Hollis, & A. C. Danks (Woodbury: AIP), 279

[50] Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., & Tokunaga, A. T. 1980, *Astrophys. J.* **238**, 24

[51] Salpeter, E. E. 1955, *Astrophys. J.* **121**, 161

[52] Sandage, A. 1986, *Astr. Astrophys.* **161**, 89

[53] Satyapal, S., Watson, D. M., Pipher, J. L., Forrest, W. J., Greenhouse, M. A., Smith, H. A., Fischer, J., & Woodward, C. E. 1997, *Astrophys. J.* **483**, 148

[54] Scalo, J. M. 1986, *Fund. Cosm. Phys.* **11**, 1

[55] ——. 1990, in *Windows on Galaxies*, ed. A. Renzini, G. Fabbiano, & J. S. Gallagher (Dordrecht: Kluwer), 125

[56] ——. 1998, in *38th Herstmonceux Conference, The Stellar Initial Mass Function*, ed. G. Gilmore, I. Parry, & S. Ryan (San Francisco: ASP), in press

[57] Schaerer, D., & Vacca, W. D. 1998, *Astrophys. J.* 497 618

[58] Sirianni, M., Nota, A., Clampin, M., & Leitherer, C. 1998, in preparation

[59] Terlevich, E. 1987, *MNRAS* **224**, 193

[60] Tolstoy, E. 1996, *Astrophys. J.* **462**, 684

[61] Vallenari, A., Chiosi, C., Bertelli, G., Aparicio, A., & Ortolani, S. 1996, *Astr. Astrophys.* **309**, 367

[62] Vanbeveren, D., Van Bever, J., & De Donder, E. 1997, *Astr. Astrophys.* **317**, 487

[63] Walborn, N. R. 1991, in *Massive Stars in Starbursts*, ed. C. Leitherer, N. Walborn, T. Heckman, & C. Norman (Cambridge: CUP), 145

[64] Wang, B., & Silk, J. 1993, *Astrophys. J.* **406**, 580

[65] Yee, H. K. C., Ellingson, E., Bechtold, J., Carlberg, R. G., & Cuillandre, J.-C. 1996, *Astron. J.* **111**, 1783