A METHOD FOR MEASURING VARIATIONS IN THE STELLAR INITIAL MASS FUNCTION

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A METHOD FOR MEASURING VARIATIONS IN THE STELLAR INITIAL MASS FUNCTION.[1]

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ABSTRACT

We present a method for investigating variations in the upper end of the stellar Initial Mass Function (IMF) by probing the production rate of ionizing photons in unresolved, compact star clusters with ages $\leq 10^7$ yr and with different masses. We test this method by performing a pilot study on the young cluster population in the nearby galaxy NGC5194 (M51a), for which multi–wavelength observations from the Hubble Space Telescope are available. Our results indicate that the proposed method can probe the upper end of the IMF in galaxies located out to at least ∼10 Mpc, i.e., a factor ≈200 further away than possible by counting individual stars in young compact clusters. Our results for NGC5194 show no obvious dependence of the upper mass end of the IMF on the mass of the star cluster down to $\approx 10^3$ M$_\odot$, although more extensive analyses involving lower mass clusters and other galaxies are needed to confirm this conclusion.

Subject headings: galaxies: star clusters: general – galaxies: star formation – galaxies: individual (NGC5194) – stars: massive – stars: mass function

1. INTRODUCTION

The distribution of stellar masses at birth (the stellar Initial Mass Function, or IMF, Salpeter 1955) is the fundamental property, together with the efficiency of star formation, that quantifies the conversion of gas into stars in galaxies. It enters, directly or indirectly, in the determination of many physical quantities of stellar populations and galaxies, such as the conversion of luminosity to mass and star formation rate (SFR). The IMF is often parametrized by the broken power law form of Kroupa (2002) or the log–normal form of Chabrier (2003).

Although many studies indicate that the stellar IMF is consistent with a universal form (see, for a review, Bastian et al. 2010), a few recent investigations cast doubts on the universality in *all environments*.

By comparing galaxy–integrated properties of large samples of nearby galaxies at multiple wavelengths, Hoversten & Glazebrook (2008), Meurer et al. (2009), Lee et al. (2009), and Boselli et al. (2009) find that, on average, the ionizing/non–ionizing flux ratio of galaxies decreases for decreasing galaxy luminosity or mass or SFR or SFR/area. Lee et al. (2009) exclude, based on statistical arguments, that galaxy–integrated stochastic sampling or variations in the star formation histories alone can fully account for the observed trend. A systematic variation of the high end of the IMF with some galactic or local parameter (luminosity, SFR, SFR/area, gas density) has been suggested as one of the possible ways to explain the observations (Krumholz & McKee 2008; Meurer et al. 2009; Pflamm–Altenburg et al. 2009; Lee et al. 2009), although other scenarios are possible (e.g., Dong et al. 2008; Kotulla et al. 2008; Gogarten et al. 2009; Hunter et al. 2010; Goddard et al. 2010).

The model suggested by Pflamm–Altenburg et al. (2009) invokes the existence of two correlations: one between a galaxy's SFR and its clusters' maximum mass (e.g., Larsen 2002), and another (deterministic) between a cluster mass and the most massive *possible* star the cluster can form (Weidner & Kroupa 2006). The nature of the second correlation implies that clusters are not subject to the effect of stochastic sampling of the IMF (Elmegreen 2006), i.e. 100 clusters each with mass=10^2 M$_\odot$ would not be equivalent to one 10^4 M$_\odot$ cluster, as the former will systematically lack the high–mass stars contained in the latter.

The standard approach to deriving the functional form of an IMF, i.e. counting the individual stars contained in single–age, young stellar populations (typically $\lesssim$3 Myr old star clusters), is difficult to apply over statistically large samples of clusters at a given mass and in a variety of galactic environments, and provides limited leverage for discriminating stochastic sampling from systematic trends in the IMF. Significant blending will occur for massive stars due to crowding in the centers of star clusters (Maíz–Apellaníz 2008; Ascenso et al. 2009), even with the angular resolution of the Hubble Space Telescope, for distances larger than those of the Magellanic Clouds (∼55 kpc). These difficulties may account for the contrasting results obtained by Maschberger & Clarke (2008), who concluded that the most massive stars in Milky-Way clusters are stochastically drawn from a universal IMF, and Weidner, Kroupa & Bonnell (2010), who claimed evidence for a systematic trend between the masses of clusters and those of their most massive stars.

Here we present an alternate method that exploits the integral properties of star clusters to place limits on variations of the high–end IMF. Each star cluster is treated

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as single unit, and IMF variations are investigated by measuring the dependence of the ionizing photon rate, normalized by the cluster mass, on cluster mass (section 2). This method extends the Corbelli et al. (2009) approach (the cluster birthline) by normalizing the ionizing photon rate to the age–independent cluster mass, instead of the age–dependent bolometric luminosity. Our method, however, requires that accurate ages for each cluster be determined. We test our approach using observations of the young star cluster population in the nearby galaxy NGC5194 (section 3). A summary of findings and future directions are given in section 4.

2. METHOD AND PREDICTIONS

Stellar population synthesis models provide specific predictions for the ionizing photon rate, N(H^o), produced by a single–age stellar population as a function of time, for a given IMF, mass, and metallicity. Compact star clusters represent a close approximation to the idealized case of a single–age population. The rate N(H^o) decreases with increasing age, as massive stars die out, and ionized gas generally becomes undetectable in clusters older than ∼8–10 Myr (more than 100 times fainter than at 1–2 Myr age). Most HII regions form expanding shells around the central cluster (Martin 1998), thus decreasing the surface brightness of the ionized gas emission lines even further. For practical purposes, ionized gas emission will not be easily detected from star clusters older than ≈6–8 Myr.

Measuring N(H^o) from a star cluster at a given (young) age is equivalent to measuring the number of massive stars distributed according to an IMF. This, in models, includes fractional stars in the high end of the IMF, for low–mass clusters. Real clusters, however, do not contain fractions of stars, and, for masses$\lesssim$a few$\times10^4$ $M_\odot$, they will be subject to stochastic sampling of the IMF, even if the underlying IMF is 'universal', i.e., independent of cluster mass (Elmegreen 2006). Stochastic sampling induces a dispersion on the number of stars at a given stellar mass that are present in a real cluster, and the dispersion increases for decreasing cluster mass. This, in turn, affects a number of observational parameters, including the inferred mass and N(H^o) from clusters (e.g., Cerviño et al. 2002; Cerviño & Luridiana 2004). The scatter on the mass determination increases from 6% for a 10^5 $M_\odot$ cluster to ∼50% for a 10^3 $M_\odot$ cluster; the scatter on N(H^o) increases from ∼10% to 80% for the same cluster mass range (Cerviño et al. 2002). In our approach, the impact of stochastic IMF sampling is minimized by combining large numbers of same–mass, young clusters to a cumulative equivalent mass ≈10^5 $M_\odot$, since a 'universal' IMF would be fully sampled in a cluster of this mass, and stochastic uncertainties are reduced to 10% or less in both M_{cl} and N(H^o).

Figure 1, left, shows the model expectations for N(H^o) (as traced by the Hα luminosity, L(Hα)) per unit cluster mass, as a function of cluster mass, for both cases of a 'universal' IMF (Kroupa 2002) with fractional stars and a cluster–mass–dependent IMF with the maximum possible stellar mass depending on the cluster mass (Weidner & Kroupa 2006). Results similar to those of Weidner & Kroupa (2006) would be obtained if the IMF became steeper at the high end for decreasing cluster mass. The L(Hα)/M_{cl} ratio is averaged over the age ranges 1.5–5 Myr and 2–8 Myr for constant star formation, in order to bracket the uncertainty in cluster ages found in most observational analyses. While our default model has metallicity 1.5 solar (to match NGC5194, see below), we show examples also at 1/3 and 3.5 solar metallicity. The metal content of the ionized gas has, in fact, strong influence on the ratio L(Hα)/M_{cl}; this parameter will be critical when comparing star cluster populations belonging to different galaxies, while its impact will be less important when comparing clusters at different masses *within* the same galaxy, under the reasonable assumption that no systematic trend exists between a cluster mass and its metal content.

Stochastic sampling of the stellar IMF in low–mass clusters, combined with photometric uncertainties and reddening, can also affect age determinations from multi–wavelength data. Clusters younger than ∼10 Myr that do not have ionized gas emission can be assigned older ages; conversely, clusters older than 10 Myr can be assigned ages ∼6–9 Myr (Chandar et al. 2010b; Fouesneau & Lançon 2010). Thus samples of young, low–mass clusters are 'polluted' by either addition of old clusters or loss of young members. The two may compensate each other to some degree, but this is still unquantified. Furthermore, masses may be underestimated by up to a factor of 2 (Fouesneau & Lançon 2010). We discuss both effects below, when applying our approach to actual data.

3. APPLICATION: A TEST CASE

We test our method on the nearby star–forming galaxy NGC5194 (D∼8.4 Mpc, Tully 1988), for which extensive multi–wavelength, broad– and narrow–band, archival imaging from the Hubble Space Telescope exists (GO–10452 and GO–10501). The galaxy represents an ideal target for this test: it is nearly face–on ($i\sim20^o$), thus minimizing line–of–sight overlaps among clusters, and its cluster population has been extensively studied (e.g. Bastian et al. 2005; Chandar et al. 2010b). The HST observations of NGC5194 include U (with WFPC2), BVI and Hα (with ACS) for the entire disk, and Pα(λ=1.8756 μm, with NICMOS) for the inner ∼3 kpc radius (Scoville et al. 2001). The galaxy has a mean metal abundance about twice solar, which remains super–solar across the entire disk up to R_{25} (Moustakas et al. 2010).

We use the sample of clusters identified by Chandar et al. (2010b), and refer the reader to that paper for the sample selection and measurements. Descriptions of the selection and age–dating methods for star cluster populations in external galaxies can be found also in Whitmore et al. (2010, applied to the Antennae Galaxies) and Chandar et al. (2010a, applied to NGC5236). We summarize here some of the steps that are relevant to the present paper. For all clusters, ages and extinctions are determined from the χ^2 minimization between the observed U,B,V,I and Hα (non–continuum–subtracted) photometry and predictions from the Bruzual & Charlot (2003, 2007 Update) stellar population models combined with a Milky–Way–type extinction curve (Fitzpatrick 1999). The choice of the extinction curve does not impact the results, because most curves are degenerate in the wavelength range from U to I (Calzetti 2001). Changing the population synthesis models, e.g., to Starburst99 (Leitherer et al. 1999), also has minimal impact on the results in the case of young clusters ($\lesssim$10 Myr). The use of the non–continuum–subtracted Hα photometric point (which becomes a R–band point in the absence of ionized gas) adds leverage for separating young, extincted clusters from old, relatively unextincted ones, even in those cases where the young clusters do not ionize gas (Chandar et al. 2010b). The typical uncertainty is a factor $\sim$2 in the final age determination, and $\sim$60% in the mass. The mass of each cluster is estimated from its extinction-corrected *V* band luminosity and the age-dependent mass-to-light ratio from the stellar population models, assuming a Kroupa/Chabrier stellar IMF. Changing the upper mass limit of the IMF from 120 to 30 $M_\odot$ changes the mass estimate by $\approx$2.5X, which is within the range of uncertainties we consider. We consider two mass bins, located at the two extremes of the sampled range in the cluster mass distribution: $\sim 1.5\times10^3$ $M_\odot$ and $\sim 4\times10^4$ $M_\odot$. They span about a factor 30 in mean mass and a factor 300 in individual cluster masses.

We inspect each cluster visually, and remove from the sample any cluster located in a sufficiently crowded region to hamper Hα line measurements. Our final, visually inspected, sample consists of 86 clusters in the mass range 0.5–2 10^3 $M_\odot$ and 57 in the range 2–15 10^4 $M_\odot$, all younger than 10 Myr. Of the 86 clusters in the lowest mass bin, 39 (45%) are undetected in Hα down to our 3 σ limit of 7×10^{36} erg s^{-1} (calculated in a 5 pixels radius aperture = 10 pc). As mentioned in section 2, some young clusters can be assigned ages older than 10 Myr, and vice–versa. We address this issue by adopting two extreme scenarios: case (a): all clusters whose colors indicate young ages are included in the average of each mass bin; case (b): only clusters which have colors of young populations *and* also have Hα detections above 3 σ are included in the mass bin average. In order to account for the possibility that cluster masses in the low–mass bin may be underestimated by as much as a factor 2 (Fouesneau & Lançon 2010), we include clusters with masses as low as 500 $M_\odot$. Of the 57 clusters in the higher mass range, only 6 (11%) are below 3 σ in Hα.

Photometric measurements of the hydrogen recombination lines (continuum–subtracted Hα+[NII] and Pα) are performed at the positions of the clusters, with aperture sizes that scale according to the cluster's mass, i.e., according to the expected Strömgren radius of the HII region. Aperture sizes are chosen to be about 0.35 $R_{Stroemgren}$, because of crowding of the clusters, and age–dependent aperture corrections are implemented based on the few 'isolated' HII regions identified in our sample. The final photometry is visually inspected to check for contamination from neighboring sources; the local background, determined for each aperture from annuli 2 pixels wide around each region, is subtracted from each photometric measurement, in order to avoid contamination by diffuse emission not associated with the cluster. The uncertainty in the final Hα+[NII] flux from uncertainties in the aperture correction range from about 20% for the youngest and most luminous regions to about 80% in clusters older than $\sim$5–6 Myr. [NII] contamination in the narrow–band filter is removed by using the average galactic [NII]/Hα ratio (Moustakas et al. 2010). The Pα image only covers a portion of the NGC5194 disk, and is used here to derive ionized gas extinction corrections region by region for the area of overlap between the ACS and NICMOS mosaics (see, also, Scoville et al. 2001), for a total of 29 regions. The median values of the gas extinction corrections in each cluster mass bin are then adopted for the regions outside of the overlap area. This may lead to an overestimate of the dust extinction correction of Hα in each mass bin, as the mean extinction shows a gradient of decreasing values towards the outer regions (Calzetti et al. 2005); this will not impact the relative comparison between mass bins, only their absolute values.

In Figure 1, right, the ratio $L(H\alpha)/M_{cl}$=< $L(H\alpha)$>/<M_{cl}> for each of the two cluster mass bins is shown for the two color–age cases (a) and (b), as cyan and magenta points, respectively. The error bars of the high–mass bin are dominated by photometric and aperture–correction uncertainties, while those of the low–mass bin contain a significant contribution from the stochastic uncertainty in cluster mass determinations. The absolute values of $L(H\alpha)/M_{cl}$ are similar for the two mass bins, within the 1 σ uncertainty, for both sets of points. The absence of an obvious differential trend in $L(H\alpha)/M_{cl}$ for the two mass bins is consistent with a universal, stochastically–sampled, IMF. However, we cannot completely eliminate the scenario for which the maximum possible mass of a star increases with the cluster mass, as the data are only 1–2 σ away from this model's expectations (triangles).

The data follow the 2–8 Myr age average points (asterisks) of the 1.5 solar metallicity stellar population models, implying the following, non–exclusive, possibilities: (1) our criteria select clusters fairly uniformly distributed in the age range 2–8 Myr; (2) the models used in Figure 1, right, have too low metallicity for NGC5194, and a higher metallicity model should be used (cf. Figure 1, left panel); (3) significant, mass–independent, ionizing photon leakage is present in our regions, which we have not attempted to correct for in our analysis.

4. CONCLUSIONS AND FUTURE WORK

We have presented a method to test for variations of the high–end of the stellar IMF that exploits the integrated properties of star clusters, rather than resolved star counts. This approach can overcome statistical limitations in IMF determinations and average out effects of stochastic sampling by leveraging the large numbers of star clusters in galaxies. The ratio of the ionizing photon rate (as measured by the extinction–corrected Hα emission) from young clusters to cluster mass provides a powerful tool to test for such variations. A basic requirement for this method is to isolate the young (<10 Myr) star cluster population, and measure its ionized gas emission. Accurate ($\sim$2X) ages can be obtained with high–angular–resolution (e.g., HST) multi–color observations; a minimum set appears to be UBVRI (Chandar et al. 2010b), although the addition of the UV can add an extinction leverage (Calzetti et al. 2005) to further reduce the age uncertainty. Ionized gas emission measurements also need to be corrected for dust extinction, requiring observations of two hydrogen recombination lines. Comparisons between galaxies further requires that the metallicity of each galaxy is known, as the ionizing photon rate is highly dependent on metallicity.

We have tested this method by performing a pilot study on the cluster population in the nearby galaxy NGC5194. Our analysis shows that, when a sufficiently large number of similar–mass clusters is summed together to average out effects of stochastic sampling of the IMF, the mean Hα luminosity normalized by the mean cluster mass is relatively independent of the cluster mass, down to $M_{cl} \sim 10^3$ $M_\odot$. This is consistent with an effectively universal IMF independent of the cluster mass. We do not find strong evidence that the maximum possible mass of a star in a cluster decreases systematically with decreasing cluster mass (as proposed by Weidner & Kroupa 2006). However, this is not the most stringent test of the stochastic sampling model because clusters more massive than 10^3 $M_\odot$ are expected to contain more than 1 O–type star. Clearly, statistics need to be expanded by including lower cluster masses, and cluster populations from other galaxies, spanning a range of internal and external environments. The proposed method enables tests of variations of the high–end IMF up to at least ∼10 Mpc distance (NGC5194 is located at 8.4 Mpc distance), and possibly more, depending on the crowding of the cluster population. This distance range is at least a factor of 200 larger than what has been achieved so far with direct star counts.

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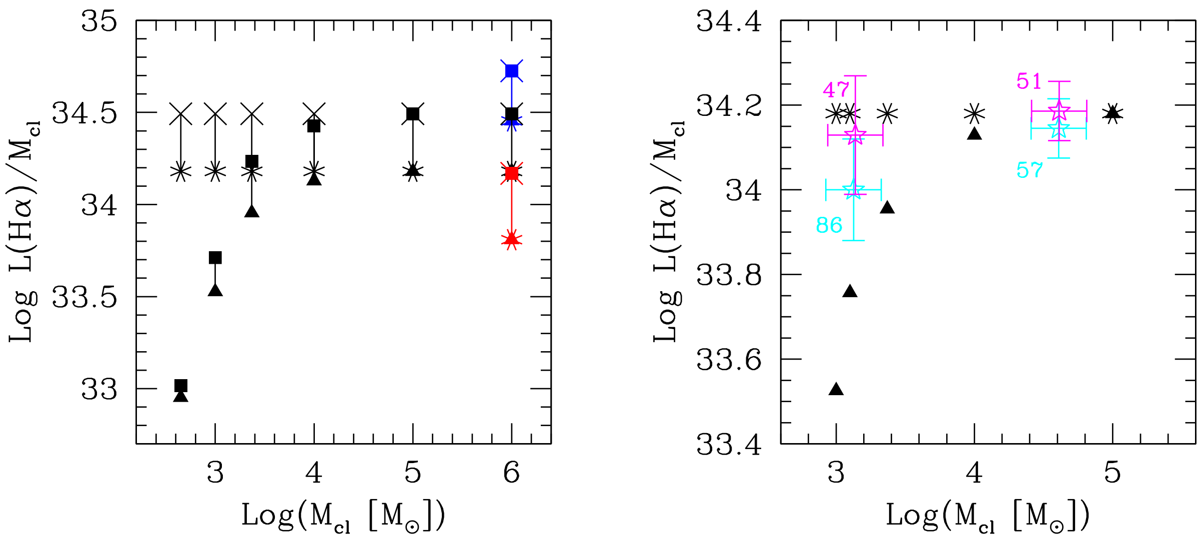

FIG. 1.— **LEFT:** The expected ratio L(Hα)/M$_{cl}$ as a function of the cluster mass M$_{cl}$ both for a universal IMF (crosses and asterisks), and for a cluster–mass–dependent IMF (filled squares and triangles, Weidner & Kroupa 2006). The models are from Starburst99 (2007 Update, Leitherer et al. 1999), and assume averages over large numbers of clusters. The mean L(Hα)/M$_{cl}$ ratios are averaged over two age ranges: 1.5–5 Myr (crosses and squares) and 2–8 Myr (asterisks and triangles), joined by vertical bars, under the assumption of constant star formation for each age range. We assume that clusters younger than 1.5–2 Myr are too dust–enshrouded to provide significant contribution at optical wavelengths. The black symbols are for 1.5 solar metallicity models; examples of higher (∼3.5 solar, red) and lower (∼1/3 solar, blue) metallicity are shown at a representative mass. **RIGHT:** The ratio $<$L(Hα)$>$/$<$M$_{cl}$ $>$ as a function of the mean cluster mass M$_{cl}$ in two mass bins for NGC5194, for clusters younger than ∼8–10 Myr (stars with 1 σ error bars), including all clusters within each mass bin (cyan, bottom symbols), and including only clusters with Hα flux detections $>$3 σ (magenta, top symbols). The number of clusters in each mass bin is shown close to the symbols. Expectations from models with 1.5 solar metallicity and averaged over the 2–8 Myr age range are shown (asterisks and triangles), as they are the closest match to the NGC5194 high–mass data.