

STOCHASTIC STAR FORMATION AND A (NEARLY) UNIFORM STELLAR INITIAL MASS FUNCTION

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ABSTRACT

Recent observations indicate a lower $H\alpha$ to FUV ratio in dwarf galaxies than in brighter systems, a trend that could be explained by a truncated and/or steeper initial mass function (IMF) in small galaxies. However, at low star formation rates (SFRs), the $H\alpha$ to FUV ratio can vary due to stochastic sampling even for a universal IMF, a hypothesis that has, prior to this work, received limited investigation. Using SLUG, a fully stochastic code for synthetic photometry in star clusters and galaxies, we compare the $H\alpha$ and FUV luminosity in a sample of ~ 450 nearby galaxies with models drawn from a universal Kroupa IMF and a modified IMF, the integrated galactic initial mass function (IGIMF). Once random sampling and time evolution are included, a Kroupa IMF convolved with the cluster mass function (CMF) reproduces the observed $H\alpha$ distribution at all FUV luminosities, while a truncated IMF as implemented in current IGIMF models underpredicts the $H\alpha$ luminosity by more than an order of magnitude at the lowest SFRs. We conclude that the observed luminosity is the result of the joint probability distribution function of the SFR, CMF, and a universal IMF, consistent with parts of the IGIMF theory, but that a truncation in the IMF in clusters is inconsistent with the observations. Future work will examine stochastic star formation and its time dependence in detail to study whether random sampling can explain other observations that suggest a varying IMF.

Key words: galaxies: dwarf – galaxies: star formation – galaxies: statistics – galaxies: stellar content – stars: statistics – ultraviolet: galaxies

Online-only material: color figures

1. INTRODUCTION

The stellar initial mass function (IMF), an essential ingredient for numerous astrophysical problems, is commonly assumed to be invariant with time and with galactic properties. This ansatz follows from a lack of evidence for its variation, despite searches covering a wide range of environments (e.g., Kroupa 2001; Chabrier 2003; Bastian et al. 2010), more than from theoretical understanding of the processes that regulate the mass distribution of stars. However, several recent studies have questioned the idea of a universal IMF in both nearby and distant galaxies.

Considering a few examples in the local universe, a truncated and/or steeper IMF has been invoked to explain an apparent correlation between the masses of clusters and the masses of their largest members (Weidner & Kroupa 2006, though see Lamb et al. 2010 for an opposing view), or between galaxy colors and $H\alpha$ equivalent widths (Hoversten & Glazebrook 2008; Gunawardhana et al. 2011), as well as between the ratio of $H\alpha$ to FUV luminosities ($L_{H\alpha}/L_{FUV}$) and the surface brightness (Meurer et al. 2009) or the star formation rates (SFRs; Lee et al. 2009; Weidner et al. 2011) in galaxies. However, these claims remain controversial, and alternative interpretations have been offered, without resorting to IMF variations (Boselli et al. 2009; Corbelli et al. 2009; Calzetti et al. 2010; Lamb et al. 2010).

In this Letter, we focus on observations of systematic variations in $L_{H\alpha}/L_{FUV}$ (e.g., Meurer et al. 2009; Lee et al. 2009; Boselli et al. 2009) that have been used to argue strongly for a non-universal IMF (e.g., Meurer et al. 2009; Weidner et al. 2011). Recombination lines such as $H\alpha$ ultimately come from the ionizing photons produced primarily by very massive stars, while FUV luminosity is driven by less massive stars ($\sim 50 M_{\odot}$

for $H\alpha$, $\sim 10 M_{\odot}$ for FUV, using a Salpeter 1955 IMF). As a result, the ratio $L_{H\alpha}/L_{FUV}$ can be used as a probe for the massive end of the IMF, although the interpretation of observations is complicated by additional factors (e.g., dust). Recently, both Meurer et al. (2009, hereafter M09) and Lee et al. (2009, hereafter L09) reported that $L_{H\alpha}/L_{FUV}$ varies systematically with galaxy properties, which may imply a variation of the IMF. Boselli et al. (2009, hereafter B09) have cautioned that dust correction or a bursty star formation history (SFH) can produce the observed trends even if the underlying IMF is universal, but this idea has not been explored in detail with models. While they cannot rule out variations in the IMF, L09 also argue that the underlying cause for the observed trend is not clear and stochastic effects at low SFR need to be explored further.

Following these suggestions (see also Williams & McKee 1997; Cerviño & Valls-Gabaud 2003; Haas & Anders 2010; Eldridge 2011), in this work we ask whether the observed $L_{H\alpha}/L_{FUV}$ is consistent with a random but incomplete sampling of a canonical or modified IMF. To test these hypotheses, we combine observations from B09, L09, and M09 with models from SLUG² (Fumagalli et al. 2011; da Silva et al. 2011), a novel fully stochastic code for synthetic photometry of stellar clusters and galaxies.

2. THE OBSERVED GALAXY SAMPLE

We compile a sample of 457 galaxies from B09, L09, and M09 with integrated $H\alpha$ and FUV luminosities, together with corrections for dust extinction and [N II] contamination. Due to differential absorption, particular care is required when performing dust corrections. Here we follow the procedure adopted by each author in their studies, a choice motivated by

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² <http://sites.google.com/site/runslug/>

the fact that the different dust extinctions are consistent across the three samples. We refer to the original works for additional discussion.

Similarly, a careful analysis of the selection biases should be a prerequisite for comparison with models. Unfortunately, these data sets have been assembled adopting different selection criteria (a nearly complete volume limited sample for L09, a subset of galaxies selected from the H I mass function for M09, and a sample of galaxies with multi-wavelength observations for B09) that are difficult to characterize. We will therefore emphasize only those results that are believed to be less sensitive to selection biases.

3. STOCHASTIC EFFECTS AND SLUG MODELS

The IMF describes the relative probability with which stars at any mass are formed. At high SFRs, the large number of stars guarantees a nearly complete sampling of the IMF, and the maximum stellar mass m_{\max} that can be found in a galaxy approaches the theoretical upper end $m_{\max,*}$ of the IMF. At low SFRs instead, due to the smaller number of stars that are formed, the probability of finding massive stars decreases. The IMF is not fully sampled, and $m_{\max} \ll m_{\max,*}$. In this regime, stochastic effects become important to describe the observed $L_{\text{H}\alpha}/L_{\text{FUV}}$ distribution, regardless of the IMF functional form. In addition to finite sampling in mass, $L_{\text{H}\alpha}/L_{\text{FUV}}$ is also affected by finite sampling in time since massive stars experience evolutionary phases of short duration (e.g., WN or WC phases) during which their ionizing luminosities can vary significantly.

Since the majority of stars is believed to form in embedded star clusters (e.g., Lada & Lada 2003), two additional effects should be considered. First, the maximum stellar mass in a cluster cannot exceed the cluster mass M_{ecl} . Second, at low SFRs, a time-averaged continuous SFR results in a series of small “bursts” separated in time and associated with the formation of a new cluster. Provided that stars form with a modest spread in ages, gaps in the ages of clusters increase the probability of observing a galaxy when the most massive stars have already left the main sequence.

Because it treats these types of stochastic sampling correctly, SLUG is the ideal tool to test whether incomplete sampling of a canonical IMF can reproduce the deficiency of H α observed in low-luminosity galaxies without resorting to a modified IMF. For any given SFH, a fraction f_c of the total stellar population is assumed to form in clusters. In this case, SLUG randomly draws a set of clusters from a cluster mass function (CMF) $\psi(M_{\text{ecl}}) = M_{\text{ecl}}^{-\beta}$ and populates them with stars randomly selected from an IMF $\phi(m) = m^{-\gamma}$ over some specified mass interval. Currently, all the stars within a cluster are assumed to be coeval. The remaining fraction $1 - f_c$ of the total stellar population are formed in the field, simulated by randomly selecting stars from an IMF. The ensemble of clusters and stars is then evolved with time and at each time step the luminosity of individual stars is combined to quantify the number of ionizing photons and L_{FUV} for the simulated galaxy.

In this work, we consider two classes of models. The “Kroupa model” is based on a universal Kroupa (2001) IMF in the mass interval $0.08\text{--}120 M_{\odot}$ and a CMF with $\beta = 2$ between 20 and $10^7 M_{\odot}$. To test the effects of clustering we run two sets of simulations, one with $f_c = 0$ (all stars in the field, similar to the Monte Carlo in L09) and one with $f_c = 1$ (all stars in clusters). These extreme cases bracket all possible solutions, although the observations of Lada & Lada (2003) suggest that

reality is likely closer to $f_c = 1$ than to $f_c = 0$. The “IGIMF model” is instead based on the integrated galactic initial mass function (IGIMF; Kroupa & Weidner 2003), a modified IMF in which m_{\max} is a function of M_{ecl} that, in turn, depends on the galaxy SFR. The IGIMF implementation follows the minimal-1 and minimal-2 formulations (Pflamm-Altenburg et al. 2007), with a Kroupa (2001) IMF and a CMF with $\beta = 2$, minimum mass of $20 M_{\odot}$ and maximum mass derived from the SFR averaged over 10^7 yr. In both the Kroupa $f_c = 1$ and the IGIMF model, the IMF integrated over a galaxy is modulated by the galaxy star formation and the CMF. While in the $f_c = 1$ model the relations between these quantities emerge from a pure stochastic realization of the IMF and CMF, the IGIMF relies on prescriptions for these correlations that imply a truncation in the CMF and the IMF.

For both models, we adopt stellar libraries with the Padova asymptotic giant branch (AGB) tracks at solar metallicity (Bressan et al. 1993), the Smith et al. (2002) implementation of Hillier & Miller (1998) and Lejeune et al. (1997) atmospheres, and Maeder & Meynet (1988) winds. We run 10^5 simulated galaxies randomly drawn from a Schechter function, similar to the observed UV luminosity function (Wyder et al. 2005), with $\text{SFR } 4.5 \times 10^{-5}\text{--}5 M_{\odot} \text{ yr}^{-1}$. We use 10 time steps of 80 Myr per galaxy to improve the statistics. Each of them is independent since the 80 Myr interval ensures that all massive stars that form in one time step are gone by the next one. To further improve the statistics at higher luminosity (observations are biased toward higher L_{FUV}), we add 2000 galaxies uniformly distributed in logarithmic bins of SFR. Due to escape or dust absorption before ionization, only a fraction $f_{\text{H}\alpha}$ of the Lyman continuum photons produces ionizations that ultimately yield H α photons. To account for this effect, we correct the H α luminosity in the models by a factor $f_{\text{H}\alpha} = 0.95$ (B09). Although the exact value for $f_{\text{H}\alpha}$ is uncertain (L09), any choice in the range $f_{\text{H}\alpha} = 1\text{--}0.6$ (e.g., B09; Hirashita et al. 2003) would leave our basic results unchanged. We further emphasize that reasonable choices of metallicity, stellar libraries, time steps, or even IMF (Kroupa versus Salpeter) yield very similar results.

SLUG simulations and theoretical predictions are displayed in Figure 1. Stochastic effects are evident in the distributions, with simulated galaxies scattered in proximity to the expected luminosities for a fully sampled IMF. Since previous studies (e.g., Haas & Anders 2010) have highlighted the importance of the minimum mass in the CMF ($M_{\text{cl,min}}$) for this type of calculation, we display in the top panel of Figure 1 the mean values for additional simulations that are similar to the $f_c = 1$ model, but with $M_{\text{cl,min}} = 500 M_{\odot}$.

4. DISCUSSION

The main result of this analysis is summarized in Figure 1. At $L_{\text{FUV}} > 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$, observed galaxies lie close to the value of $L_{\text{H}\alpha}/L_{\text{FUV}}$ expected for both a fully sampled Kroupa IMF and the IGIMF, but at fainter luminosity and lower SFR the data deviate from the fully sampled Kroupa IMF curve toward the fully sampled IGIMF curve. This trend has been taken as evidence in support of the IGIMF, but both IMFs are subject to stochastic effects. When we properly include these using SLUG, we see that realizations drawn from the IGIMF are completely inconsistent with a significant fraction of the observed galaxies, particularly at $L_{\text{FUV}} \sim 10^{25}\text{--}10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$. Conversely, realizations drawn from a Kroupa IMF span a larger range of luminosity and overlap with most of the observed sample, with

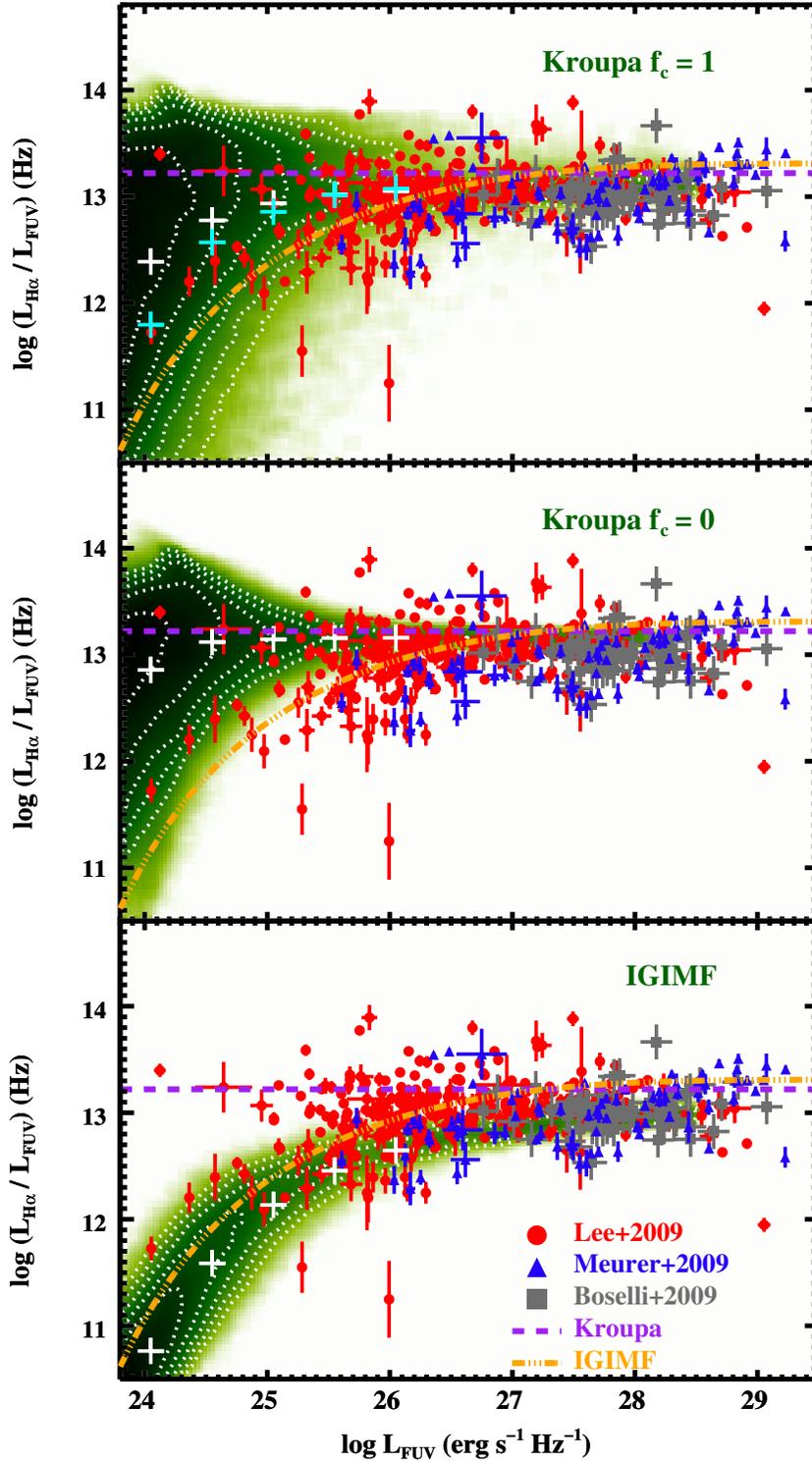


Figure 1. Observed $H\alpha$ and FUV luminosities in a sample of nearby galaxies (L09 red circles; B09 gray squares; M09 blue triangles). We also show (in green), $\sim 10^5$ SLUG models for a Kroupa IMF with and without clusters (top and middle panel, respectively) and for the IGIMF (bottom panel). Analytic predictions for the Kroupa IMF and IGIMF are superimposed (purple dashed and orange triple-dot dashed lines). White crosses mark the mean of the simulated distributions, while the cyan crosses (top panel) are for a $f_c = 1$ model with $M_{cl,min} = 500 M_\odot$.

(A color version of this figure is available in the online journal.)

clustering responsible for a further increase in the luminosity spread (compare the $f_c = 1$ and $f_c = 0$ models).

The width in the simulated distributions follows from the treatment of m_{max} and clustering. For a universal IMF, m_{max} can assume any value up to $m_{max,*}$, regardless of the SFR. At

low SFRs, realizations that lack massive stars are frequent and skew the distribution to low $L_{H\alpha}$ and low L_{FUV} . At the same time, realizations with massive stars are still possible and some models are distributed near or even above the theoretical expectation for a fully sampled IMF. The narrower scatter found for the

Table 1
Summary of the H α Statistics in Four Bins of FUV Luminosity from Figure 2

Type ^a	Number ^b	Mean log $L_{H\alpha}$ ^c (erg s ⁻¹)	Fully Sampled log $L_{H\alpha}$ ^d (erg s ⁻¹)	Dispersion ^e	Probability ^f	$N(\sigma)$ ^g
24.0 < log L_{FUV} < 25.0						
Data	10	37.1	...	0.64
Kroupa $f_c = 1$	241817	37.0	37.7	0.86	0.5995	0.5
Kroupa $f_c = 0$	362593	37.3	37.7	0.55	0.5515	0.6
IGIMF	64253	35.6	36.4	0.72	0.0034	2.9
25.0 < log L_{FUV} < 26.0						
Data	86	38.5	...	0.49
Kroupa $f_c = 1$	25571	38.3	38.7	0.55	0.1073	1.6
Kroupa $f_c = 0$	24705	38.5	38.7	0.30	0.1205	1.6
IGIMF	9363	37.7	38.2	0.45	0.0000	6.9
26.0 < log L_{FUV} < 27.0						
Data	153	39.5	...	0.45
Kroupa $f_c = 1$	4248	39.5	39.7	0.40	0.3524	0.9
Kroupa $f_c = 0$	4238	39.6	39.7	0.29	0.0002	3.7
IGIMF	3576	39.2	39.6	0.37	0.0003	3.6
27.0 < log L_{FUV} < 28.0						
Data	135	40.5	...	0.35
Kroupa $f_c = 1$	3494	40.6	40.7	0.34	0.4042	0.8
Kroupa $f_c = 0$	3562	40.6	40.7	0.29	0.0090	2.6
IGIMF	3296	40.4	40.7	0.33	0.0365	2.1

Notes.

^a Type of distribution for which the statistics are listed.

^b Number of observed and simulated galaxies included in each log L_{FUV} bin.

^c Mean of the log $L_{H\alpha}$ distributions.

^d log $L_{H\alpha}$ for a fully sampled IMF.

^e Standard deviation of the log $L_{H\alpha}$ distributions.

^f Kolmogorov–Smirnov probability P associated with the hypothesis that the observed and simulated distributions are drawn from the same parent population. Although the absolute values for the listed probabilities are difficult to interpret given the poorly characterized selection biases, the relative differences between the $f_c = 1$ and the IGIMF models quantitatively support our conclusion.

^g Equivalent number of standard deviations $N = \sqrt{2} \operatorname{erfc}^{-1}(P)$.

$f_c = 0$ model emphasizes that stochastic sampling of the IMF alone cannot reproduce the entire range of observed luminosity (cf. L09). In the $f_c = 1$ model, simulated galaxies that lie at the lowest $L_{H\alpha}$ for any given L_{FUV} have an excess of older and massive clusters. This is because at low SFR, a massive cluster represents a significant event in the galaxy SFH that, on average, increases the time interval between the formations of clusters and produces an intrinsic level of burstiness that results in a wider luminosity distribution (see also da Silva et al. 2011). This effect is obviously amplified in models with $M_{cl,min} = 500 M_{\odot}$, as evident from the lower H α /FUV luminosity in these simulations. Note that irregular SFHs are typical of dwarf galaxies (Weisz et al. 2008) and models with bursty star formation may reproduce the observed luminosity distribution equally well. Conversely, in the IGIMF theory, at lower SFRs, $m_{max} \ll m_{max,*}$. Further, only clusters with low mass can be drawn. The narrower mass range that is accessible translates to a narrower spread in luminosity, and none of the models can significantly exceed the expected luminosities for a fully sampled IGIMF (see L09).

Due to incompleteness, statistical comparisons between data and simulations are not straightforward. This is complicated by the fact that, at any SFR, both H α and FUV luminosities are subject to scatter and a truly independent variable is lacking. Nevertheless, in Figure 2 and Table 1, we attempt to quantify

the agreement between models and observations by comparing the statistics of the H α distributions in intervals of L_{FUV} .

Considering the center of the H α distributions, the IGIMF and $f_c = 1$ realizations diverge, moving toward lower FUV luminosity. At the lowest L_{FUV} , the two distributions are separated by ~ 2 dex, with the data clearly favoring the Kroupa IMF. Figure 2 demonstrates that truncated IMF and CMF as in the IGIMF produce systematically lower $L_{H\alpha}$ than observed. This is particularly evident for the interval $25 < \log L_{FUV} < 26$ that is characterized by large enough statistics (~ 100 galaxies) and likely not affected by severe incompleteness. To quantify this claim, we perform a Kolmogorov–Smirnov test comparing the observed distribution with 10,000 random sub-samples of the models, extracted to have a size comparable to the data. We report the results in Table 1. We see that the observed data and the Kroupa $f_c = 1$ models are generally consistent with being drawn from the same parent distribution, while the hypothesis that the data and the IGIMF models originate from the same parent distribution can be ruled out. The $f_c = 0$ model also appears to be inconsistent with the data, though not by as much as the IGIMF model.

Finally, in Figure 3 we compare for each individual data point the observed $L_{H\alpha,obs}$ with the simulated $L_{H\alpha,mod}$, averaged over an interval of FUV that is the larger of 0.1 dex and the error on the observed L_{FUV} . This difference is then normalized to

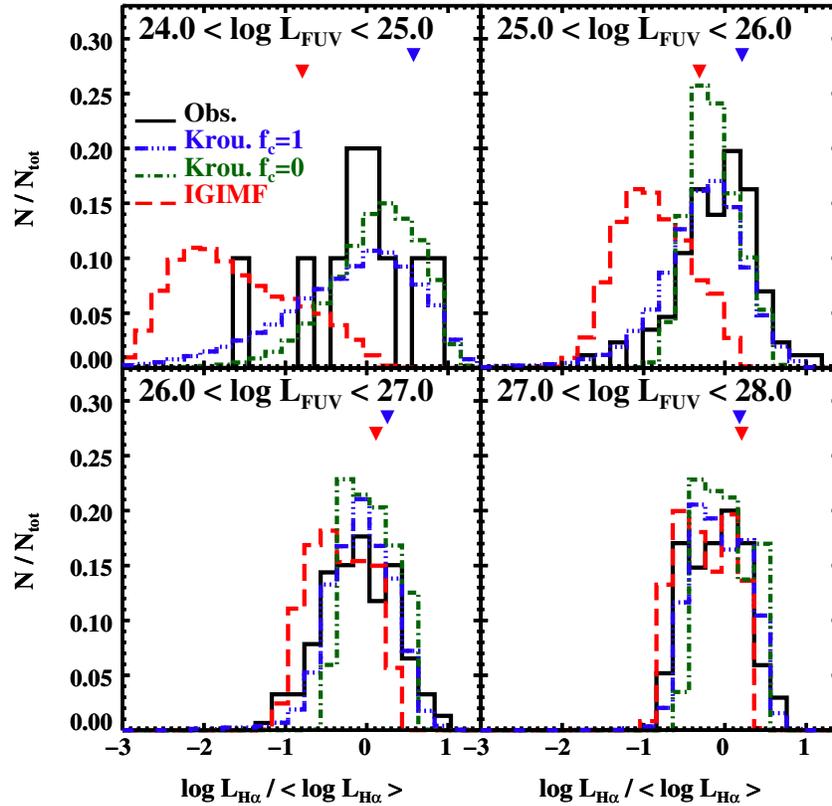


Figure 2. Distributions of $H\alpha$ luminosity in intervals of L_{FUV} for the observed galaxies (solid black histogram) and for SLUG models based on the Kroupa IMF with and without clusters (blue dash-triple-dotted and green dash-dotted histograms) and for the IGIMF (red dashed histogram). Distributions are centered on $\langle L_{H\alpha} \rangle$, the logarithmic mean of the observed $H\alpha$ luminosity in each bin. The two downward triangles indicate the mean $L_{H\alpha}$ for a fully sampled Kroupa IMF (blue) and IGIMF (red).

(A color version of this figure is available in the online journal.)

$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{mod}}^2}$, where σ_{obs} is the error on $L_{H\alpha, \text{obs}}$ and σ_{mod} is the standard deviation of the models. This quantity is defined such that a distribution centered on zero with dispersion of unity indicates perfect agreement between models and data (see right panels).

In Figure 3, the center of the $f_c = 1$ model (top panel) is consistent with the observed galaxies within $2\sigma_{\text{tot}}$ for $L_{FUV} < 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$ and within $3\sigma_{\text{tot}}$ for brighter luminosity, where σ_{obs} becomes comparable to σ_{mod} . Conversely, due to the narrower scatter, the $f_c = 0$ model (central panel) is only partially consistent with observations, as previously suggested by the K-S test. Also, simulated galaxies have higher $L_{H\alpha}$ compared to the observed galaxies. Based on results of two independent tests, we favor the $f_c = 1$ model over the $f_c = 0$ simulations. The IGIMF model (bottom panel) reproduces instead the observed $L_{H\alpha}$ only at high L_{FUV} and there is a clear systematic offset between the data and the models at $L_{FUV} < 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$. Although the usual notion of probability associated with σ_{tot} does not apply since the $H\alpha$ distributions are not Gaussian, we conclude that observations are better described by models based on the Kroupa IMF than on the IGIMF, particularly at fainter luminosity and when clusters are included.

Data are very sparse below $L_{FUV} \sim 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1}$, where the separation between a universal IMF and a steeper/truncated IMF is most evident, precluding us from concluding that no variation in the IMF occurs at very low luminosity. Moreover, we have not explored correlations with the galaxy surface brightness, suggested by M09 to be the physical quantity

related to the IMF variation. Also, selection biases are not well characterized and a putative population of galaxies with $L_{H\alpha} < 10^{36} \text{ erg s}^{-1}$ and $L_{FUV} \sim 10^{25} - 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$ would call into question a universal IMF. Further we assume that all stars born in an individual cluster are coeval, and future work will be required to investigate the effects of relaxing this assumption. Conversely, the observed existence of galaxies with $L_{H\alpha} \sim 10^{38} - 10^{39} \text{ erg s}^{-1}$ and $L_{FUV} \sim 10^{24} - 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$ poses a direct challenge to the truncation in the IMF and CMF as currently implemented in IGIMF theory. As illustrated in Figure 1, if the IGIMF model is correct, it should be impossible for galaxies to occupy this region of luminosity space. The conclusion is strengthened by the fact that we have implemented only a minimal IGIMF. The standard IGIMF would predict even less $L_{H\alpha}$, exacerbating the discrepancy with the observations. Uncertainties in the measurements, particularly in the dust corrections, together with the fact that our models are highly idealized (simple SFH, single metallicity, lack of any feedback), may explain the existence of galaxies non-overlapping with IGIMF models, but the discrepancy we found is most likely larger than the errors at faint $L_{H\alpha}$.

5. SUMMARY AND CONCLUSION

Using SLUG, a fully stochastic code for synthetic photometry in star clusters and galaxies, we have compared the $H\alpha$ to FUV luminosities in a sample of ~ 450 nearby galaxies with models from a universal Kroupa IMF and a modified IMF, the IGIMF. Our principal findings are: (1) simulated galaxies based on a Kroupa IMF and stochastic sampling of stellar masses

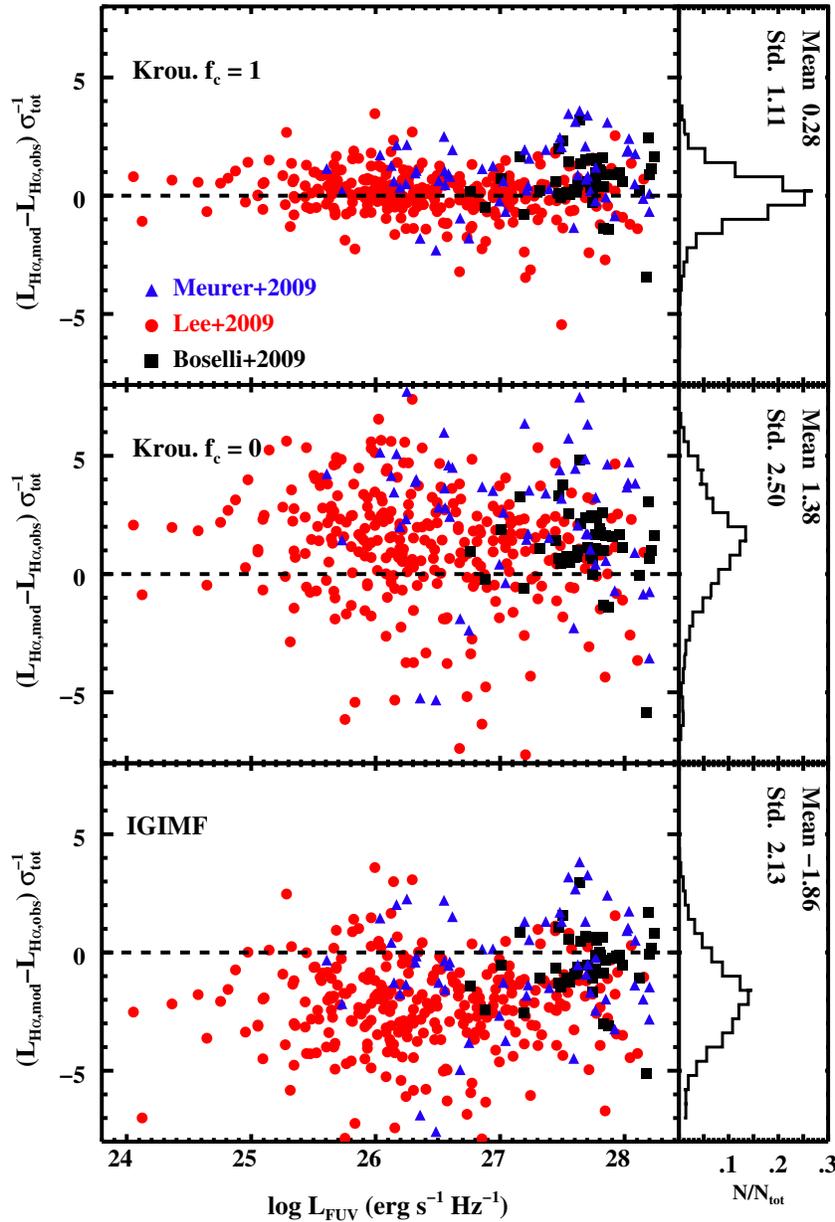


Figure 3. Difference between $L_{H\alpha}$ in individual observations and the mean of the simulated galaxies at comparable L_{FUV} , normalized to the model standard deviation and observational uncertainty. Histograms and Gaussian statistics are shown in the right panels.

(A color version of this figure is available in the online journal.)

are consistent with the observed $L_{H\alpha}$ distribution, (2) only models where stars are formed in clusters account for the full scatter in the observed luminosity, and (3) realizations based on a truncated IMF as currently implemented in the IGIMF underestimate the mean $H\alpha$ luminosity.

Based on this result, and since other factors not included in our simulations (e.g., dust, escape fraction of ionizing radiation, bursty SFHs) can mimic some of the features of the observed luminosity distribution (B09, L09), we conclude that present observations of the integrated luminosity in nearby galaxies are consistent with a universal IMF and do not demand a truncation at its upper end.

While we show that the current IGIMF implementation provides a poor description of available observations, our work is consistent with the fundamental idea behind the IGIMF, i.e., that the SFR, the CMF, and the IMF jointly produce the observed luminosity distribution of galaxies. However,

our analysis emphasizes that the correlations between these quantities emerge naturally from stochastic sampling and that a further modification to the IMF in clusters as proposed in the IGIMF model is not needed to account for the integrated luminosities in galaxies. Further, our calculation highlights how clusters introduce the level of burstiness required to fully account for the observed luminosities, owing to the combined effects of the cluster age distribution and the short life time of massive stars. Time dependence might be a key element currently missing in models of the integrated IMF in galaxies.

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