The Fraction of Stars That Form in Clusters in Different Galaxies

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Abstract

We estimate the fraction of stars that form in compact clusters (bound and unbound), \( \Gamma_F \), in a diverse sample of eight star-forming galaxies, including two irregulars, two dwarf starbursts, two spirals, and two mergers. The average value for our sample is \( \Gamma_F \approx 24\% \pm 9\% \). We also calculate the fraction of stars in clusters that survive to ages between \( \tau_1 \) and \( \tau_2 \), denoted by \( \Gamma_S(\tau_1, \tau_2) \), and find \( \Gamma_S(10, 100) = 4.6\% \pm 2.5\% \) and \( \Gamma_S(100, 400) = 2.4\% \pm 1.1\% \), significantly lower than \( \Gamma_F \) for the same galaxies. We do not find any systematic trends in \( \Gamma_F \) or \( \Gamma_S \) with the star formation rate (SFR), the SFR per unit area (\( \Sigma_{SFR} \)), or the surface density of molecular gas (\( \Sigma_{H_2} \)) within the host galaxy. Our results are consistent with those found previously from the CMF/SFR statistic (where CMF is the cluster mass function), and with the quasi-universal model in which clusters in different galaxies form and disrupt in similar ways. Our results, however, contradict many previous claims that the fraction of stars in bound clusters increases strongly with \( \Sigma_{SFR} \) and \( \Sigma_{H_2} \). We find that the previously reported trends are largely driven by comparisons that mixed \( \Gamma_F \approx \Gamma_S(0, 10) \) and \( \Gamma_S(10, 100) \), where \( \Gamma_S(0, 10) \) was systematically used for galaxies with higher \( \Sigma_{SFR} \) and \( \Sigma_{H_2} \), and \( \Gamma_S(10, 100) \) for galaxies with lower \( \Sigma_{SFR} \) and \( \Sigma_{H_2} \).

Key words: galaxies: star clusters: general – stars: formation

1. Introduction

Stars and star clusters have a common origin in the dense regions of molecular clouds (e.g., Lada & Lada 2003; McKee & Ostriker 2007). It has long been known that the stellar initial mass function (IMF)—a direct product of star formation processes—is similar among different galaxies, possibly even “universal” (Bastian et al. 2010). The common origin of stars and clusters suggests that there may also be similarities among cluster populations in different galaxies. We have found evidence for such similarities in the mass and age distributions of clusters, \( \psi(M) \equiv dN/dM \) and \( \chi(\tau) \equiv dN/d\tau \). Both distributions can be represented by power laws, \( \psi(M) \propto M^\beta \) and \( \chi(\tau) \propto \tau^\gamma \), with exponents that are approximately (but not exactly) the same in different galaxies: \( \beta \approx -2 \) and \( \gamma \approx -0.7 \) (Fall & Chandar 2012; see also Whitmore et al. 2007). The similarity of these distributions suggests that the formation and disruption of clusters are governed by “quasi-universal” processes.

We showed recently that the mass functions of young clusters (with ages \( \tau < 10^7 \) years), when divided by the star formation rate (SFR), are also similar among different galaxies (Chandar et al. 2015; hereafter CFW15; Mulia et al. 2016). In our sample of eight galaxies, the amplitude of the cluster mass function (CMF) and the SFR vary by factors \( \sim 10^3 \), while their ratio (CMF/SFR) varies by less than a factor of two. Moreover, we find no significant correlations between the CMF/SFR statistic and the other properties of the galaxies. These results mean that the rates of star and cluster formation are essentially proportional to each other—another sign of quasi-universality.

The CMF/SFR statistic is closely related to another important quantity \( \Gamma \), the fraction of stars that form in compact clusters. Indeed, CMF/SFR and \( \Gamma \) are proportional to each other (as we show in Section 2). \( \Gamma \) has figured prominently in several recent studies of cluster populations (e.g., Bastian 2008; Goddard et al. 2010; Kroupa 2012; Adamo et al. 2015; Johnson et al. 2016). It is usually defined as the fraction of stars that form in gravitationally bound clusters, i.e., those with negative total energy (kinetic plus potential). However, since in practice the binding energies of clusters are never measured or even estimated, \( \Gamma \), despite its putative de
for clusters, in order to avoid the biases that have crept into previous studies of $\Gamma$.

The remainder of this paper is arranged as follows. In Section 2 we derive relations between the quantities $\Gamma$, CMF/SFR, and the mass and age distributions, $\psi(M)$ and $\chi(\tau)$, of the clusters. In Section 3 we determine new values of SFR, $\Sigma_{\text{SFR}}$, and $\Sigma_{\text{HI}}$ for our sample galaxies, and in Section 4 we summarize the cluster catalogs and present the age and mass distributions of the clusters. In Section 5 we determine new values of $\Gamma$ and assess whether they or our previously derived CMF/SFR statistics show trends with any galaxy property. In Section 6 we compare our new results with those from previous observational and theoretical studies, and in Section 7 we discuss the physical implications of our results. In Section 8 we summarize our main conclusions.

2. Relations between the Statistical Properties of Cluster Populations

As explained in the Introduction, this paper is concerned with several statistical properties of cluster populations: the mass and age distributions, $\psi(M)$ and $\chi(\tau)$, the CMF normalized by the SFR (CMF/SFR), and the fraction of stars in clusters $\Gamma$. Because clusters are progressively destroyed, $\Gamma$ will depend on the age interval over which it is determined, as shown in Figure 1. Thus, it is essential to distinguish between the fraction of stars in forming clusters, which we henceforth denote by $\Gamma_f$, and the fraction of stars in surviving clusters, which we denote by $\Gamma_s$. In this section, we derive some useful formulae for estimating $\Gamma_f$ and $\Gamma_s$ from observations. We also show how these quantities are mathematically related to $\psi(M)$, $\chi(\tau)$, and CMF/SFR. In the following sections, we present our observational determinations of $\Gamma_f$, $\Gamma_s$, and CMF/SFR, and we show that they have approximately the expected behavior.

With these issues in mind, we distinguish between two versions of the joint mass-age distribution of a cluster population: one for forming clusters, $f(M, \tau)$, and the other for surviving clusters, $g(M, \tau)$. In general, $g(M, \tau)$ will be less than $f(M, \tau)$, except near $\tau = 0$, because clusters are progressively destroyed by a variety of internal and external dynamical processes. Both $f(M, \tau)$ and $g(M, \tau)$ are of theoretical interest, but only $g(M, \tau)$ is directly observable (since $f(M, \tau)$ includes all clusters that form, whether or not they survive to an age $\tau$). All the statistical properties of cluster populations discussed in this paper can be derived from $g(M, \tau)$. The mass function $\psi(M)$ is the integral of $g(M, \tau)$ over all $\tau$, while the age distribution $\chi(\tau)$ is the integral of $g(M, \tau)$ over all $M$.

The fraction of stars that form in clusters is simply the ratio of the formation rates of clusters and stars: $\Gamma_f = \text{CFR}/\text{SFR}$. Another way to express this is in terms of the masses of recently formed clusters and stars in a small but common age interval $0 < \tau < \tau_a$ that we specify later:

$$M_s(< \tau_a) = \tau_a \text{ SFR}, \quad (1)$$

$$M_c(< \tau_a) = \int_0^{\tau_a} \int_0^\infty Mf(M, \tau)dMd\tau. \quad (2)$$

Thus, we have

$$\Gamma_f = \frac{M_c(< \tau_a)}{M_s(< \tau_a),} \quad (3a)$$

$$= \frac{1}{\tau_a \text{ SFR}} \int_0^{\tau_a} \int_0^\infty Mg(M, \tau)dMd\tau. \quad (3b)$$

If $\tau_a$ is chosen to be small enough that disruption can be neglected, i.e., $f(M, \tau) \approx g(M, \tau)$ for $\tau \leq \tau_a$, we then also have

$$\Gamma_f \approx \frac{1}{\tau_a \text{ SFR}} \int_0^{\tau_a} \int_0^\infty Mg(M, \tau)dMd\tau. \quad (4)$$

At this stage, it is important to note that $f(M, \tau)$, $g(M, \tau)$, and hence $\Gamma_f$ pertain to all compact clusters, regardless of whether they are gravitationally bound or unbound. Many compact clusters will either be born unbound or will become unbound by internal stellar feedback soon after they are born (often called “infant mortality”). The internal dynamical or crossing times of clusters vary widely, but $\tau_e \sim 10^6$ years may be taken as a typical value. N-body simulations show that once a cluster becomes unbound, it takes a time $\tau_d \sim 10^6 \sim 10^7$ years or more to dissolve into the surrounding stellar field (e.g., Baumgardt & Kroupa 2007). For much of this time, it will retain the appearance of a bound cluster, will be counted in cluster samples, and hence will be included in determinations of $g(M, \tau)$.

The choice of the age $\tau_a$ in Equations (3) and (4) involves several competing constraints. On the one hand, $\tau_a$ must be small enough that the dissolution of clusters can be neglected, as we have noted. It must also be small enough that temporal variations in the CFR and SFR can be safely neglected. On the other hand, $\tau_a$ must be large enough that the age interval $0 < \tau < \tau_a$ includes enough clusters in real samples for accurate determinations of $\Gamma_f$. These constraints lead to $\tau_a \sim 10^7$ years. This value of $\tau_a$ also corresponds approximately to the period over which a new generation of stars produces ionizing radiation and hence H$\alpha$ emission.

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**Figure 1.** Previously derived fractions of stars in clusters in different age intervals (compiled by Adamo et al. 2015) plotted against the mean surface density of SFR in the host galaxy. The average result for M31 from Johnson et al. (2016) is also shown. This plot shows that different age ranges have been used for different galaxies, highlighted by the different color symbols. There has been a tendency in the literature to use the 10–100 Myr age interval for galaxies with lower $\Sigma_{\text{SFR}}$ and the 1–10 Myr age interval for galaxies with higher $\Sigma_{\text{SFR}}$. This has led to a steep apparent trend. The dashed line represents the empirical relationship determined by Goddard et al. (2010) from six galaxies that had a mix of intervals used to determine $\Gamma$, and the dotted curve shows the predicted relationship from Kruijssen (2012).
We next consider some practical issues in determining $\Gamma_F$. For a complete sample of clusters, with individual masses and ages $M_i$ and $\tau_i$, Equation (4) can be replaced by a discrete sum

$$\Gamma_F \approx \frac{1}{\tau_{\alpha_{\mathrm{SFR}}}} \sum_i M_i \text{ for } \tau_\alpha < \tau_\alpha.$$  

(5)

Most cluster samples are complete only above a limiting mass $M_{\text{lim}}$ set by the flux-detection limit and the distance of the galaxy. For such mass-limited samples, the sum in Equation (5) must be broken into two parts: a sum over detected clusters with $M_i > M_{\text{lim}}$ and $\tau_\alpha < \tau_\alpha$, and an integral over the mass function of undetected, less massive clusters. Thus,

$$\Gamma_F \approx \frac{1}{\tau_{\alpha_{\mathrm{SFR}}}} \sum_i M_i + \int_{M_{\text{lim}}}^{\infty} M \psi(M) dM.$$  

(6)

The lower limit on the integral above represents the transition between clusters and individual stars, for which we adopt $M_{\text{lim}} = 10^2 M_\odot$.

The mass functions of young star clusters can be represented by a power law, $\psi(M) = A M^{\beta}$, over a large range of mass, $10^2 M_\odot \lesssim M \lesssim 10^6 M_\odot$, with nearly the same exponent $\beta \approx -2$ in different galaxies (Fall & Chandar 2012). Thus, Equation (6) becomes

$$\Gamma_F \approx \frac{1}{\tau_{\alpha_{\mathrm{SFR}}}} \sum_i M_i + \frac{A}{2 + \beta} \left( M_{\text{lim}}^{2+\beta} - M_{\text{min}}^{2+\beta} \right) \text{ for } \beta = -2.$$  

(7a)

$$\approx \frac{1}{\tau_{\alpha_{\mathrm{SFR}}}} \left( \sum_i M_i + A \ln \left( \frac{M_{\text{lim}}}{M_{\text{min}}} \right) \right) \text{ for } \beta = -2.$$  

(7b)

This is the equation we use to compute $\Gamma_F$. We determine the normalization $A$ for each galaxy from the clusters more massive than $M_{\text{lim}}$. For distant galaxies, for which $M_{\text{lim}}$ is large, the second term in the brackets of Equation (7) can be comparable to or even larger than the first term. We discuss corrections for dust attenuation to estimates of the SFR in Section 3.1 and to counts of clusters in Section 5.1.

We now consider the fraction of stars in surviving clusters $\Gamma_3(\tau_\alpha, \tau_2)$ in an interval of age $\tau_\alpha < \tau < \tau_2$. By analogy with Equations (3) and (4), this is given by

$$\Gamma_3(\tau_\alpha, \tau_2) = \frac{1}{(\tau_2 - \tau_\alpha)} \int_{\tau_\alpha}^{\tau_2} \int_0^\infty M g(M, \tau) dM d\tau.$$  

(8)

Because $g(M, \tau) dM d\tau$ is defined to be the number of surviving clusters in $(M, M + dM)$ and $(\tau, \tau + d\tau)$, Equation (8) is exact for all values of $\tau_\alpha$ and $\tau_2$. As we have noted, in the special case $\tau_\alpha = 0$ and $\tau_2 = \tau_\alpha$, the fractions of stars in forming and surviving clusters are nearly equal: $\Gamma_F \approx \Gamma_3(0, \tau_\alpha)$. When determining $\Gamma_3(\tau_\alpha, \tau_2)$ from a mass-limited sample of clusters, the integrals in Equation (8) must be replaced by a sum over the detected clusters with $M_i > M_{\text{lim}}$ and $\tau_\alpha < \tau_i < \tau_2$ and integrals over the mass-age distribution of undetected, less massive clusters by straightforward extensions of Equations (6) and (7).

It is instructive at this stage to re-express $\Gamma_3(\tau_\alpha, \tau_2)$ in an alternative but equivalent form. With this in mind, we define the “average” mass function $\overline{\psi}$ of clusters with ages in the interval $\tau_\alpha < \tau < \tau_2$ as follows:

$$\overline{\psi}(M, \tau) = \frac{1}{(\tau_2 - \tau_\alpha)} \int_{\tau_\alpha}^{\tau_2} g(M, \tau) d\tau.$$  

(9)

Multiplying this by $M$, integrating over all $M$, and using Equation (8), we obtain

$$\Gamma_3(\tau_\alpha, \tau_2) = \frac{1}{\mathrm{SFR}} \int_0^\infty M \overline{\psi}(M, \tau) dM.$$  

(10)

In a previous study, we named the function $\overline{\psi}(M, \tau)$ the mass function, $M_{\text{CFW15}}$, and $M_{\text{CMF}}$ for the CMF/SFR statistic (CFW15, Mulia et al. 2016). Thus, we expect to find that $\Gamma_3(\tau_\alpha, \tau_2)$ is also similar for these eight galaxies.

The fractions of stars in forming and surviving clusters, $\Gamma_F$ and $\Gamma_3$, are closely related to the age distribution $\chi$, as we have demonstrated explicitly. In previous work, we found empirically that the mass and age distributions, $\psi$ and $\chi$, are effectively independent of each other (Fall & Chandar 2012). Thus, the joint mass-age distribution of surviving clusters is, to a good approximation, separable:

$$g(M, \tau) = \psi(M) \chi(\tau).$$  

(11)

It helps at this stage to introduce the average value of $\chi$ over an age interval $\tau_\alpha < \tau < \tau_2$:

$$\overline{\chi}(\tau_\alpha, \tau_2) = \frac{1}{(\tau_2 - \tau_\alpha)} \int_{\tau_\alpha}^{\tau_2} \chi(\tau) d\tau.$$  

(12)

Inserting $g(M, \tau)$ from Equation (11) into Equations (4) and (8) and then using Equation (12), we derive the basic relation between $\Gamma_F$, $\Gamma_3$, and $\chi$:

$$\frac{\Gamma_F}{\Gamma_3(\tau_\alpha, \tau_2)} = \frac{\overline{\chi}(0, \tau_\alpha)}{\overline{\chi}(\tau_\alpha, \tau_2)}.$$  

(13)

This result has a pleasing simplicity: apart from normalization factors, $\Gamma_3(\tau_\alpha, \tau_2)$ and $\overline{\chi}(\tau_\alpha, \tau_2)$ are the same function of $\tau_\alpha$ and $\tau_2$. Thus, if $\chi(\tau)$ declines with increasing $\tau$, as expected from the disruption of clusters, $\overline{\chi}(\tau_\alpha, \tau_2)$ and hence $\Gamma_3(\tau_\alpha, \tau_2)$ will decline with increasing $\tau_\alpha$ and $\tau_2$.

To estimate $\Gamma_F/\Gamma_3(\tau_\alpha, \tau_2)$, we proceed as follows. In previous work, we found that the age distribution can be represented by a power law, $\chi(\tau) \propto \tau^\gamma$, over the age range $10^7 \lesssim \tau \lesssim 10^9$ years with similar (but not exactly the same) exponents in different galaxies: $-1.0 \lesssim \gamma \lesssim -0.5$ (Fall & Chandar 2012). For ages below $\tau_\alpha \sim 10^7$ years, the shape of $\chi(\tau)$ is less certain; it could continue to rise toward $\tau = 0$, or it could flatten off. We recall that this age range includes both bound clusters and unbound clusters that have not yet dissolved away. With this in mind, we consider two simple models for $\chi(\tau)$. The first (model 1) is a pure power law with an exponent $\gamma > -1$ for all $\tau$, while the second (model 2) is flat for $0 < \tau < \tau_\alpha$ and a power law with an (unrestricted) exponent $\gamma$ for $\tau \geq \tau_\alpha$. From Equations (12) and (13), we have

$$\frac{\Gamma_F}{\Gamma_3(\tau_\alpha, \tau_2)} = \frac{\gamma(\tau_2 - \tau_\alpha)}{\tau_2^{\gamma+1} - \tau_\alpha^{\gamma+1}}.$$  

(14a)

$$\frac{\Gamma_F}{\Gamma_3(\tau_\alpha, \tau_2)} = (1 + \gamma) \frac{\tau_\alpha^{\gamma+1} - \tau_\alpha^{\gamma+1}}{\tau_2^{\gamma+1} - \tau_\alpha^{\gamma+1}}.$$  

(14b)
These formulae, which differ by a factor $1 + \gamma$, are expected to bracket the true values of $\Gamma_F / \Gamma_S (\tau_1, \tau_2)$.

We now compare the predictions above with the observations plotted in Figure 1. We identify $\Gamma_F$ and $\Gamma_S (10, 100)$ with the observed $\Gamma$ for $0 < \tau < 10^7$ years (blue dots) and $10^7 < \tau < 10^8$ years (green dots), respectively. Thus, we set $\tau_0 = \tau_1 = 10$ years and $\tau_2 = 10^7$ years in Equations 14(a) and (b). For $\gamma = -0.7$, a typical exponent of the age distribution, these equations predict $\Gamma_F / \Gamma_S (10, 100) \approx 9$ (model 1) and $\Gamma_F / \Gamma_S (10, 100) \approx 3$ (model 2). Lower (more negative) values of $\gamma$ increase $\Gamma_F / \Gamma_S (\tau_1, \tau_2)$ and vice versa for both models. For comparison, the median observed $\Gamma_F$ and $\Gamma_S (10, 100)$ in Figure 1 are 23% and 4.2%, respectively; hence $\Gamma_F / \Gamma_S (10, 100) \approx 5$, well within the range spanned by models 1 and 2. We note that the observed $\Gamma$ values plotted in Figure 1 have substantial uncertainties (because they were derived by heterogeneous procedures) and that the exponent $\gamma$ is not known in most cases (and may vary somewhat among galaxies). Nevertheless, the rough agreement we find between the predicted and observed $\Gamma_F / \Gamma_S (10, 100)$ already indicates that much of the claimed correlation between $\Gamma$ and $\Sigma_{SFR}$ is spurious. We make more detailed comparisons based on our homogeneously derived values of $\Gamma_F$, $\Gamma_S$, and $\gamma$ later in this paper.

3. Galaxy Properties

The galaxies in our sample are the LMC, the SMC, NGC 4214, NGC 4449, M83, M51, Antennae, and NGC 3256, which includes irregulars, spirals, and mergers that span wide ranges in distance, luminosity or mass, SFR, and $\Sigma_{SFR}$. This sample, while small, is reasonably representative of nearby star-forming galaxies in general. Some of the basic properties of our sample galaxies, discussed in this section, are listed in Table 1.

3.1. Star Formation Rates

We determined the current SFR for each galaxy from extinction-corrected H$\alpha$ luminosities (CFW15; Mulia et al. 2016). H$\alpha$-based SFRs are sensitive to the most recently formed massive stars, with $\approx 90\%$ of the emission coming from stars younger than $\approx 7$ Myr (e.g., Kennicutt & Evans 2012). We use the most recent H$\alpha$ flux measurements listed in the NED and correct for contamination by [N II] emission, and assume the distances given in column 2 of Table 1 when converting into H$\alpha$ luminosities. In order to correct for attenuation by dust, we use the 24 $\mu$m flux and the formula given in Kennicutt & Evans (2012). Their calibration is based on the STAR-BURST99 models (Leitherer et al. 1999), which assume solar metallicity, a Kroupa (2001) IMF, similar to the Chabrier IMF assumed for the clusters, and a constant rate of star formation. The resulting SFRs are listed in column 3 of Table 1 and in column 2 of Table 2. These cover a range of approximately three orders of magnitude, from 0.06 $M_\odot$ yr$^{-1}$ for the SMC, to 50 $M_\odot$ yr$^{-1}$ for the merging NGC 3256 system.
measurements, corrections made for attenuation by dust, temporal variations in the SFR, uncertainties in the calibration used to convert the measured fluxes into SFR, and the leakage of Lyman-continuum photons from the parent galaxy. We found that our SFR estimates agreed to within \( \approx 50\% \) of previously published H\(_\alpha\)-based rates, and adopt this as our uncertainty here.

The cluster catalogs used in this work provide near-full coverage of the SMC, NGC 4214, NGC 4449, M51, the Antennae, and NGC 3256. We determined the fractional coverage of the optically luminous portion of each galaxy in CFW15 and Mulia et al. (2016), and give these values in column 4 of Table 1.

Because our sample includes irregular, dwarf, and merging galaxies, it is possible that the SFR over the last \( \approx 400 \) Myr may have been different from the current SFR determined from the H\(_\alpha\) luminosity. If this is the case, our estimates in Section 5 for the fraction of stars in surviving clusters, \( \Gamma_\alpha(10, 100) \) and \( \Gamma_\alpha(100, 400) \), would be affected (but not those for \( \Gamma_S \)). Therefore, we have also estimated the SFR for each galaxy from flux measurements at other wavelengths. Far-ultraviolet (FUV) and infrared-based SFRs are sensitive to stars formed over a longer timescale than H\(_\alpha\)-based determinations, approximately the last \( \approx 100 \) Myr and a few \( \times 100 \) Myr instead of just the last \( \approx 10 \) Myr. We use the most recent GALEX FUV and Spitzer 24 \( \mu m \) fluxes from the literature and the formulae given in Kennicutt & Evans (2012) to derive an extinction-corrected FUV-based SFR (by including the 24 \( \mu m \) flux to correct for attenuation by dust) and the 24 \( \mu m \) flux measurements alone to determine an infrared-based SFR. These are listed in Columns 3 and 4 of Table 2. A comparison between different measurements for the same galaxy and waveband suggests that the fluxes are uncertain at the \( \approx 25\% \) level.

The four closest galaxies in our sample, the LMC and SMC, NGC 4214, and NGC 4449, also have previously published CMD-based star formation histories. We determine the average SFR between 10–100 Myr ago and 100–400 Myr ago from these analyses, and also compile these values in Table 2. Table 2 shows some very interesting results. If we compare the H\(_\alpha\)-based (\( \tau \lesssim 10 \) Myr) SFR with the average 10–100 Myr and 100–400 Myr CMD-based SFRs, the LMC, SMC, NGC 4214, and NGC 4449 do not appear to have had strong variations over the past \( \approx 400 \) Myr, with most of the values within 50% of one another. FUV and 24 \( \mu m \) based SFRs, which we determined for NGC 4214 and NGC 4449, give similar results to those from the other techniques and tracers.

Figure 2 plots the SFRs listed in Table 2 in the three age intervals of interest: \( \approx 10 \) Myr (H\(_\alpha\)-based SFR), 10–100 Myr (CMD-based SFR for the four closest galaxies, FUV-based SFR for the others), and 100–400 Myr (CMD-based SFR for the four closest galaxies, IR-based SFR for the others). Interestingly, the SFRs do not vary strongly over this age range in any of our sample galaxies. More importantly, there are no systematic trends with age; the SFR increases slightly with age in some galaxies and decreases slightly in others. Our main conclusion from Figure 2 is that all of the galaxies in our sample appear to have had fairly constant average rates of star formation, to within \( \approx 50\% \), over the age intervals of interest here.

### 3.2. SFR Densities

The rate of star formation per unit area, \( \Sigma_{SFR} \), has been suggested to play an important role in the fraction of stars that form in bound clusters (e.g., Kruijssen 2012). We have already summarized our method for determining the SFR of each galaxy. Next, we determine the area covered by young clusters in each galaxy, using the same images as those used to produce the catalogs. We do not include outlying regions where no young clusters are detected, and estimate that the uncertainty in our star-forming areas is \( \approx 50\% \). We record these areas in column 5 of Table 1. \( \Sigma_{SFR} \) is determined by dividing the total SFR (corrected by the fractional coverage) by the area, and it is listed in column 6. The \( \Sigma_{SFR} \) values cover approximately three orders of magnitude, from \( \approx 9.2 \times 10^{-4} \) M\(_\odot\) yr\(^{-1}\) kpc\(^{-2}\) for the dwarf irregular SMC to \( \approx 1.0 \) M\(_\odot\) yr\(^{-1}\) kpc\(^{-2}\) for the merger NGC 3256. The galaxies in our sample have an approximately linear relationship between SFR and \( \Sigma_{SFR} \).

We also list previously published values for \( \Sigma_{SFR} \) (from the compilation in Adamo et al. 2015) in column 7 of Table 1. These are within a factor of two of our new determinations for the LMC, SMC, M83, M51, and NGC 3256; Adamo et al. (2015) did not list values for NGC 4449 or the Antennae. There is no standard method for estimating the star-forming area within a galaxy, and if a significant area with no star formation is included, then \( \Sigma_{SFR} \) can be underestimated. The previous estimate of \( \Sigma_{SFR} \) for NGC 4214 is nearly six times lower than the one that we estimate here. This is at least in part due to the larger distance (and hence larger area) previously assumed for this galaxy. Regardless, our conclusions do not
change if the literature values for $\Sigma_{\text{SFR}}$ are used instead of our newly determined ones.

3.3. Gas Densities

The amount of molecular gas and how densely it is packed into galaxies might also play a role in star and cluster formation (e.g., Kruĳssen 2012). We list the average surface density of H$_2$ gas ($M_H \, \text{pc}^{-2}$) in Column 8 of Table 1, taken from the compilation in Kruĳssen & Bastian (2016) for seven of our galaxies, and from that in Kruĳssen (2012) for NGC 3256. These come from low-transition maps of CO, which are used to infer the distribution of H$_2$ molecular gas. We update the values of $\Sigma_{\text{H}}$ for M51 (using data from Leroy et al. 2013) and the Antennae (using data from Zhang et al. 2001). The values of $\Sigma_{\text{H}}$ extend from $\approx9 M_\odot \, \text{pc}^{-2}$ in the SMC to $\approx125 M_\odot \, \text{pc}^{-2}$ in NGC 3256, a much smaller range ($\approx10^3\times$) than those of SFR and $\Sigma_{\text{SFR}}$ ($\approx10^3\times$).

4. Star Cluster Catalogs and Properties

4.1. Observations

The data and cluster selection criteria for our sample galaxies are presented and summarized in CFW15 and Mulia et al. (2016). Candidate clusters were required to be compact but not to be round. Here, we briefly summarize the catalogs used in this work, and refer the reader to the original work for more details.

**LMC and SMC.** We use the ground-based UBVR catalogs from Hunter et al. (2003), where clusters were selected by visual examination of candidates compiled from previously published catalogs. The catalogs include young clusters ($\tau \lesssim 10$ Myr), but not low-density H II regions, with a total of 854 clusters in the LMC and 239 in the SMC. In Chandar et al. (2010a), we estimated the age and mass of each cluster and assessed the completeness of the catalog. The data used by Hunter et al. (2003) cover $\approx70\%$ and $\approx90\%$ of the recent star formation in the LMC and SMC, as traced by H$\alpha$ emission (CFW15).

**NGC 4214.** We use a new catalog of 334 candidate star clusters, selected from images taken with the WFC3 on board the *Hubble Space Telescope* (HST) as part of program GO-11360, which covers the star-forming part of the galaxy in its entirety. Cluster candidates were selected to be broader than the point-spread function (PSF), with close pairs of stars and background galaxies eliminated by visual inspection. Aperture photometry in $UBVH\alpha$ images was performed in a manner similar to that described in Chandar et al. (2010c) for cluster candidates in the nearby spiral galaxy M83.

**NGC 4449.** We use the $UBVH\alpha$ catalog of 129 clusters published by Rangelov et al. (2011) based on observations made with the Advanced Camera for Surveys (ACS) on board the HST (ACS/WFC ($BVH\alpha$)) and the WFPC2 ($U$ band), also on the HST. The selection method was similar to that used for NGC 4214 and M83. The observations cover nearly the entire galaxy.

**M83.** We use a new $UBVH\alpha$ catalog of 3186 compact clusters selected from seven fields observed with the *HST/WFC3* (B. Whitmore et al. 2017, in preparation). These fields cover $\approx60\%$ of the optically luminous portion of M83. The cluster selection procedure was similar to that followed for NGC 4214 and NGC 4449.

**NGC 3256.** We use the catalog of 3812 compact clusters published by Chandar et al. (2016), based on *HST ACS/WFC ($BV$/$H\alpha$) and WFPC2 ($U$ band) observations. These cover $\approx90\%$ of the optically luminous portion of M51.

**Antennae.** We use the $UBVH\alpha$ catalog published by Whitmore et al. (2010) based on *HST ACS/WFC ($BVH\alpha$) and WFPC2 ($U$ band) observations. Clusters were selected to be objects brighter than $M_V = -9$, which eliminates nearly all individual, luminous stars.

**NSC 2536.** We use the $UBVH\alpha$ catalog of 505 clusters published by Mulia et al. (2016) based on *HST* observations that cover the entire main body of the galaxy. Clusters were selected to be broader than the PSF.

Photometry for each cluster in each catalog was compared with predictions from stellar population models in the appropriate filters, in order to estimate the mass, age, and extinction of the cluster. All of the cluster masses have been determined assuming a Chabrier (2003) IMF, including for M51 and the Antennae, for which the published masses assumed a Salpeter (1955) IMF.

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Figure 3. Age distributions of star clusters in our sample galaxies in the indicated mass intervals. The lines show power laws, $dn/d\tau \propto \tau^{\gamma}$, with the best-fitting exponents $\gamma$ listed in Table 3. All of these results have been published previously, except for NGC 4214 and M83. For M83, our results here supersede the earlier one by Chandar et al. (2014), because we now use a cluster catalog based on seven pointings with the *Hubble Space Telescope,* rather than just two.
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4.2. Age Distributions

In Figure 3 we show the age distributions of mass-limited samples of star clusters for each galaxy studied here. We have been careful to restrict the age range for each distribution to stay above the luminosity limit of the cluster catalog (which is set mostly by the distance to the galaxy). For NGC 3256, we restrict our age–mass ranges to remain within the completeness limit for the dustier inner portion of the galaxy, as discussed in Muiña et al. (2016).

Each age distribution can be represented by a simple power law, $\chi(\tau) \propto dN/d\tau \propto \tau^\gamma$, as found in previous studies (Fall & Chandar 2012). We list the best-fit exponents $\gamma$ in Table 3. Most of them (but not all) are close to the median value $\gamma = -0.7$. We emphasize that we have derived the exponents $\gamma$ of the age distribution self-consistently from the same data that we have used to derive the fraction of stars in forming and of the age distribution, see especially the discussion of the SMC in the Appendix of Chandar et al. (2010a).

The exponents we have derived for the age distribution in the eight galaxies in our sample are generally in line with those derived in other studies; most lie in the range $-1.0 \lesssim \gamma \lesssim -0.2$ (e.g., Fall et al. 2005; Whitmore et al. 2007; Chandar et al. 2010a, 2014; Silva-Villa & Larsen 2011; Bastian et al. 2012; Messa et al. 2017). The typical value for whole galaxies is $\gamma \approx -0.7 \pm 0.3$ (Fall & Chandar 2012). For M83, our galaxy-wide value of $\gamma \approx -0.4$ agrees nicely with that determined by Silva-Villa et al. (2014) from an independent cluster catalog based on the same observations.

Figure 4. Mass functions of star clusters in our sample galaxies in three age intervals: $\tau < 10$ Myr (circles), $10 < \tau < 100$ Myr (triangles), and $\tau > 100$–400 Myr (squares). The lines show power laws, $dN/dM \propto M^\beta$, with the best-fitting exponents, most of which are close to $\beta = -2.0$.

For M51, our galaxy-wide value of $\gamma \approx -0.65$ is somewhat steeper than but similar to the $\gamma \approx -0.4$ recently found by Messa et al. (2017) from an independent cluster catalog based on different observations (with only ~60% of our coverage) and a different selection method. There is some evidence for regional variations in $\gamma$. In particular, the age distribution in M83 becomes flatter toward the outer parts of the galaxy (Silva-Villa et al. 2014).

The only exception to these results is the claim that the age distribution in M31 is essentially flat (Johnson et al. 2016). We note, however, that the published plots actually show a gradually declining age distribution (see, e.g., Figure 7 in Fouesneau et al. 2014, especially the bottom panel). We have fit a power law, $\chi(\tau) \propto \tau^\gamma$, to the M31 data in Johnson et al. (2016) over the age range $10$ Myr $< \tau < 250$ Myr, and find $\gamma \approx -0.25 \pm 0.1$ for mass ranges above $10^3 M_\odot$. Thus, all galaxies studied so far have declining age distributions, indicating the progressive disruption of their clusters. We recall that even $\gamma = -0.2$ implies a disruption rate of $(1 - 10^{-0.3}) = 37\%$ per decade (factor of 10) in age, while $\gamma = -0.4$, $-0.7$, and $-1.0$ imply disruption rates of 60%, 80%, and 90%, respectively.

4.3. Mass Functions

The CMFs are shown in Figure 4 in each of the three age intervals $<10$ Myr, $10$–100 Myr, and $100$–400 Myr for all of our sample galaxies. Each mass function can be represented by a simple power law, $\psi(M) \propto dN/dM \propto M^\beta$, with no obvious curvature at either the high- or low-mass end. The best-fit

### Table 3

| Galaxy | Mass Interval | $\gamma$ |
|--------|---------------|----------|
| LMC    | 4.0–4.8       | -0.75 ± 0.07 |
| LMC    | 3.4–4.0       | -0.68 ± 0.07 |
| LMC    | 2.8–3.4       | -0.54 ± 0.10 |
| SMC    | 3.5–4.5       | -0.73 ± 0.17 |
| SMC    | 3.0–3.5       | -0.70 ± 0.16 |
| NGC 4214 | > 3.2     | -1.15 ± 0.18 |
| NGC 4214 | 2.8–3.2    | -0.59 ± 0.02 |
| NGC 4449 | 4.3–6.0   | -1.30 ± 0.22 |
| NGC 4449 | 4.0–4.3   | -0.92 ± 0.12 |
| M83    | > 4.0        | -0.37 ± 0.08 |
| M83    | 3.5–4.0      | -0.43 ± 0.17 |
| M51    | 4.5–6.0      | -0.62 ± 0.07 |
| M51    | 4.0–4.5      | -0.64 ± 0.20 |
| M51    | 3.8–4.0      | -0.71 ± 0.03 |
| Antennae | > 5.0    | -1.05 ± 0.11 |
| Antennae | 4.3–5.0   | -1.04 ± 0.30 |
| NGC 3256 | 6.0–6.8   | -0.59 ± 0.17 |
| NGC 3256 | 5.6–6.0   | -0.49 ± 0.10 |

Note.

* Least-squares fits to log $(dN/d\tau) = \gamma \log \tau + \text{const.}$

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4 All of the age distributions we have derived, in this and earlier papers, are for mass-limited subsamples of clusters. These can differ significantly from age distributions derived from luminosity-limited subsamples, as discussed in detail by Chandar et al. (2010b), see especially the discussion of the SMC in the Appendix of Chandar et al. (2010a).
exponents are all close to the median value $\beta = -2.0$. There is little variation in $\beta$ with age interval or from one galaxy to another, again indicating that the mass and age distributions are nearly independent of one another. The lower limit of each mass function $M_{\text{lim}}$ is approximately set by the luminosity limit of the cluster catalog. We have been careful to stay brighter than this limit for each age interval. If incompleteness were a problem, we would expect the observed mass functions to flatten out near $M_{\text{lim}}$, contrary to what Figure 4 shows. We compile values of $M_{\text{lim}}$ in Table 4. The upper end of each mass distribution is not constrained.

5. Correlations between $\Gamma$ and CMF/SFR with Galaxy Properties

An open question in this field is whether the fraction of stars forming in clusters varies with the global $\Sigma_{\text{SFR}}$, SFR, or $\Sigma_{\text{He}}$ of the host galaxy. In this section, we first use the CMFs to determine the fraction of stars in clusters within the $<10$ Myr, $10–100$ Myr, and $100–400$ Myr intervals of age, and then determine whether these fractions vary with any of the galaxy properties discussed above. We also compare with the residuals in the amplitudes of the CMF/SFR distributions, as a check on the results.

5.1. The Fraction of Stars in Forming Clusters

We now estimate the fraction of stars that form in clusters $\Gamma_F$ for each of the galaxies in our sample from Equation (7). We recall that this is the ratio of the masses of newly formed clusters and stars, $\Gamma_F = M_C(<\tau_\text{e})/M_0(<\tau_\text{e})$, in a small age interval $0 < \tau < \tau_\text{e}$ (see Equation (3)). As we noted in Section 2, the choice of $\tau_\text{e}$ is subject to several competing constraints, the most important of which is that all newly formed clusters, whether gravitationally bound or unbound, appear intact and are thus included in cluster catalogs. These constraints lead to $\tau_\text{e} \sim 10^7$ years. In this case, $\Gamma_F$ is not sensitive to the exact choice of $\tau_\text{e}$ because both $M_C(<\tau_\text{e})$ and $M_0(<\tau_\text{e})$ are affected in nearly the same way. We adopt $\tau_\text{e} = 10^7$ years.

Some of the youngest clusters, particularly those less than 1–3 Myr old, are too deeply embedded in dusty natal material to be included in optical samples such as the ones we analyze here. This suggests that the counts of optically detected clusters in the age range $0 < \tau < 10$ Myr should be corrected upward by factors of $\sim 10/9$ to $\sim 10/7$ to account for the undetected clusters. Corrections of this size are consistent with a multwavelength study that found a correspondence of $\sim 85\%$ between optically detected clusters and 6 cm radio sources in the Antennae galaxies (Whitmore & Zhang 2002). With this in mind, we adopt a conservative correction factor for missing clusters of $10/9$. Others in this field have adopted correction factors up to $10/7$ (Goddard et al. 2010). Evidently, this correction, which affects the absolute values of $\Gamma_F$, is uncertain at the factor of 1.15 level. We emphasize, however, that it has no effect on the relative values of $\Gamma_F$ among different galaxies, the main focus of this paper. Our new determinations of $\Gamma_F$ are shown as the blue circles in Figure 5 and compiled in Table 5.

The other main uncertainties in $\Gamma_F$, given the assumptions specified above, come from the observed CMFs and SFRs. Uncertainties in the CMF for most galaxies are dominated by

### Table 4

| Galaxy | $\log M_{\text{lim}}$ (<10 Myr) | $\log M_{\text{lim}}$ (10–100 Myr) | $\log M_{\text{lim}}$ (100–400 Myr) |
|--------|-------------------------------|-----------------------------------|-----------------------------------|
| LMC    | 2.5                           | 3.2                               | 3.25                              |
| SMC    | 2.5                           | 3.2                               | 3.25                              |
| NGC 4214 | 3.4                          | 4.0                               | 4.0                               |
| NGC 4449 | 3.3                          | 3.7                               | 4.0                               |
| M83    | 3.5                           | 3.9                               | 4.0                               |
| Antennae | 4.0                          | 4.25                              | 4.5                               |
| NGC 3256 | 5.2                          | 5.2                               | 5.5                               |

### Table 5

| Galaxy | $\Gamma_F$ (<10 Myr) | $\Gamma_F$ (10, 100 Myr) | $\Gamma_F$ (100, 400 Myr) |
|--------|---------------------|-------------------------|-------------------------|
| LMC    | 27^{+18}_{-9}      | 5^{+1}_{-1}             | 3^{+2}_{-1}             |
| SMC    | 36^{+23}_{-12}     | 3^{+1}_{-1}             | 1^{+1}_{-1}             |
| NGC 4214 | 8^{+5}_{-2}     | 2 ± 1                    | 2 ± 1                    |
| NGC 4449 | 28^{+19}_{-9}    | 3^{+2}_{-1}             | 4^{+2}_{-1}             |
| M83    | 12^{+14}_{-6}      | 10^{+5}_{-4}            | 2 ± 1                    |
| M51    | 30^{+18}_{-10}     | 5^{+1}_{-1}             | 3^{+2}_{-1}             |
| Antennae | 22^{+14}_{-7}    | 6^{+4}_{-3}             | 3^{+2}_{-1}             |
| NGC 3256 | 26^{+17}_{-8}    | 3^{+1}_{-1}             | 1^{+1}_{-1}             |

Mean, $\sigma$ 24 ± 9  4.6 ± 2.5  2.4 ± 1.1

### Figure 5

Some of the main results of this work: our new determinations of $\Gamma_F$ (blue circles) for eight galaxies show that $\sim 24\%$ of stars form in clusters, and that this fraction does not vary systematically with $\Sigma_{\text{SFR}}$ of the host galaxy (the best fit is shown as the gray line). Our calculations for $\Gamma_F$(10, 100) (green squares) and $\Gamma_F$(100, 400) (red triangles) are also plotted for the same galaxies, and show that there is a systematic decrease in the fraction of stars in surviving clusters with increasing age, a reflection of cluster disruption. The color bar on the left shows that the predicted decrease from a $\gamma = -0.7$ disruption model, starting at $\Gamma = 24\%$ (the mean $\Gamma_F$ value determined for this sample), provides a good match to our observational results.
selection, particularly for \( \tau \lesssim 10 \) Myr clusters, where catalogs from different groups are known to vary the most, due to crowding and other factors (e.g., Bastian et al. 2012; Chandar et al. 2014). CFW15 quantified the uncertainties in the CMF at different ages and found that the selection of clusters can affect the amplitude of observed mass functions in this age range at the \( \approx 10\% \) level (but only at the \( \approx 4\% \) level at older ages); we therefore assume that the estimates of the total mass in clusters are uncertain at this level, except for the LMC and SMC, the two galaxies with the lowest SFR and \( \Sigma_{\text{SFR}} \) in our sample, where we include an additional 20\% uncertainty to account for stochastic sampling of the mass function based on Monte Carlo simulations. CFW15 also included a detailed discussion and estimates of the different sources of uncertainty in the SFR determinations, which were summarized in their Table 2. The SFR estimate for each galaxy was found to be uncertain by \( \approx 50\% \), based on a comparison with previous H\( \alpha \)-based determinations. We adopt this level of uncertainty here when estimating the errors in \( \Gamma \). We do not, however, account for any systematic uncertainty in the SFR calibration, which may be overestimated for lower metallicity populations because the ionizing luminosity increases by \( \approx 0.4 \pm 0.1 \) dex for a tenfold decrease in the metallicity (see Kennicutt & Evans 2012 and references therein). We recalculate \( \Gamma_f \) using CMFs and SFRs that vary by the uncertainties discussed above, and take the minimum and maximum values as the most likely range of \( \Gamma_f \). Including all possible systematics and assumptions, we estimate that the final values of \( \Gamma_f \) are uncertain by no more than a factor of \( \approx 1.7 \).

5.2. The Fraction of Stars in Surviving Clusters

For the same galaxies, we also calculate and plot the fraction of stars found in surviving clusters, \( \Gamma_3(10, 100) \) and \( \Gamma_3(100, 400) \). For these calculations, we assume the same H\( \alpha \)-based SFRs as used for \( \Gamma_f \), i.e., we assume a constant rate of star formation, since we found in the previous section that this is a reasonable assumption for the galaxies studied here. We find mean values and standard deviations of \( \Gamma_f \approx \Gamma_3(10, 10) \approx 24 \pm 9\% \), \( \Gamma_3(10, 100) \approx 4.6\% \pm 2.5\% \), and \( \Gamma_3(100, 400) \approx 2.4\% \pm 1.1\% \). The results for \( \Gamma_3(10, 100) \) and \( \Gamma_3(100, 400) \) do not change significantly if we adopt FUV- or IR-based SFRs instead (see Section 4.1.1).

In Figure 5 we see that the decline from \( \Gamma_3(10, 100) \) to \( \Gamma_3(100, 400) \) is smaller than the decline from \( \Gamma_f = \Gamma_3(0, 10) \) to \( \Gamma_3(10, 100) \). Nevertheless, both declines are statistically significant because they occur for every galaxy in our sample (with the exception of NGC 4449) from \( \Gamma_3(10, 100) \) to \( \Gamma_3(100, 400) \). This decrease in the fraction of stars found in clusters is consistent with the observed decline in the cluster age distributions out to these ages. The smaller decline from \( \Gamma_3(10, 100) \) to \( \Gamma_3(100, 400) \) than from \( \Gamma_3(0, 10) \) to \( \Gamma_3(10, 100) \) reflects the differences in the age intervals, a factor of 3 in the first case and a factor of 9 in the second.

We now compare the predicted and observed ratios \( \Gamma_f/\Gamma_3(10, 100) \) and \( \Gamma_f/\Gamma_3(100, 400) \). The median exponent of the age distribution from Table 3 is \( \gamma = -0.7 \). As discussed in Section 2, for \( \gamma = -0.7 \), the predictions for \( \Gamma_f/\Gamma_3(10, 100) \) are \( \approx 9 \) for model 1 and \( \approx 3 \) for model 2. The median values of \( \Gamma_f \approx 27\% \) and \( \Gamma_3(10, 100) \approx 5\% \) for the eight galaxies in our sample from Table 5 gives \( \Gamma_f/\Gamma_3(10, 100) \approx 5 \), comfortably within the range of predictions from models 1 and 2. Interestingly, our results, which have been derived using a homogeneous procedure, are quite similar to the median \( \Gamma \) values plotted in Figure 1, which were derived from heterogeneous procedures. This suggests that the age interval used to determine \( \Gamma \) has a stronger impact on the results than other assumptions (for example, the exact value of \( M_{\text{min}} \)), whether the assumed shape of the mass function is a power law or Schechter function, etc.). The predictions for \( \Gamma_f/\Gamma_3(100, 400) \) for \( \gamma = -0.7 \) are \( \approx 29 \) for model 1 and \( \approx 8.5 \) for model 2. The ratio of the median \( \Gamma_f \) to median \( \Gamma_3 \) for our galaxies is \( \Gamma_f/\Gamma_3(100, 400) \approx 27/3 \approx 9 \), again within the range spanned by the predictions from the models. We also find rough agreement between the observed ratios \( \Gamma_f/\Gamma_3(10, 100) \) and \( \Gamma_f/\Gamma_3(100, 400) \) and the predicted ranges from models 1 and 2 for most individual galaxies in our sample, after taking into account the uncertainties on the exponent \( \gamma \).

5.3. Do \( \Gamma_f \) or \( \Gamma_3 \) Correlate with Galaxy Properties?

Figure 5 shows some of the main results of this work. The blue circles show our new determinations of \( \Gamma_f \) plotted against \( \Sigma_{\text{SFR}} \) of the host galaxy. The best fit (shown as the gray line) is flat, and it indicates that there is no significant trend in the fraction of stars in forming clusters across galaxies with increasing \( \Sigma_{\text{SFR}} \). The lower two gray lines, which connect the green and red points, show that there is no significant trend in the fraction of stars in surviving clusters across galaxies with increasing \( \Sigma_{\text{SFR}} \). The dotted lines connecting the blue, green, and red points for each galaxy highlight another important result: the fraction of stars in clusters depends strongly on the age interval that is used. The systematic decrease in this fraction with increasing age is a natural consequence of the declining age distributions observed for these galaxies, which in turn reflects the disruption of clusters. These average observational results are similar to predictions from the simple disruption models discussed at the end of Section 2. The labeled color bar on the left side of Figure 5 shows the good agreement between our observations and these predictions.

In the left panel of Figure 6, we show that our new results differ from the relationship found by Goddard et al. (2010) as the dashed line, where \( \Gamma \) increases approximately linearly by a factor of \( \approx 10 \) over the range covered by our data. One key difference is that our work compares results made from the same age intervals in different galaxies. Our study presents the first determination of \( \Gamma \) made using clusters younger than 10 Myr in galaxies with low \( \Sigma_{\text{SFR}} \ll 0.003 \) (i.e., the LMC and SMC, since Goddard et al. 2010 published values for \( \Gamma_3(10, 100) \) rather than \( \Gamma_3(0, 10) \)). We further discuss the reasons for the discrepancy between our new results for \( \Gamma \) and the previous results in Section 6.

The middle panel of Figure 6 plots \( \Gamma \) versus SFR. The blue points and best-fit line again show no statistically significant correlation, indicating that \( \Gamma_f \) does not increase systematically with the overall SFR (as determined from H\( \alpha \)) of the host galaxy for our sample. The blue circles in the right panel of Figure 6 show that there is also no statistically significant trend between \( \Gamma_f \) and \( \Sigma_{\text{H}2} \). We conclude that our sample does not reveal any trends in the fraction of stars that form in clusters (bound or unbound), with \( \Sigma_{\text{SFR}}, \text{SFR}, \) or \( \Sigma_{\text{H}2} \) in the host galaxy, over a fairly large range of these properties.

Next, we compare the results from older surviving (and hence bound) clusters, \( \Gamma_3(10, 100) \) (green squares) and \( \Gamma_3(100, 400) \) (red triangles), which encode information about
their formation plus disruption rates, with $\Sigma_{\text{SFR}}$ (left panel), SFR (middle), and $\Sigma_{\text{H}_2}$ (right). Our study presents the first determinations of $\Gamma_{\text{S}}(10, 100)$ and $\Gamma_{\text{S}}(100, 400)$ in galaxies with high $\Sigma_{\text{SFR}} \gtrsim 0.03$ (i.e., the Antennae and NGC 3256), since Goddard et al. (2010) and Mulia et al. (2016) published values for $\Gamma_{\text{S}}(0, 10)$ rather than $\Gamma_{\text{S}}(10, 100)$ in NGC 3256.

We find no statistically significant correlation for any of the fits in Figure 6. $\Gamma_{\text{S}}(10, 100)$ shows a very weak ($\approx 2\sigma$) trend with $\Sigma_{\text{H}_2}$, but not with $\Sigma_{\text{SFR}}$ or SFR. If instead we use CMD-based SFRs for the four closest galaxies and the FUV-based ones for the four more distant ones, even this weak trend disappears. Values of $\Gamma_{\text{S}}(100, 400)$ also show no statistically significant correlation with any galaxy property, regardless of whether we adopt the Ho$^\ast$- or CMD-based SFRs for the four closest galaxies and IR-based SFRs for the four more distant ones. Taken together, our results for $\Gamma_{\text{S}}$ and $\Gamma_{\text{S}}$ suggest that not only is there no systematic variation in the fraction of stars forming in clusters across galaxies with a large range in $\Sigma_{\text{SFR}}$, $\Sigma_{\text{H}_2}$, or $\Sigma_{\text{SFR}}$, there is also no significant systematic variation in the fraction of stars in surviving clusters, even though these fractions are strongly affected by the disruption of the clusters. These results are consistent with our proposal that both the formation and disruption of clusters are governed by quasi-universal processes.

5.4. Do Residuals in the CMF/SFR Amplitude Correlate with Galaxy Properties?

We recently developed a new method, which we call CMF/SFR, to compare the formation rates of stars and clusters (CFW15). In this method, we compare the mass functions, $\psi(M) = dN/dM$, of recently formed clusters in different galaxies, before and after dividing by the SFRs, and use this as a check on our new results for $\Gamma_{\text{S}}$. The top left panel of Figure 7 shows the observed CMFs for very young clusters ($\tau < 10$ Myr) for the eight galaxies considered in this work. The amplitudes of the CMFs reflect differences in the sizes of the cluster populations among the galaxies and span a vertical range of $\approx 10^2$. The observed mass functions can be represented by featureless power laws, $dN/dM \propto M^\beta$, with $\beta \approx -1.9$, but each with a different normalization. Some works have suggested that there is an exponential steepening at the upper end of the mass function for $M \geq M_C$, where $M_C$ varies between a few $\times 10^4 M_\odot$ and $\approx 10^6 M_\odot$ depending on the type of galaxy (e.g., Portegies Zwart et al. 2010). However, these claims are based on the absence of just a handful of clusters relative to an extrapolated power law, and are not statistically significant. There is no evidence for a cutoff or steepening in the mass functions.
presented here. The top right panel in Figure 7 shows the CMF/SFR distributions with Hα-based SFRs. These all lie very close to one another in the vertical direction.

We apply the technique developed in CFW15 to quantify the observed scatter by fitting the CMF for each galaxy in the form
\[ dN/dM = A \times \text{SFR} \times (M/10^4 M_\odot)^{-1.9}. \]
These fits are shown as the solid lines in the panels on the right in Figure 7. The coefficient \( A \) measures the proportionality between the number of clusters and the SFRs. The dispersion \( \sigma(\log A) \) in the best-fit values of \( \log A \) quantifies the scatter in the amplitudes and hence in the CMF/SFR relation among the galaxies. If the amplitudes of the CMFs were exactly proportional to the SFRs in their host galaxies, then the distributions in the top right panel (for \( \tau < 10 \) Myr clusters) would all lie on top of one another, forming a single sequence. This is very nearly what we find, with a scatter of only \( \sigma(\log A) = 0.23 \), similar to the dispersion expected from errors in the CMFs and SFRs.

Although to first order the CMF/SFR distributions have very similar amplitudes, it is conceivable that there are weak correlations with properties of the host galaxy. In Figure 8 we present the residuals in the amplitudes \( \log A \) versus \( \Sigma_{\text{SFR}}, \text{SFR}, \) and \( \Sigma_{\text{H}_2} \) of the host galaxy. If the formation of the clusters were only proportional to the SFR of the host galaxy, then we would not expect to observe any trends in these diagrams. If, on the other hand, the fraction of stars born in clusters were to increase with \( \Sigma_{\text{SFR}}, \text{SFR}, \) or \( \Sigma_{\text{H}_2} \), this would manifest itself as a statistically significant increase in the residuals of \( \log A \) with these parameters. Figure 8 does not reveal any statistically significant trends in the residuals of the CMF/SFR amplitudes for \( \tau < 10 \) years clusters (blue circles) with any of these galactic properties. This is consistent with and supports our new results for \( \Gamma_F \).

We can use older surviving clusters to test the similarity of the formation plus disruption rates in our galaxies by comparing the functions \( \bar{\psi}(M|\tau_1, \tau_2)/\text{SFR} \). The middle and bottom right panels in Figure 7 show that these distributions for \( 10–100 \) Myr and \( 100–400 \) Myr clusters also lie very close to one another, with dispersions \( \sigma(\log A) = 0.27 \) and \( 0.24 \), respectively, when we use the Hα-based SFRs. The dispersions are similar if we use the same combinations of CMD, FUV, and IR-based SFRs as in Section 5.3.

Figure 8 shows residuals in the \( \bar{\psi}(M|\tau_1, \tau_2)/\text{SFR} \) amplitudes with galaxy properties as the green squares (10–100 Myr) and red triangles (100–400 Myr). This plot does not reveal any statistically significant increasing trends in the residuals of the CMF/SFR amplitudes for these older clusters with \( \Sigma_{\text{SFR}}, \text{SFR}, \) or \( \Sigma_{\text{H}_2} \). In fact, the only weak (<3σ) trends (for \( \Sigma_{\text{SFR}} \) for 10–100 Myr and 100–400 Myr clusters) are decreasing. The results are similar if we use the CMD, FUV, and IR-based SFRs. Overall, we find that these trends are consistent with the estimated observational uncertainties alone. We conclude that the CMF/SFR method gives results that are consistent with those found for \( \Gamma_F \) and \( \Gamma_3 \).

6. Comparison with Previous Results

6.1. Observational Results

In the previous section, we found that the two different (but related) methods, \( \Gamma \) and CMF/SFR, give consistent results for the galaxies in our sample and that neither method reveals a significant trend for the proportion of star formation in clusters with \( \Sigma_{\text{SFR}}, \text{SFR}, \) or \( \Sigma_{\text{H}_2} \) among different galaxies.

Our new results for \( \Gamma \) appear to contradict previously published ones, which have reported a strong correlation on galaxy scales between \( \Gamma \) and \( \Sigma_{\text{SFR}} \) and between \( \Gamma \) and \( \Sigma_{\text{H}_2} \) (e.g., Goddard et al. 2010; Kruisjes 2012; Adamo et al. 2015; Johnson et al. 2016; Kruisjes & Bastian 2016). However, we find that our results for \( \Gamma \) actually agree fairly well with previously published values when the same set of assumptions is used, in particular, the same interval of age. We also find that the specific catalog or method used to select the clusters does not have much affect on the results. For the LMC and SMC, we find \( \Gamma_3(10, 100) \) values of 5% and 3%, respectively, from our mass and age estimates, and 7% and 5% from the Hunter et al. (2003) mass and age estimates. These are quite similar to the \( \Gamma_3(10, 100) \) values of 5.8% ± 0.5% and 4.2±1.9% found for the LMC and SMC by Goddard et al. (2010) using the same cluster catalogs. For M83, we apply our method to the independent catalog published by Silva-Villa et al. (2014) and

\footnote{The results for NGC 3256 are the least certain because it is the most distant galaxy in our sample. However, we do not find any statistically significant correlations among any of the parameters plotted in Figure 8 when we remove NGC 3256 from our fits.}
Table 6

Previous Determinations and Assumptions for $\Gamma_c$ and $\Gamma_2$

| Galaxy       | Distance (Mpc) | $\Gamma_2$ or $\Gamma_3$ | $\Sigma_{\text{SFR}}$ ($M_\odot$ yr$^{-1}$ kpc$^{-2}$) | Age Range (Myr) | $M_{\text{min}}$ ($M_\odot$) | CMF Shape | Spherically Symmetric? | Reference |
|--------------|----------------|--------------------------|------------------------------------------------|-----------------|--------------------------|-----------|------------------------|-----------|
| LMC          | 0.05           | 5.8 ± 0.5                | 1.52 ± 10$^{-3}$                                  | 10–100         | 100                      | Power law | No                     | (1)       |
| SMC          | 0.06           | 4.2 ± 0.03               | 6.83 ± 10$^{-4}$                                  | 10–100         | 100                      | Power law | No                     | (1)       |
| M31          | 0.7            | 5.9 ± 0.3                | 2.34 ± 10$^{-3}$                                  | 10–100         | 100                      | Schechter | No                     | (2)       |
| IC10         | 0.7            | 4.2                      | 0.03                                               | 1–10           | 100                      | Power law | Yes                    | (3)       |
| NGC 1569     | 2.2            | 13.9 ± 0.8               | 2.8 ± 10$^{-2}$                                   | 1–10           | 100                      | Power law | No                     | (1)       |
| NGC 7793     | 3.3            | 2.5 ± 0.3                | 6.43 ± 10$^{-3}$                                  | 10–100         | 10                       | Schechter | No                     | (4)       |
| NGC 4449     | 3.8            | 9                       | 0.04                                               | 1–10           | 100                      | Power law | No                     | (5)       |
| NGC 4395     | 4.2            | 1.0 ± 0.6                | 4.66 ± 10$^{-3}$                                  | 10–100         | 300                      | Schechter | No                     | (4)       |
| NGC 1313     | 4.4            | 3.2 ± 0.2                | 1.13 ± 10$^{-2}$                                  | 10–100         | 10                       | Schechter | No                     | (4)       |
| M83          | 4.5            | 18.2 ± 3.0               | 1.3 ± 10$^{-2}$                                   | 1–10           | 100                      | Power law | Yes                    | (6)       |
| NGC 45       | 4.8            | 5.2 ± 0.3                | 1.01 ± 10$^{-3}$                                  | 10–100         | 10                       | Schechter | No                     | (4)       |
| NGC 6946     | 5.5            | 12.5 ± 1.3               | 4.6 ± 10$^{-3}$                                   | 1–10           | 100                      | Power law | No                     | (1)       |
| NGC 2997     | 9.6            | 10.0 ± 2.6               | 9.4 ± 10$^{-3}$                                   | 1–10           | 100                      | Power law | Yes                    | (7)       |
| NGC 3256     | 36.0           | 22.9 ± 3.8               | 0.62                                               | 1–10           | 100                      | Power law | No                     | (1)       |
| ESO 338-IG04 | 37.5           | 50.0 ± 10.0              | 1.55                                               | 1–10           | 100                      | Power law | No                     | (8)       |
| SBS 0335-052E| 54.0           | 49.0 ± 15.0              | 0.95                                               | 1–10           | 100                      | Power law | No                     | (8)       |
| Mrk 930      | 71.4           | 25.0 ± 10.0              | 0.59                                               | 1–10           | 100                      | Power law | No                     | (8)       |
| ESO 185-IG13 | 76.3           | 26.0 ± 5.0               | 0.52                                               | 1–10           | 100                      | Power law | No                     | (8)       |
| Haro 11      | 82.3           | 50.0 ± 10.0              | 2.16                                               | 1–10           | 100                      | Power law | No                     | (8)       |

References. (1) Goddard et al. (2010); (2) Johnson et al. (2016); (3) Lim & Lee (2015); (4) Silva-Villa & Larsen (2011); (5) Annibali et al. (2011); (6) Adamo et al. (2015); (7) Ryon et al. (2014); (8) Adamo et al. (2011).

We find $\Gamma_2(0, 10) = 17\%$, $\Gamma_3(10, 100) = 13\%$, and $\Gamma_3(100, 400) = 4\%$. These are roughly similar to the values of 12\%, 10\%, and 2\% determined in Section 5 from our own M83 cluster catalog, and also to the value $\Gamma_3(0, 10) = 18\%$ determined by Adamo et al. (2015) from the Silva-Villa catalog with similar assumptions. This comparison of $\Gamma$ results for M83 between different works is particularly revealing because Silva-Villa et al. (2014) applied different criteria to select clusters, requiring that they be found, in an attempt to select only bound clusters, while we did not. These results suggest that $\Gamma$ may not be particularly sensitive to the details of cluster selection.6

Why have previous works (e.g., Goddard et al. 2010; Kruisjzen 2012; Adamo et al. 2015) found a different result, one where $\Gamma$ varies strongly with $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{H}_\odot}$? While earlier studies also integrated over the CMF, as we have done here, they made a variety of different assumptions for different parameters when calculating $\Gamma$, most importantly, the age interval (shown in Figure 1), the lower mass cutoff $M_{\text{min}}$, and the assumed shape of the CMF (among others). In Table 6 we list previously published values for the fraction of stars found in clusters in 19 galaxies, taken from the recent compilation by Adamo et al. (2015), plus the newly published result for M31 from the PHAT team (Johnson et al. 2016). We also list the assumptions used in each case, taken from the original work. There is a large range, from just 1\%–3\% for some galaxies all the way up to 50\% for others.

Figure 1 reveals a simple bias that has propagated through the literature, leading to an apparent strong trend between $\Gamma$ and $\Sigma_{\text{SFR}}$. We now examine this diagram in more detail. This figure plots previously published values, as compiled in Table 6, but color-coded by the age interval that was used. There is a striking trend: the $\Gamma_3(0, 10) \approx 10^2$ values (determined from very young $\tau < 10$ Myr clusters) shown in blue are systematically higher than the $\Gamma_3(10, 100)$ values shown in green, and previous works have preferentially determined $\Gamma_3(10, 100)$ for galaxies with lower $\Sigma_{\text{SFR}}$ but $\Gamma_3(0, 10)$ for galaxies with higher values of $\Sigma_{\text{SFR}}$, and then plotted $\Gamma_3(0, 10)$ and $\Gamma_3(10, 100)$ values all together. It is easy to understand why these choices might have been made. Galaxies with high $\Sigma_{\text{SFR}}$ tend to be farther away, and hence samples are usually restricted to the brightest clusters, which tend to be young. Meanwhile, galaxies with low $\Sigma_{\text{SFR}}$ tend to have relatively few very young clusters. Unfortunately, these choices have led to systematic biases that are (mostly) responsible for the strong trend that has been claimed in many previous works. In contrast, by determining $\Gamma_3(0, 10)$, $\Gamma_3(10, 100)$, and $\Gamma_3(100, 400)$ for all eight galaxies in our sample, we have been able to compare results determined from the same age range among the different galaxies.

Table 6 demonstrates that even beyond the choice of an appropriate age interval, a variety of different assumptions have been made for $\Gamma_c$ calculations in different galaxies. While most works have assumed a minimum cluster mass $M_{\text{min}} = 100 M_\odot$, different values have been assumed for a few of the galaxies. Some works have assumed that the CMF is a pure power law, while others have assumed that it has a Schechter-like downturn at the high-mass end, which can introduce differences in $\Gamma$ at the $\approx 10\%$ level, depending on the adopted $M_c$ value. In future studies, it is critical that authors compare $\Gamma$ values (and CMF/SFR statistic) among galaxies determined from a consistent set of assumptions, as we have done here. We recommend that the interval $\tau \lesssim 10^7$ years be used to calculate $\Gamma_c$ when one is interested in the fraction of stars in forming clusters (bound and unbound), but note that older intervals of age can be used to calculate $\Gamma_3$, the fraction of stars in surviving clusters at later times. Regardless, the same age interval should be used to calculate the fraction of stars in clusters when comparing results among different galaxies.

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6 The selection of clusters in only 3 out of the 19 previously studied galaxies compiled in Table 6 (M83, IC10, and NGC 2997) attempted to discern whether they were bound based solely on their appearance.
At this point, it is instructive to look in more detail at a specific galaxy with a well-studied cluster population. The LMC has formed many massive, young compact clusters, including the well-known R136 in the 30 Doradus nebula ($M \approx 10^5 M_\odot$), and others such as H88-267, H88-301, KMK88-88, NGC 2080, BSDL2596, NGC 2074, and SL360 ($M \approx 10^4 M_\odot$). Well over 100 other very young clusters are known throughout the LMC. In Figure 9 we show a small, approximately 1 × 2 kpc portion of the LMC imaged in Hα, covering the Southern Molecular Ridge (e.g., Indebetouw et al. 2008). R136 and several other clusters clearly have Hα emission, as expected for clusters younger than $\tau \approx 10$ Myr, a good check on the age estimates for clusters in the LMC. These young star-forming regions continue along the ridge to the south well beyond this image. We find a total mass of $\approx 3.55 \times 10^5 M_\odot$ for clusters with estimated ages $\tau \lesssim 10$ Myr and masses down to $M_{\text{lim}} = 10^3 M_\odot$ from our age–mass estimates and those determined independently by Hunter et al. (2003) for their LMC catalog. The LMC has a current SFR of 0.25 $M_\odot$ yr$^{-1}$ (see Table 1), which implies a total stellar mass $\tau_0 \times \text{SFR} = 2.25 \times 10^6 M_\odot$ formed over the last $\tau_0 = 10$ Myr. The observed clusters more massive than $M_{\text{lim}} = 10^3 M_\odot$ contain $\approx 16\%$ of this mass ($3.55 \times 10^5/2.25 \times 10^6$). The correction for clusters with masses between $M_{\text{lim}}$ and $M_{\text{min}} = 10^2 M_\odot$ and for very young, highly obscured clusters ($\approx 10/9$; see the discussion in Section 5.1) brings the estimated fraction of stars formed in clusters to $\approx 27\%$. Interestingly, the single most massive young cluster in the LMC, R136, alone accounts for $\approx 4\%$ of the stellar mass formed in this period ($10^5/2.25 \times 10^6$).

Our value of 27% is approximately five times higher than the value previously published by Goddard et al. (2010) because they calculated $\Gamma_\tau(10, 100)$ rather than $\Gamma_F$. Hence, using the same $\tau < 10$ Myr interval for both the LMC and the galaxies with high $\Sigma_{\text{SFR}}$ and SFR gives essentially the same $\Gamma_F$ values: $\approx 27\%$ for the LMC and $\approx 26\%$ for the average of the three galaxies in our sample with the highest $\Sigma_{\text{SFR}}$.

### 6.2. Theoretical Predictions

Our observational results present a challenge to theoretical models of the formation and early evolution of star clusters. In particular, Kroupijsen (2012) predicts that the fraction of stars that form in bound clusters has a strong dependence on $\Sigma_{\text{SFR}}$, shown by the dotted line in Figures 1 and 6. Instead, we find that the fraction of stars in clusters of different ages, measured by $\Gamma_\tau$, $\Gamma_\tau(10, 100)$, and $\Gamma_\tau(100, 400)$, has essentially no dependence on their galaxy-wide stellar and interstellar environments, as measured by SFR, $\Sigma_{\text{SFR}}$, and $\Sigma_{\text{HI}}$.

Based on $\Gamma_\tau$ alone, this test is inconclusive because it includes an unknown mixture of bound and unbound clusters younger than $\approx 10^7$ years ($\approx 10$ crossing times) (Kroupijsen & Bastian 2016). Up to this age, both bound and unbound clusters remain relatively compact and virtually impossible to distinguish from each other, as demonstrated by N-body simulations (Baumgardt & Kroupa 2007). However, after $\approx 10^7$ years, only bound clusters remain compact, while unbound clusters expand and dissolve in the surrounding stellar field. Thus, $\Gamma_\tau(10, 100)$ and $\Gamma_\tau(100, 400)$ represent the fraction of stars that form in bound clusters that survive to ages 10–100 Myr and 100–400 Myr ($\approx 10$–100 and 100–400 crossing times), respectively. Since the survival probabilities of clusters (determined by the shapes of their age distributions) are similar among different galaxies, we conclude that the fraction of stars that form in bound clusters is also similar, in contradiction with the Kroupijsen (2012) model.

On the other hand, the near constancy of $\Gamma_\tau$, $\Gamma_\tau(10, 100)$, and $\Gamma_\tau(100, 400)$ is fully consistent with, and even expected for, the quasi-universal model. In this model, the formation and disruption of clusters depend mainly on local processes in the interstellar medium, and these are assumed to operate in much the same way from one galaxy to another. Thus, the cluster...
formation rate is simply a constant $\Gamma_F$ times the SFR. Similarly, the (fractional) disruption rate of clusters is also nearly constant, leading to the near constancy of $\Gamma_S(10, 100)$ and $\Gamma_S(100, 400)$.

7. Discussion

We have used two different techniques, $\Gamma_F$ and CMF/SFR, to study the relationship between star and cluster formation in eight galaxies with a large range of star formation and gas properties. We find that when applied consistently among galaxies, both techniques give similar results.

To first order, we find that star and cluster formation rates are proportional to one another, with a similar $\Gamma_F \approx 24\% \pm 9\%$ fraction of stars forming in compact clusters in galaxies that cover a large range in $\Sigma_{\text{SFR}}$, SFR, and $\Sigma_{\text{H}_2}$. Neither technique supports the strong correlations found in previous works, which appear to be the result of systematic biases. However, with only eight galaxies in our sample, we cannot rule out that undetected weak trends may be present. A similar study, but with a larger sample of galaxies, is needed to detect and quantify any such trends.

We also find that the fraction of stars in surviving clusters, quantified here by $\Gamma_S(10, 100)$ and $\Gamma_S(100, 400)$, declines rapidly with age. Based on the work and conclusions presented in Sections 5.3 and 5.4, this effect is much too strong to be explained by variations in the SFRs in our galaxies, and instead must reflect the disruption of the clusters. This conclusion is not surprising, given the declining shapes of the cluster age distributions shown in Figure 3.

Johnson et al. (2016) found a modest increase in $\Gamma_S(10, 100)$ (from $\approx 4\%$ to $\approx 8\%$) with $\Sigma_{\text{SFR}}$ in the range between 0.0005 and 0.003 M$_\odot$ yr$^{-1}$ kpc$^{-2}$ in eight regions within M31 from the PHAT survey (Dalcanton et al. 2012; Williams et al. 2014). It seems quite plausible that there are variations in $\Gamma_S(10, 100)$ (as well as in $\Gamma_S(0, 10)$ and $\Gamma_S(100, 400)$) on the smaller physical scales studied by Johnson et al. (2016) because similar variations have been found for the cluster age and mass distributions in kpc-scale regions of other galaxies (e.g., Chandar et al. 2014; Adamo et al. 2015). We note that while the results for $\Gamma$ presented in Johnson et al. (2016) for M31 are based on homogeneous procedures, their compilation of results for other galaxies suffers from the same selection bias and heterogeneous procedures shown here in Figure 1.

The observed shapes of the CMFs provide additional constraints on disruption processes. The older mass functions plotted in Figures 4 and 7 do not show any significant flattening at the low-mass end, as would be expected if lower mass clusters were disrupted earlier than higher mass clusters (e.g., Fall et al. 2009). Therefore, the disruption rates of clusters must be approximately independent of their masses, at least over the mass-age ranges studied here. Fall & Chandar (2012) review the primary disruption mechanisms for star clusters and explain why their rates are independent of mass, or nearly so.

One of the mechanisms that can disrupt star clusters is tidal interactions with passing giant molecular clouds (GMCs; Spitzer 1958; Binney & Tremaine 2008). In this context, it may seem puzzling that the values of $\Gamma_S(10, 100)$ and $\Gamma_S(100, 400)$ show little or no dependence on the surface density of molecular gas $\Sigma_{\text{H}_2}$. There are two possible reasons for this. First, in our sample of eight galaxies, $\Sigma_{\text{H}_2}$ varies by only a factor of $\sim 10$, thus making any trend difficult to detect. Second, the characteristic timescale $\tau_d$ for disruption by this mechanism may be too long to show up in the age intervals examined here, $\tau < 4 \times 10^8$ years. For clusters in the solar neighborhood, the disruption timescale is $\tau_d \approx 3 \times 10^8$ years, with uncertainties of at least a factor of 2 (Binney & Tremaine 2008). For clusters in other galaxies, the uncertainties are much greater because $\tau_d$ depends in general on the characteristic internal densities of the clusters $\rho_h$ and the mass spectrum, mass–radius relation, number density, and velocity dispersion of the GMCs. Unfortunately, we do not have reliable estimates of most of these quantities outside the Milky Way. In a particular limit, the catastrophic regime, $\tau_d$ depends only on $\rho_h$ and $\Sigma_{\text{H}_2}$; but in order to determine whether this case is applicable, rather than the opposite limit, the diffusive regime, one must know the values of all the other quantities listed above (see Binney & Tremaine 2008 for a clear and thorough analysis). Thus, we simply do not have enough information about the properties of clusters and GMCs in other galaxies to estimate $\tau_d$ reliably.

Our new results for $\Gamma$ and CMF/SFR support the quasi-universal model (e.g., Whitmore et al. 2007; Fall & Chandar 2012; Chandar et al. 2014, CFW15), which postulates that clusters in different galaxies form and disrupt in similar ways, with relatively minor variations within and among galaxies. The “initial” mass functions of young ($\tau \lesssim 10$ Myr) star clusters have a nearly universal power-law shape, $dN/dM \propto M^\beta$, with $\beta \approx -2$ (see Figure 1 of Fall & Chandar 2012 and Figure 4 here). Here, we have shown that the normalization of this power law is set by the overall SFR of the host galaxy, with a similar $\approx 24\%$ of stars forming in compact clusters in different galaxies. Because the shapes of the mass functions do not change much with age, the disruption of the clusters must be roughly independent of their initial masses (e.g., Fall et al. 2005 Chandar et al. 2010a, 2010b, 2010c; Fall & Chandar 2012). The rapid decline in the age distributions, $dN/d\tau \propto \tau^\gamma$ with $\gamma \approx -0.7$ for $\tau \gtrsim 10$ Myr, the signature of this disruption, is also reflected in the differences we find between $\Gamma_F$ and $\Gamma_S(10, 100)$ and $\Gamma_S(100, 400)$. The joint distribution of masses and ages for the quasi-universal model for cluster formation and disruption can then be written in compact form as $g(M, \tau) = c \times \text{SFR} \times M^{\beta/2}$, with $c \approx 0.24$, $\beta \approx -2$, and $\gamma \approx -0.7$. This appears to apply, at least approximately, to the cluster populations in star-forming galaxies over a wide range of conditions. We do expect small, second-order regional variations in the properties of the clusters within galaxies, but larger, uniform cluster samples will be needed in order to detect these.

8. Summary

In this work, we compiled catalogs of star clusters in eight different galaxies (the LMC, SMC, NGC 4214, NGC 4449, M83, M51, the Antennae, and NGC 3256), which includes irregulars, dwarf starbursts, spirals, and mergers that span a fairly broad range in star-forming properties. For these eight galaxies, we measured consistently the fraction of stars that form in compact clusters, $\Gamma_F$, and the fraction of stars in clusters that survive to older ages, $\Gamma_S(\tau_1, \tau_2)$. We also compared the mass functions of the clusters, before and after dividing by the SFRs (the CMF/SFR method), as a check on our new results for $\Gamma_F$ and $\Gamma_S$. The main conclusions of this paper are the following:
1. The typical fraction of stars that form in compact clusters, bound and unbound, is $\Gamma_F \approx \Gamma_S(0, 10) \approx 24\% \pm 9\%$, for galaxies in our sample. This is confirmed by a more detailed study of clusters in the LMC. We estimate that this result is uncertain by no more than a factor of $\approx 1.7$.

2. The fraction of stars in surviving clusters declines with age: $\Gamma_S(10, 100) = 4.6\% \pm 2.5\%$ and $\Gamma_S(100, 400) = 2.4\% \pm 1.1\%$. These values support a picture in which $\approx 70\%$–$80\%$ of the clusters disrupt in each decade in age, with similar results among different galaxies.

3. Our new results for $\Gamma_F$ and $\Gamma_S$ are similar to those from the CMF/SFR method. Neither method shows any significant dependence on $\Sigma_{SFR}$, SFR, or $\Sigma_{HI}$ of the host galaxy. This appears to contradict previously published results, which have claimed a strong increase in $\Gamma_F$ with $\Sigma_{SFR}$ and $\Sigma_{HI}$. However, the previous results were biased in such a way that older (younger) clusters were used to calculate $\Gamma_S$ ($\Gamma_F$) in galaxies with lower (higher) $\Sigma_{SFR}$, which then resulted in the apparent trends.

4. An important conclusion from this paper is that future studies that compare cluster populations among different galaxies should adopt a consistent set of assumptions and procedures.

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