On the fraction of star clusters surviving the embedded phase

Q. E. Goddard,* N. Bastian and R. C. Kennicutt
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA

Accepted 2010 February 10. Received 2010 February 10; in original form 2009 September 16

ABSTRACT
In this paper we derive ages and masses for 276 clusters in the merger galaxy NGC 3256. This was achieved by taking accurate photometry in four wavebands from archival Hubble Space Telescope images. Photometric measurements are compared to synthetic stellar population (SSP) models to find the most probable age, mass and extinction. The cluster population of NGC 3256 reveals an increase in the star formation rate (SFR) over the last 100 Myr and the initial cluster mass function (ICMF) is best described by a power-law relation with slope \( \alpha = 1.85 \pm 0.12 \).

Using the observed cluster population for NGC 3256 we calculate the implied mass of clusters younger than 10-Myr old, and convert this to a cluster formation rate over the last 10 Myr. Comparison of this value with the SFR indicates the fraction of stars found within bound clusters after the embedded phase of cluster formation, \( \Gamma \), is 22.9\( \pm \)1.3 per cent for NGC 3256. We carried out an in-depth analysis into the errors associated with such calculations showing that errors introduced by the SSP fitting must be taken into account and an unconstrained metallicity adds to these uncertainties. Observational biases should also be considered.

Using published cluster population data sets we calculate \( \Gamma \) for six other galaxies and examine how \( \Gamma \) varies with environment. We show that \( \Gamma \) increases with the SFR density and can be described as a power-law type relation of the form \( \Gamma \) (per cent) = \((29.0 \pm 6.0)\Sigma_{SFR}^{0.24\pm0.04} \ (M_\odot \ yr^{-1} \ kpc^{-2})\).

Key words: stars: formation – galaxies: stellar content – galaxies: structure.

1 INTRODUCTION

Galaxy mergers produce some of the most extreme star formation events in the universe, inducing starbursts with intensities [i.e. star formation rates (SFRs)] orders of magnitude larger than in quiescent galaxies. In the distant universe these can be seen as hyperluminous infrared (IR) galaxies (e.g. Verma et al. 2002) with SFRs exceeding a few thousand solar masses per year. In the local universe, ongoing mergers like Arp 220 (e.g. Scoville et al. 1998; Wilson et al. 2006) and NGC 3256 (e.g. Zepf et al. 1999; Trancho et al. 2007b) have SFRs of a few tens to hundreds of solar masses per year, and due to their proximity, can be resolved with Hubble Space Telescope imaging. In these systems large numbers of superstar clusters are often found, with ages of a 1–500 Myr and masses up to \( \sim 8 \times 10^5 \ M_\odot \) (Maraston et al. 2004). We can think of star clusters as simple stellar populations which can be modelled relatively easily. This, combined with their high surface brightness that allows them to be easily detected, and their long lifetimes, make them ideal tracers of the star formation history of a galaxy.

NGC 3256 is a relatively nearby starburst galaxy that is clearly the result of a recent galactic merger. It displays two prominent tidal tails, thought to have been produced during the first encounter between two spiral galaxies approximately 500 Myr ago (Zepf et al. 1999; English et al. 2003). Zepf et al. (1999) catalogued over 1000 young star clusters in the main body of the merger using Hubble Space Telescope (HST) imaging. Trancho et al. (2007b) discovered three massive (1–3 \( \times \) \( 10^5 \ M_\odot \)) clusters within one of the tidal tails, whose ages and velocities place their formation within the tidal debris. Additionally, Trancho et al. (2007a) (hereafter T07a) studied a further sample of 23 clusters in the main body of the remnant and found that the clusters had metallicities of \( \sim 1.5 \ Z_\odot \) masses in the range \( 2–4 \times 10^5 \ M_\odot \) and ages from a few to 150 Myr. The current SFR of NGC 3256 is \( \sim 50 \ M_\odot \ yr^{-1} \) (Bastian 2008); however, its SFR appears to have been increasing for the past \( \sim 200 \) Myr (see Section 2.5) and T07a argue that it is likely to continue to increase in the future.

The age distribution of clusters reveals the underlying star formation history of the host galaxy. The mass distribution of clusters gives information on the cluster initial mass function (CIMF) which is often approximated by a power-law of the form \( N dm \propto M^{-\alpha} dm \), with \( \alpha \sim 2 \) (Elmegreen & Efremov 1997; Zhang & Fall 1999; Bik et al. 2003; de Grijs et al. 2003c). More recently, it has been shown that the CIMF may have a truncation at high masses, being well described by a Schechter function (Schechter 1976) which is a power-law in the low-mass regime and has an exponential cut-off.

*E-mail: qeg20@cam.ac.uk

© 2010 The Authors. Journal compilation © 2010 RAS
above a given mass, $M_\star$ (Gieles et al. 2006a; Bastian 2008; Gieles 2009b; Larsen 2009).

In order to obtain accurate cluster ages and masses either spectroscopy or photometry may be used. Although spectra yield more accurate results, photometry is more applicable to large sample sets. In order to break the age–dust degeneracy, a cluster must be observed in at least four broad photometric bands and cover the Balmer break (Anders et al. 2004a). By comparing the observed colours and magnitudes of each cluster to synthetic stellar population (SSP) models, we can estimate the age, mass and extinction of each cluster. This technique has been used on several cluster populations, the Antennae (Fall, Chandar & Whitmore 2005; Anders et al. 2007), NGC 1569 (Anders et al. 2004a) and M51 (Bastian et al. 2005b).

If all stars are formed in clusters, then only a small percentage of them are still within clusters at the end of the embedded phase (Lada & Lada 2003). For up to the first 3 Myr of a cluster’s lifetime it remains embedded in the progenitor molecular cloud until stellar winds, ionizing flux from massive stars, and stellar feedback expel the remaining gas (see Goodwin 2009, for a recent review). In expelling this gas many clusters become unbound and subsequently disperse into the surrounding medium (Lada & Lada 2003), a process commonly described as ‘infant mortality’. Even if clusters do survive the embedded phase intact other disruption mechanisms may come into effect, such as stellar evolutionary mass-loss, two-body relaxation and giant molecular cloud (GMC) encounters. These mechanisms generally operate over longer time-scales, being a few tens of Myr for stellar evolution (e.g. Bastian et al. 2009) and hundreds of Myr for GMC encounters (Gieles et al. 2006c), except when the GMC number density is particularly high (e.g. Lamers, Gieles & Portegies Zwart 2005).

After a cluster disrupts the stars disperse and become part of the galactic background. Comparing the fraction light emitted from clusters to the total (i.e. background plus clusters) galactic emission gives an indication of the fraction of stars within bound clusters. Meurer et al. (1995) estimated that 20–50 per cent of ultraviolet light in starburst galaxies comes from star clusters. Zepf et al. (1999) calculated the fraction of light from clusters in the $B$ band to be 15–20 per cent and half that in the $I$ band for the galaxy NGC 3256. However, the most comprehensive set of results comes from Larsen & Richtler (2000), listing the fraction of light from clusters in both the $U$ band [$T_U(U)$] and $V$ band [$T_V(V)$] for 32 galaxies with varying SFRs. Larsen & Richtler (2000) found that $T_U(U)$ increases with the SFR of the host galaxy and the derivative relationship can be expressed as a linear relation. The Star Formation Rate (SFR) is the rate at which stars form in a given interval of time.

Measuring the fraction of light from clusters is a relative easy calculation assuming foreground stars can be eliminated from the sample. However, it is presently unknown, but calculable, how these values may be influenced by the presence of bursts of star formation in the past and differential extinction of younger clusters. Hence the fraction of light observed in clusters will be a (possibly complicated) combination of the fraction of stars formed in clusters, the star formation history of the galaxy, the cluster disruption time-scale/rate, and the difference in the amount of extinction towards clusters and the field.

In this paper we attempt to improve the situation by deriving ages and masses for clusters in the galaxy NGC 3256, which in turn is used to calculate a cluster formation rate (CFR) over the last 10 Myr. Comparing this inferred CFR to the SFR (measured by Hα fluxes or IR luminosities) we compute the fraction of stars in clusters younger than 10 Myr which have survived the embedded phase intact, a value hereafter referred to as $\Gamma$ (Bastian 2008). We pay particular attention to the possible sources of uncertainty which may affect these calculations. Using other data sets of cluster ages and masses for different galaxies we perform the same calculation for an additional six galaxies in an attempt to find how $\Gamma$ varies with environment.

Throughout this paper we will define a ‘cluster’ as a gravitationally bound, centrally concentrated group of stars that can be identified on high-resolution optical imaging. Hence, clusters refer to objects that have survived the transition from being embedded in their natal GMC to an exposed state. We assume that this process takes place approximately 3 Myr after the cluster forms. We adopt a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, which places NGC 3256 at a distance of 36.1 Mpc given it has a recession velocity relative to the local group of $+2804 \pm 6$ km s$^{-1}$. This corresponds to a distance modulus of 32.79.

This paper is structured as follows. We begin in Section 2 by introducing the data set for NGC 3256 and the methods we used to determine the age and masses of clusters in the galaxy. In Section 3 we detail how we calculated $\Gamma$ for NGC 3256 and go on to carefully examine all the possible sources of error in making such a calculation. In Section 4 we introduce other data sets taken from the literature and calculate $\Gamma$ for each. In Section 5 we search for trends with $\Gamma$ and galactic properties and discuss the implication. Finally, in Section 6 we present our conclusions and summarize our main results.

## 2 OUR STUDY OF NGC 3256

### 2.1 The data

We used archival HST Advanced Camera for Surveys (ACS) images of NGC 3256 across four filters, $F330W$ (PI: Holland Ford; ID: 9300), $F435W$ (PI: Alex Fillippenko; ID: 10272), $F555W$ (ID: 9300) and $F814W$ (ID: 9300). Details of all the images used can be found in Table 1. The High Resolution Camera (HRC) images all cover the same area apart from the HRC $F435W$ image which is offset. To ensure we were examining the same area in all four bands we used the ACS Wide Field Camera (WFC) $F435W$ (PI: Aaron S. Evans; ID: 10592) image over the HRC $F435W$ image. The WFC image has the advantage of a longer exposure time, though the pixel scale is slightly larger, 0.05 arcsec compared to 0.027 arcsec. Throughout this paper we will refer to the $F330W$, $F435W$, $F555W$ and $F814W$ in the Cousins–Johnson $U$, $B$, $V$ and $I$ notation, although we stress that no transformations have been applied.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Camera</th>
<th>Exposure time (s)</th>
<th>Aperture correction</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>F330W</td>
<td>HRC</td>
<td>2000</td>
<td>0.418</td>
<td>$U$</td>
</tr>
<tr>
<td>F435W</td>
<td>HRC</td>
<td>840</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>F555W</td>
<td>HRC</td>
<td>760</td>
<td>0.397</td>
<td>$V$</td>
</tr>
<tr>
<td>F814W</td>
<td>HRC</td>
<td>660</td>
<td>0.405</td>
<td>$I$</td>
</tr>
<tr>
<td>F435W</td>
<td>WFC</td>
<td>1320</td>
<td>0.328</td>
<td>$B$</td>
</tr>
</tbody>
</table>

*We refer to the filters by their closest Cousins–Johnson filter name; however, no transformations have been applied.*

---

2.2 Cluster selection and photometry

We selected star clusters using the SExtractor program (Bertin & Arnouts 1996), run on the $B$-band WFC image in order to maximize the number of clusters detected. We changed the SExtractor detection parameters to maximize the number of objects found, attempting to avoid blending of objects in the most crowded regions. We set a minimum detection limit as $4\sigma$ above the local background as determined by SExtractor, and a minimum object area of 8 pixels. Coordinates of the clusters were translated from the $B$-band image into coordinates for the other bands using the GEOMAP and GEOXYTRAN routines within IRAF.

Photometry across all images was carried out using the APER routine from the DAOPHOT package in IRAF. We did not use the photometry from SExtractor to ensure a consistent and unbiased method in all wavebands. We used an aperture of radius 7.0 pixels for the HRC images and 3.5 pixels for the WFC image. An annulus with radius 8 pixels and a thickness of one pixel was used to measure the local background in the HRC images, radii and thickness of the annulus were adjusted accordingly for the WFC image. Aperture corrections were calculated based on several bright, isolated and spatially resolved clusters, by comparing their flux in an aperture of 30 (HRC) pixels relative to our adopted 7 (HRC) pixel aperture. The resulting aperture corrections are shown in Table 1.

We corrected the photometry for foreground Galactic extinction, using the extinction law of Savage & Mathis (1979), and a dust extinction value of $A_V = 0.122$, taken from Schlegel, Finkbeiner & Davis (1998).

In total we measured fluxes for 904 clusters in NGC 3256 across the $U$, $B$, $V$ and $I$ bands. Fig. 1 shows a colour–colour diagram of clusters within a magnitude limit ($m_B < 21.0$). Fig. 2 shows a colour composite image of NGC 3256. To avoid overcrowding we have only marked the positions of the 276 cluster that have good fits to SSP models, more details on this selection can be found in Section 2.3.

![Figure 1. Colour–colour diagram for clusters below the magnitude limit $m_B < 21.5$ (simply to avoid overcrowding the figure). Clusters have not been reddening corrected. We have only included clusters that met our criteria for a good fit to the SSP models, as explained in Section 2.3. The lines show solar metallicity SSP models, the solid line is based on the Padova isochrones whilst the dashed line is based on the Geneva isochrones. The red dashed segment shows the ‘red loop’, few clusters are ever associated with this feature.](image)

![Figure 2. Colour composite image of NGC 3256. We have marked on the positions of the 276 clusters classified as good fits in Section 2.3.](image)

2.3 Determination of cluster parameters

In order to determine the age, mass and local extinction for each cluster the photometric values were compared to those of cluster evolution models, in a similar fashion to Bik et al. (2003) and Bastian et al. (2005a). We used the most recent GALEV simple stellar population (SSP) models (Anders & Fritze-v. Alvensleben 2003; Anders et al. 2004a). Although SSP models exist based on both the Padova and Geneva isochrones, we have only used the Padova tracks to determine cluster parameters. The Geneva tracks display a feature known as the red loop and tend to produce a poor fit to data compared to the Padova tracks (Whitmore & Zhang 2002). The GALEV models have the advantage of being produced with colours matching the HST filters; this avoids errors associated with converting between HST filters and the standard Cousins–Johnson system. In addition, the GALEV models include gaseous emission lines and continuum emission. The youngest data points in the GALEV models are 4 and 8 Myr; this can lead to poor fitting of the youngest clusters (Bastian et al. 2005a). To avoid this we linearly interpolate between the youngest model ages for all filters. This produces SSP tracks which are regularly sampled at intervals of 0.02 in log time. The determined age of a young cluster is not bound to 4 or 8 Myr in this case and can take a more precise value with a better fit over the four wavebands.

We have used a three-dimensional maximum likelihood fitting method developed by Bik et al. (2003). The method is described in detail there, and so we only summarize the process in this paper. We also note that this method has been tested against colour–colour methods and has shown itself to be superior (de Grijs, Bastian & Lamers 2003b; Parmentier, de Grijs & Gilmore 2003).

In simple terms the method works as follows. The GALEV SSP models give a grid of colours as a function of age. We then apply extinction to each model in steps of 0.02 in $E(B-V)$ to extend the grid. Each cluster then has its observed spectral energy distribution compared to the grid using a minimum $\chi^2$ test. The model with the age and extinction which produces the lowest $\chi^2$ is chosen, and a range of acceptable values is calculated. As the GALEV model magnitudes are scaled to a mass of $10^6$ $M_\odot$, the difference between the observed magnitudes and model magnitudes can be converted to a mass, given the distance modulus and extinction. The accuracy of this fitting method is not studied directly here as it has been...
reported previously (Bastian et al. 2005a), for the majority of the sample errors on the age and mass are less than 0.3 dex.

After obtaining the best fit for each cluster we sought to determine if the fit was good or not. In fitting cluster parameters a $\chi^2$ value is calculated and this is one way of identifying a good fit. However, for bright objects with low photometric errors the $\chi^2$ value may be high and thus result in a bad fit. To avoid such instances we use the standard deviation, defined in equation (1):

$$\sigma^2 = \frac{\sum (m_i - m_{\text{mod}})^2}{n_{\text{filters}}}. \tag{1}$$

The $\sigma^2$ value is summed over all four wavebands. The spectral energy distributions were compared to the values predicted by the best-fitting models and compared by eye. This was done to establish a minimum value for $\sigma^2$, $\sigma_{\text{mod}}^2$. We also computed a histograms of $\sigma^2$ for all sources and approximating the distribution with a Gaussian and took the $1/e$ point. This value was very close to an appropriate value for $\sigma_{\text{mod}}$, determined by visual inspection at 0.03.

In the resulting analysis of the properties of cluster system of NGC 3256 we only consider those clusters which pass the following criteria:

(i) detected in all four wavebands, at least $5\sigma$ above the background;
(ii) uncertainties in the magnitude of all wavebands $\leq 0.2$ mag;
(iii) is well fitted by an SSP model ($\sigma \leq 0.03$).

The number of clusters which passed these rigorous selection criteria depends on the metallicity of the SSP model used. With a solar metallicity Padova model we accept 276 objects, and with a twice solar metallicity we accept 285 objects. Details of the 276 clusters accepted using the solar metallicity Padova tracks can found with the electronic version of this paper, an example of this data is shown in Table 5. It should be noted that the higher number of accepted objects produced by the twice solar metallicity models is not an indication of the global metallicity of the galaxy. Metallicity is very hard to fit accurately with only photometry, as shown by Bastian et al. (2005a). T07a found the metallicity to range between 1.1 and 1.7 $Z_{\odot}$ for 23 clusters in NGC 3256.

T07a presented optical spectroscopy of 23 clusters in NGC 3256. We have attempted to compare our results with those of T07a; however, there are several problems that we encountered. First, the astrometry presented by T07a is not accurate enough to identify any one cluster from our study, we were forced to visually inspect images from the two studies and then attempted to find the most likely matching clusters. Secondly, several of the clusters presented by T07a are in fact complexes, comprising several clusters. Out of the 10 clusters in the T07a study that lie within the same field of view as our study we found that eight had corresponding clusters in our study which matched our criteria for a good cluster fit. The remaining two clusters from the T07a were both complexes located in extremely crowded regions of the galaxy and could correspond to any one of several clusters in our study. Of the eight matched clusters T07a states that six of these were emission-line objects and have reported ages of less than 10$^{6.8}$ yr. We find that ages for seven of these clusters is also under 10$^{6.8}$ yr, the remaining object has an age between 10$^{6.7}$ and 10$^{6.9}$ which appears to be consistent with the findings of T07a. We have also be able to match two absorption-line clusters from the T07a study, both of these clusters have reported ages that are consistent within their respective errors.

2.4 Cluster properties of NGC 3256

We can determine the properties and history of NGC 3256 by examining the clusters that reside within the galaxy. With the age, mass and extinction of the clusters known we can derive several important properties. Fig. 3 shows the age–mass distribution for NGC 326 derived from the solar metallicity Padova SSP models. Immediately obvious from Fig. 3 is the lack of low-mass, old clusters. This is due to the fact that clusters dim as they age and so eventually become fainter than our detection limit. We can also note the large number of clusters seen with ages below 10 Myr and over a large range of masses. Although the cluster fitting method can create some observed structure in the age–mass diagram (Gieles et al. 2005) it is unlikely to do so over all masses at low ages. We can conclude that there is a genuine overdensity of clusters with ages below 10 Myr. This can be interpreted as a lack of older clusters which could be due in part to the disruption of clusters, a point we shall address when we look as the cluster formation history in Section 2.5.

Various mass limits are shown on Fig. 3 as horizontal dashed lines. Due to the effects of old clusters becoming fainter, higher mass limits result in a population which is complete up to a larger range of cluster ages. For example, a mass limit of log($M/M_{\odot}$) > 4.5 would only be complete for clusters younger than 10 Myr. A mass limit of log($M/M_{\odot}$) > 5.5 would however be complete for much older clusters, those less than ~200 Myr.

We can compute the slope of the cluster mass function for clusters younger than 10 Myr which we have shown in Fig. 4. This assumes the number of clusters of a given mass follows a power-law distribution, like that in equation (2). $n(M)$ is the number of clusters with mass $M$, $\alpha$ is a constant of normalization and $\alpha$ is the slope of the power law:

$$N(m)\, dm = \chi M^{-\alpha} \, dm. \tag{2}$$

When calculating the slope of a mass distribution for any type of object the way in which the data are binned can affect the result (Maiz Apellaniz & Ubeda 2005). To avoid such biases we have used bins with an equal number of objects in each. The minimum
and maximum limits to each bin then depend on the masses of objects within. We have chosen to calculate the mass function for young clusters with ages less than 10 Myr, in order to avoid any mass dependent cluster disruption effects, resulting in a complete sample.

This calculation produces the mass function shown in Fig. 4 where the data points are shown in black and the line of best fit is in red. The slope is fitted to data points with masses above the limit $M/\text{M}_\odot \gtrsim \log(4.3)$, below which we see a turnover in the mass function. This common turnover in cluster mass functions is due to incompleteness in the sample for low-mass clusters. The slope of the mass function for NGC 3256 was measured to be $\alpha = 1.85 \pm 0.12$, which is similar to other observed cluster populations that are generally in the range of $\alpha = 1.8–2.2$ (de Grijs et al. 2003a; McCrady & Graham 2007).

### 2.5 Cluster formation history of NGC 3256

Ages determined by fitting photometric observations to SSP models can lead to large uncertainties, especially for faint objects with large photometric errors. In constructing a cluster formation history for NGC 3256 it is important to take the uncertainty in the cluster ages into account.

We have constructed a $dN/d\tau$ distribution using the same method described by Gieles, Lamers & Portegies Zwart (2007). We do not reiterate the details laid out in Gieles et al. (2007), only the central ideas. Each cluster has a contribution to the overall age distribution as defined by an asymmetrical Gaussian spread in $\log t$. This is calculated based on the minimum and maximum allowed ages of each cluster, calculated by the SSP fitting routine.

In Fig. 5 we show the smoothed age distribution results for two different lower mass limits, $10^{4.7}$ $\text{M}_\odot$ (left-hand panel) and $10^{5.7}$ $\text{M}_\odot$ (right-hand panel). The red shaded area shows the 1σ Poisson errors, estimated by counting the number of clusters in bins of width 0.25, corresponding to the mean uncertainty in the log age values of the clusters.

Using two different lower mass limits in Fig. 5 our sample of clusters is complete up to two ages, the $10^{4.7}$ $\text{M}_\odot$ limit shown in the left-hand panel is complete for clusters younger than 20 Myr. The higher mass limit of $10^{5.7}$ $\text{M}_\odot$ shown on the right-hand panel is complete for clusters younger than 200 Myr, both of these ages are shown as a vertical line on each plot. In both panels the CFR declines for clusters older than the completeness limit, due in part to older clusters fading and becoming undetectable.

---

**Figure 4.** Mass function for clusters younger than 10-Myr old in NGC 3256, produced using bins with a constant number of clusters per mass bin. The red line is a line of best fit for points beyond the low-mass turnover.

**Figure 5.** Apparent rate of cluster formation as a function of time for NGC 3256 and two different lower cluster mass limits. Left-hand panel uses a limit of $10^{4.7}$ $\text{M}_\odot$ which is complete for clusters younger than 20 Myr, represented by the solid vertical line. The right-hand panel shows the same plot for clusters more massive than $10^{5.7}$ $\text{M}_\odot$, which is complete up to 200 Myr. The red shaded area denotes the 1σ Poisson errors as described in the text.
Focussing on the high-mass cut sample, we see that the CFR has increased by a factor of ~10 during the past ~200 Myr. This increase is expected due to the ongoing galactic merger which is presumably the cause of the ongoing starburst (Bastian et al. 2009). This interpretation is also supported by the present SFR of NGC 3256 which is ~46 M\(_{\odot}\) yr\(^{-1}\), which is approximately 10 times higher than the sum of the two progenitor spiral galaxies. As in the Antennae (Bastian et al. 2009), we do not see evidence for a high degree of long duration (>10 Myr) mass independent cluster disruption, as proposed by Fall et al. (2005). However, our high-mass cuts mean that we are insensitive to any disruption in the lower mass end of the cluster mass function, which may be strongly affected by cluster disruption during galaxy mergers (Kruijssen et al., in preparation).

3 CALCULATING THE RATIO OF STARS FORMING WITHIN CLUSTERS, \(\Gamma\)

3.1 Initial estimate

Assuming we were able to detect all the clusters within a galaxy we would be able to establish the total mass of clusters which had recently formed. Comparing this mass with a measure of the SFR over the same time-scale gives the ratio of stars forming within clusters, hereafter referred to as \(\Gamma\) (Bastian 2008).

In principle this calculation is simple but is made more complex by the incompleteness of our sample of clusters. We are not able to detect low-mass clusters, even those with young ages. Any low-mass cluster is also likely to have large photometric errors and thus be rejected as a poor fit. We know, however, our sample is likely to be complete for bright, massive, young clusters. We can then extrapolate the mass found in these clusters to calculate the total mass of all clusters.

In order to calculate the ratio of mass found above a certain mass limit we made sample cluster populations based on a power-law distribution (stochastically sampled), like that in equation (2). We made model populations with 500 000 clusters with a lower mass limit of 100 M\(_{\odot}\), and an upper limit of 10\(^{11}\) M\(_{\odot}\). This upper mass limit may appear very high but with a power-law distribution with index of \(\alpha = 2.0\) (i.e. \(\alpha = 2.0\)) we only expect 50 clusters above 10\(^9\) M\(_{\odot}\) based on this upper mass limit. To avoid erroneous results we ignore clusters with masses larger than 10\(^7\) M\(_{\odot}\). The upper mass limit allows the model populations to be fully populated for high masses. We also calculate an error associated with the fraction of mass found above a certain mass limit, this is the standard deviation of results from 200 model cluster populations. The error does not decrease with an increased number of model populations as it is limited by stochastic variations in the masses of high-mass clusters, which are rare in each model population. We have used a power-law index of \(-2.0\) in our calculations although it should be noted that an index of \(-1.85\) was measured for NGC 3256. We assume an index of \(-2.0\) as this is the value found for large samples of clusters, we do accept that this value may vary between galaxies and the implications of this are discussed further in Section 3.2.

At this point we note that sampling an initial cluster mass function (ICMF) to generate a cluster population simply to calculate the mass above a mass limit may appear to be a long winded way of making this calculation, as it is straightforward to analytically calculate these numbers for a given ICMF. However, analytical calculations do not give an estimate of the error associated with stochastic sampling of the ICMF, an effect that increases as you estimate the fraction of mass above an increasing mass limit. As estimating realistic errors for this and similar studies is one of the goals of this paper, we choose to use the Monte Carlo technique in the subsequent analysis.

With the ages and mass of clusters for NGC 3256 calculated we found the total mass of clusters less than 10-Myr old, and with a mass greater than 10\(^7\) M\(_{\odot}\). The lower mass limit of 10\(^7\) M\(_{\odot}\) was chosen as a conservative estimate to ensure our sample was complete for this range of masses and ages. This gave a mass of 1.66 x 10\(^7\) M\(_{\odot}\) contained within clusters. The fraction of mass expected above this mass limit was taken from our model cluster populations to be 0.61 ± 0.09. We expect the total mass contained within all clusters in this age range to be 2.73 ± 0.42 x 10\(^7\) M\(_{\odot}\). This was divided by the age range of 7 Myr to find the stellar mass forming in clusters per year, 3.90 ± 0.60 M\(_{\odot}\) yr\(^{-1}\). We used an age of 7 rather than 10 Myr as extremely young clusters with ages less than 3 Myr will still be embedded, and thus undetectable.

We compare the mass of stars forming within clusters to the SFR which was calculated based on the IR luminosity from Sargent, Sanders & Phillips (1989) and converted to a SFR of 46.17 M\(_{\odot}\) yr\(^{-1}\) using the conversion of Kennicutt (1998a). The conversions given by Kennicutt (1998a) are based on a Salpeter IMF. In fitting SSP models to our photometric data we used SSP models which adopt a Kroupa IMF. This has the effect of underestimating the mass of clusters compared to a similar result using SSP models based on a Salpeter IMF. If we are to compare the mass of stars in clusters to the SFR both results must be made using the same IMF. We correct the masses of clusters for this by multiplying by 1.38.

For NGC 3256, we find that the fraction of stars which remain within optically selected clusters after the embedded phase, \(\Gamma\), is 0.12 ± 0.02. This is, however, a lower limit as various selection effects and fitting artefacts must be taken into account, which will be explored below. The implications of this result are discussed in Section 5.

3.2 Sources of uncertainty

In calculating \(\Gamma\) there are several sources of error we should consider. Here we focus on the errors associated with our study of NGC 3256 and also address issues which may arise with other data sets from different galaxies. We have summarised these sources of uncertainty in Table 3.

3.2.1 Error associated with the slope of the mass function

As we previously mentioned, the slope of the cluster mass function was taken to be \(-2.0\). However, this may vary between galaxies and has an effect on the fraction of mass we infer to be above the mass limit. With a steeper slope fewer high-mass clusters are present so the fraction of mass above a mass limit is reduced. Conversely a shallower slope creates more high-mass clusters and so the fraction of mass above a mass limit is increased. We have measured this effect by making sample cluster populations with a mass function slope between \(-1.8\) and \(-2.2\). The results of these simulations are shown in Fig. 6, in which we assume a mass cut of \(M > 10^7\), the same used in our study of NGC 3256. The top panel in Fig. 6 shows how the number of objects found above the mass cut varies with differing mass function slopes.

The middle panel of Fig. 6 shows the ratio of mass within clusters with masses greater than the mass limit compared to the total mass of all the clusters, \(\mathcal{R}_c\). Over the range of 1.8 < \(\alpha\) < 2.2 this ratio changes dramatically from 0.93 to 0.25, respectively. Measured values of \(\alpha\) vary but the best estimates are close to 2.0. The bottom
fit, as defined in Section 2.3. We compared to the value for a slope of \( \alpha = 2.0 \). The middle panels displays \( R_\alpha \), the ratio of mass found in clusters above the mass limit to the total mass of all clusters. The bottom panel shows \( R_\alpha \) normalized to \( R_{2.0} \).

Figure 6. Plot showing the effect of varying the mass function index on the fraction of mass above a mass limit (\( M > 10^7 \)). The top panel shows the number of clusters found above the mass limit as a function of the ICMF index (\( -\alpha \)), normalized to the value for a slope of \( \alpha = 2.0 \). The middle panels displays \( R_\alpha \), the ratio of mass found in clusters above the mass limit to the total mass of all clusters. The bottom panel shows \( R_\alpha \) normalized to \( R_{2.0} \).

panel in Fig. 6 shows how the value of \( R_\alpha \) compares to the value for a mass function with an index of \( -2.0 \). If the cluster IMF index varies within the range \( 1.8 < \alpha < 2.2 \), then we may be underestimation or overestimating \( \Gamma \) by roughly \( \pm 50 \) per cent by assuming a single value of \( \alpha = 2.0 \).

3.2.2 Power-law or Schechter function

The exact form of the ICMF is still under debate. In the case of NGC 3256 we have assumed a simple power law of the form shown in equation (2). For other galaxies an index of \( \alpha \approx 2 \) has been found (e.g. Zhang & Fall 1999; Bik et al. 2003; de Grijs et al. 2003c; McCrady & Graham 2007) and is expected from theoretical considerations (Elmegreen & Efremov 1997). Recent studies have, however, shown that there may be truncation in the mass function at the high-mass end (Gieles et al. 2006b; Bastian 2008; Larsen 2009). This can be represented by a Schechter function (Schechter 1976) which behaves as a pure power law in the low-mass regime and has an exponential fall off above a given value, \( M_* \).

In Fig. 7 we show how the resulting mass of clusters varies for different mass cuts and different truncation values, \( M_\star \). Overall, the difference between the results with a simple power-law or a Schechter function is small. In the specific case of NGC 3256, if a truncation exists it is likely to be well above \( 10^6 \) \( M_\odot \); hence any effect on the derived \( \Gamma \) values will be minimal.

3.2.3 Error associated with fitting cluster parameters using SSP models

Bastian et al. (2005a) and Gieles et al. (2005) compared the results of SSP fitting for clusters in M51 with the results for a model population, noting that the number of clusters at certain ages and masses can be enhanced or reduced by the fitting method. This can affect the calculated total mass of clusters when extrapolating from the mass found in high-mass clusters. To investigate this we made a model population of clusters based on the solar metallicity GALEV SSP model tracks (Padova isochrones). Ages of clusters were randomly distributed in the range \( 0 < t < 10^{10} \) yr. The masses of clusters were assigned stochastically assuming a power-law distribution of slope \( -2.0 \). Based on the age, mass and distance to NGC 3256 we then assigned magnitudes from the SSP models.

Photometric errors for each band were estimated by examining the errors of the clusters measured in our sample from NGC 3256. We were able to approximate the error with the relation \( \Delta m_\nu = 10^{\nu_d + 2 \times \nu m} \). The values of \( \nu_1 \) and \( \nu_2 \) are displayed in Table 2. A random correction to the magnitude in each waveband was added in the range \( -\Delta M_\nu \) to \( + \Delta M_\nu \). We produced a catalogue of 2607 clusters which fulfilled our magnitude limit.

Table 2. Parameters for the uncertainty of the magnitudes: \( \Delta m_\nu = 10^{\nu_d + 2 \times \nu m} \).

<table>
<thead>
<tr>
<th>Filter</th>
<th>( \nu_1 )</th>
<th>( \nu_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U )</td>
<td>-5.726</td>
<td>0.228</td>
</tr>
<tr>
<td>( B )</td>
<td>-3.276</td>
<td>0.116</td>
</tr>
<tr>
<td>( V )</td>
<td>-4.881</td>
<td>0.178</td>
</tr>
<tr>
<td>( I )</td>
<td>-5.134</td>
<td>0.196</td>
</tr>
</tbody>
</table>

We ran the same fitting procedure on this artificial catalogue as we had done on the data for NGC 3256, fitting cluster photometry to the solar metallicity Padova SSP models. When examining the results of this fitting procedure we were as stringent with the artificial clusters as we were with the real data. We only accepted those results which met our criteria to be a good fit, as defined in Section 2.3. We then compared the known mass, age and extinction of the model population to the results from the model fitting. We also excluded those model clusters with ages less than 3 Myr, assuming that in reality these young clusters would be embedded and unobservable.

We have compared the age–mass distribution of the model cluster population to the results of the SSP fitting routine in Fig. 8. The colour scale represents the difference in the number of clusters found with a given age and mass compared to the input model population. The white slope across the figure shows a large deficit of clusters, this is due to the stringent limits we apply to our clusters, accepting only clusters with low errors (<0.2). Any faint clusters will have large errors and so we reject the fit. Fig. 8 shows that young clusters

are not fitted as we assume we will not detect young embedded clusters. The inset in Fig. 8 shows a comparison of the mass in clusters above a mass limit, comparing the results of cluster fitting to the known values of the input model cluster. For mass cuts below $10^5 \, M_\odot$ we tend to underestimate the mass above the mass cut. This implies that measuring the total mass of stars within clusters would be underestimated due to the effects of the fitting procedure. This effect is small however and for the mass cut used in our study of NGC 3256 results in an underestimation by 5 per cent. For the largest mass cut used we in fact overestimate this mass but only by 10 per cent, though when it is considered with higher mass cuts we are more likely to encounter errors due to the stochastic sampling of massive young clusters.

The test we have performed here to estimate the error associated with the SSP fitting does not take into account the intrinsic problems with either the Padova or Geneva SSP models. These synthetic stellar evolution tracks do not perfectly represent real star clusters, especially at young ages. Even for models without stellar rotation or binary stars the uncertainties associated with massive stars can be large, and when these effects are included the errors increase. The true effect of fitting to inaccurate SSP models is ultimately hard to quantify and the analysis we have carried out can only be considered as a rough estimate of this effect.

### 3.2.4 Error due to an unknown metallicity

In determining the cluster parameters of age, mass and extinction we have fitted the photometric data to a SSP model of a certain metallicity. Using optical spectroscopy, T07a found that the metallicity of clusters and H II regions in NGC 3256 was between 1 and 1.7 $Z_\odot$. The Padova SSP models used have only two metallicities in/near this range, namely solar and twice solar. Here we test the effect of our metallicity assumptions on our derived value of $\Gamma$.

Just as we did in Section 3.2.3 we produced model cluster populations based on the solar metallicity Padova tracks; however, we then tried to fit these data to the twice solar Padova SSP tracks. We also produced a model population based on the twice solar Padova and fitted them to the solar Padova tracks in an attempt to examine the effects of overestimating or understimating the metallicity. These results are shown in Fig. 9, the red line shows what happens when we overestimate the metallicity, using a twice solar metallicity track to fit clusters with a solar metallicity. In this case we overestimate the mass in cluster above a particular mass cut. This overestimation changes a little depending on the particular mass cut but is approximately a factor of 2 for the case of NGC 3256.

### 3.2.5 Error due to selection effects

In measuring $\Gamma$ we need to know how efficient we are at detecting massive, bright clusters, which we use to infer the total mass of stars in clusters. Measuring this efficiency is not trivial and a rigorous, quantitative discussion is not included here. Instead we examined HST images of NGC 3256, overlaying the objects selected from the B-band images. Assuming our detection was perfect all the brightest objects should have been identified. In reality this is not possible as dust will obscure some bright clusters and crowding makes identification of individual clusters difficult.

We selected the SExtractor detection parameters to minimize the chance of two close clusters being identified as a single object. A typical field from a crowded region of NGC 3256 is shown in Fig. 10, and we have overlaid the detected clusters with green circles, those clusters which passed our criteria for a good fit have been identified by yellow boxes. The brightest of clusters are all selected and have good fits to SSP models. There are several clusters which we detect but do not have good fits, on examining these clusters we find that they have either one or two wavebands with errors greater than 0.2 mag and are thus rejected, and labelled as poor fits.

We see from Fig. 10 that the actual detection of clusters is not limiting our cluster sample, the ability to accurately fit SSP models is a larger effect. However, in our synthetic cluster population models we apply the same criterion to determine good fits from...
poor fits. We are very severe in the limits we apply, disregarding any cluster which has an error greater than 0.2 mag in any of the four wavebands. It is this criterion which limits our final sample, and is taken into account by modelling cluster populations. We can test this by looking at the fraction of bright, young, massive clusters we reject as poor fits in both the real sample and synthetic cluster populations. We examined the percentage of clusters with accepted good fits, for clusters younger than 10 Myr and with masses greater than $10^{5.7} \, M_\odot$. In our sample from NGC 3256 this percentage was 47 per cent whilst in our synthetic population the result was higher at 76 per cent.

The discrepancy in these results could have several causes. First, our synthetic clusters have a more conservative estimate on the level of dust extinction than we might expect. With a greater level of dust extinction clusters become fainter, photometric errors become larger and the chance we reject the cluster fit increases. Secondly, the synthetic cluster population is entirely theoretical and so poor photometry from overcrowding or from misaligned apertures is not taken into account. We can only estimate the percentage of clusters we either miss altogether or discount due to a poor cluster fit. An estimate of 50 per cent is the worst case scenario but some of this is accounted for by our model cluster populations to which we apply the same stringent criteria for good cluster fits. Taking this into account we estimate that roughly 20 per cent of clusters are either not detected or rejected as poor cluster fits in addition to the fraction we account for based on the synthetic cluster population models.

3.3 The value of $\Gamma$ in NGC 3256

We are in a position to fully calculate the fraction of stars in clusters ($\Gamma$) for NGC 3256, including all the possible sources of error. Initial inspection of our data for NGC 3256 revealed a value of 0.117. We must account for the overestimation or underestimation introduced when we fit data to cluster models. In Section 3.2.3 we calculated that we would underestimate the mass above our mass limit by 5 per cent; however, to make this calculation we made model cluster photometry based on SSP models, and then compared this to the same models. In reality clusters are not perfectly modelled by any SSP and this underestimation is likely larger in reality. We have been rather sceptical in assuming that we only recover 80 ± 10 per cent of the mass when we use this cluster fitting method. This increases the value of $\Gamma$ from 0.12 ± 0.02 to 0.15 ± 0.03.

If we assume all our clusters were solar metallicity the we expect to recover 96 per cent of the mass using a mass cut of $10^{4.7} \, M_\odot$. A more likely scenario is that the cluster population has metallicities in the range 1–2 $Z_\odot$, this will affect the total mass estimated to be in clusters compared to the actual mass, as shown in Fig. 9. As the metallicity of each individual cluster is unknown we cannot be certain if the mass in clusters calculated is an underestimation or overestimation of the true mass. We expect clusters in NGC 3256 to be closer to a solar metallicity than twice solar, and so estimate that our cluster fitting method underestimates the total mass by a factor of $0.8^{+0.3}_{-0.2}$ taken from Fig. 9 for the mass cut used in our study. This further increases $\Gamma$ from 0.15 ± 0.03 to 0.18 ± 0.06.

We also need to consider the fraction of clusters that were not detected or thrown out as poor cluster fits. We estimated this fraction to be 20 per cent in section 3.2.5. Combining these effects we arrive at a more assured value for $\Gamma$ than the value the data initially suggest. The value used throughout the remainder of this paper is $0.23^{+0.10}_{-0.09}$.

4 RESULTS FROM OTHER DATA SETS

Fitting photometric observations to cluster evolutionary tracks is very time consuming. This paper does not attempt to replicate the workings carried out on the clusters of NGC 3256 on numerous other galaxies. Instead we have used previous results from other studies, in an effort to calculate the ratio of stars forming within clusters. The various data sources are discussed below.

4.1 NGC 1569

We use the data set of Anders et al. (2004b), which includes ages and masses for 161 clusters in the galaxy NGC 1569. Just as for NGC 3256 we consider clusters younger than 10 Myr. With the small distance to NGC 1569 Anders et al. (2004b) was able to observe many low-mass clusters, and we can use a low-mass cut to estimate the total mass in clusters. In order to avoid measurements which are affected heavily by stochastic sampling of the ICMF we must use the lowest mass limit possible whilst being wary of the observational limits. We chose three lower mass limits, $10^5$, $10^5.2$, and $10^5.4 \, M_\odot$. In the same manner as we did for NGC 3256 we extrapolated the mass found above this limit up to the total mass in clusters, this resulted in consistent answers from all three of these limits. Averaging these three results we calculated the total mass in clusters to be $3.52 \pm 0.05 \times 10^6 \, M_\odot$. Assuming we are unable to observe any embedded clusters younger than 3 Myr the resulting CFR is 0.05 $M_\odot$ yr$^{-1}$. The SFR is taken from an H$\alpha$ measurement from Moustakas & Kennicutt (2006) and the H$\alpha$ SFR calibration in Kennicutt (1998a), using the same adopted distance to NGC 1569 as Anders et al. (2004b) of 2.2 Mpc. Giving a SFR of 0.36 ± 0.02 $M_\odot$ yr$^{-1}$. $\Gamma$ is simply the ratio of the CFR to the SFR, 13.9 ± 0.8 per cent.

4.2 NGC 6946

We used data from Larsen (2002) who quoted ages and masses for 90 clusters in NGC 6946. Considering clusters younger than 10 Myr and a lower mass limit of $10^5 \, M_\odot$ we calculated the mass in clusters above this limit, giving $1.28 \times 10^7 \, M_\odot$. The fraction of mass expected above this mass limit is calculated as in previous sections and results in a total inferred cluster mass of $1.95 \pm 0.23 \times 10^5 \, M_\odot$. 

Figure 10. Colour composite image of a particularly crowded section of NGC 3256. Objects detected in the $B$ band are circled in green. Objects in yellow boxes passed our criteria for a good fit to the SSP models.
We continue to assume that clusters younger than 3 Myr are embedded an unobservable and so have an age range of 7 Myr, thus giving a CFR of $0.022 \pm 0.003 \, M_\odot \, \text{yr}^{-1}$.

The data of Larsen (2002) only comes from one pointing of the HST WFPC2 camera and does not include the whole galaxy. To calculate $\Gamma$ we need the SFR across this region only. This was found using the area covered by the WFPC2 and the SFR density taken from Larsen (2002), giving a SFR of $0.1725 \, M_\odot \, \text{yr}^{-1}$. Consequently $\Gamma$ is $12.5 \pm 3$ per cent, although we note this HST pointing included the centre of NGC 6946 and so the SFR might be higher that the global average we used.

### 4.3 Small Magellanic Cloud

We have used the data set generated by Hunter et al. (2003), a catalogue of ages and masses for 191 clusters in the Small Magellanic Cloud (SMC). This catalogue is thought to be incomplete for clusters younger than 10 Myr, so we calculated the mass in clusters between 10 and 100 Myr. With the SMC lying at a distance of $61 \pm 3$ kpc (Hilditch, Howarth & Harries 2005) the data set is complete to very low cluster masses.

Using lower mass limits of $10^{2.6}$, $10^{2.8}$, $10^{3.0}$ and $10^{3.2} \, M_\odot$ to calculate the mass in total mass in clusters gave consistent results of $1.59 \pm 0.03 \times 10^{3} \, M_\odot$. We assumed a constant CFR and SFR over the range age 10–100 Myr, giving a CFR of $1.77 \pm 0.03 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}$. The SFR which we assume to be constant over the last 100 Myr is taken from the extinction corrected H$\alpha$ luminosity value of Kennicutt & Hodge (1986), converted to a SFR of $0.043 \, M_\odot \, \text{yr}^{-1}$ using the equations given by Kennicutt (1998a).

The resulting value for $\Gamma$ is $4.2 \pm 0.2$ per cent.

Our value for $\Gamma$ agrees extremely well with the value calculated by Gieles & Bastian (2008) of 3–5 per cent, derived using size-of-sample effects on the same cluster sample. Kruisjes & Lamers (2008) looked at the ratio of clustered to field stars in the SMC and quote a minimum of $0.5$ per cent and suggest a more reasonable value of 10 per cent as their best result.

### 4.4 Large Magellanic Cloud

Ages and masses for 748 clusters in the Large Magellanic Cloud (LMC) were taken from the data set of Hunter et al. (2003). Just as in the case of the SMC this catalogue is believed to be incomplete for clusters younger than 10 Myr and so we studied clusters in the age range 10–100 Myr.

With the LMC being a relatively nearby galaxy at a distance of only $58.5$ kpc (Macri et al. 2006) the sample is complete to low mass and we calculated the mass of clusters above four mass limits $10^{2.6}$, $10^{2.8}$, $10^{3.0}$ and $10^{3.2} \, M_\odot$. The fraction of mass expected above these limits was found as described in previous sections, resulting in a total inferred mass in clusters of $6.31 \pm 0.20 \times 10^{5} \, M_\odot$. We assume a constant SFR and CFR over the 90 Myr period considered, resulting in a calculated CFR of $7.01 \pm 0.22 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}$.

The SFR ($0.12 \, M_\odot \, \text{yr}^{-1}$) and the galaxy area ($79$ kpc$^2$) are both taken from Larsen & Richtler (2000). $\Gamma$ for the LMC was thus found to be $5.8 \pm 0.5$ per cent.

### 4.5 The Milky Way (the solar neighbourhood)

Lada & Lada (2003) estimate the rate of embedded cluster formation within 2.0 kpc of the sun to be between 2 and 4 $\text{Myr}^{-1}$ kpc$^{-2}$, and claim the average mass of an embedded cluster to be $500 \, M_\odot$. Lada & Lada (2003) go on to estimate the number of embedded clusters that survive, with approximately 7 per cent surviving to the age of the Pleiades.

We convert the rate of embedded cluster formation to a mass formation rate assuming the average cluster mass of $500 \, M_\odot$, giving $0.15 \, M_\odot \, \text{yr}^{-1}$ in the solar neighbourhood. We calculate a value for $\Gamma$ by assuming the SFR is equal to the rate of embedded cluster formation. Comparing this to the mass found in older clusters, 7 per cent though estimates of this percentage varies between 4 and 14 per cent depending on the numbers used. Roberts (1957), Miller & Scalo (1978) and Adams & Myers (2001) also derived a similar percentage of star formation in clusters for the solar neighbourhood.

### 4.6 M83

Harris et al. (2001) presented a catalogue of 45 massive star clusters in the centre of M83, with reliable ages, masses and extinction values. Using this catalogue and a lower mass limit of $10^{5.6} \, M_\odot$ we calculated the total mass in clusters younger than 10 Myr to be $7.24 \pm 0.23 \times 10^{5} \, M_\odot$. To calculate the CFR we assume that clusters younger than 3 Myr old are embedded and so are unobservable. The resulting CFR is $0.10 \pm 0.01 \, M_\odot \, \text{yr}^{-1}$.

The paper of Harris et al. (2001) only covers the central region of M83 and so we used an H$\alpha$ image of M83 to measure the H$\alpha$ from the same region studied by Harris et al. (2001). We used archival narrow-band and $R$-band images of M83 taken as part of the Spitzer Infrared Nearby Galaxies Survey (SINGS) survey (Meurer et al. 2006). We measured the background subtracted flux for an identical area as that studied by Harris et al. (2001) and converted this flux to a SFR using the calibrations of Kennicutt (1998a), resulting in a SFR of $0.23 \pm 0.03 \, M_\odot \, \text{yr}^{-1}$. We correct this value for extinction using the reddening curves of Calzetti (2001). The extinction value was taken as the averaged extinction of all clusters in the Harris et al. (2001) sample, giving a correction of 1.71, the resulting dust corrected SFR is $0.39 \pm 0.06 \, M_\odot \, \text{yr}^{-1}$.

With the CFR and SFR known we calculate the value of $\Gamma$ to be $26.7 \pm 3.0$ per cent.

### 4.7 The Antennae galaxies

Ages and masses have been published for 752 clusters in the Antennae galaxies by Anders et al. (2007). We attempted to apply the same calculations as we did for other cluster populations, as described above. However, using different lower mass limits we obtained a range of values for $\Gamma$, from 60 per cent to < 100 per cent; assuming a SFR of $20 \, M_\odot \, \text{yr}^{-1}$ (Zhang, Fall & Whitmore 2001). Obviously values in excess of 100 per cent are unphysical and this problem is exacerbated by the range of quoted SFRs for the Antennae galaxies which can range from 5 to 20 $M_\odot \, \text{yr}^{-1}$ (Zhang et al. 2001; Knierman et al. 2003).

We investigated the slope of the mass function for young clusters and found that this data set presents a very shallow slope of $\alpha \approx 1.6$. Given that mass function slopes are usually in the range $1.8 < \alpha < 2.2$ (de Grijs et al. 2003a) a slope this shallow represents a very unusual population, unfortunately Anders et al. (2007) do not calculate a similar mass function for these clusters. Correcting for this shallow mass function gave results for $\Gamma$ that were still above 50 per cent and did vary significantly with the assumed lower mass limit. In comparison we noted that Fall et al. (2005) conclude that at least 20 per cent but possible all clusters form in clusters; the value for $\Gamma$ may well be high for the Antennae.
Table 3. A list of the possible sources of uncertainty in measuring $\Gamma$ for NGC 3625. The effect of each source is expressed as the factor applied to correct the measured value of $\Gamma$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Variation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMF slope ($\alpha$)</td>
<td>$\alpha = 1.8 - 2.2$</td>
<td>0.66 - 2.38</td>
</tr>
<tr>
<td>Schechter function</td>
<td>$M_* = 10^{5 - 10} M_\odot$</td>
<td>3.72 - 1.33</td>
</tr>
<tr>
<td>SSP fitting</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Metallicity</td>
<td>$Z = 0.5 - 2 Z_\odot$</td>
<td>0.5 - 2</td>
</tr>
<tr>
<td>Selection</td>
<td>–</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Table 4. Summary of results included in this paper.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>SFR $(M_\odot \text{ yr}^{-1})$</th>
<th>$A$ (kpc$^2$)</th>
<th>$\Gamma$ (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1569</td>
<td>0.3626</td>
<td>13</td>
<td>13.9 ± 0.8</td>
</tr>
<tr>
<td>NGC 3256</td>
<td>46.17</td>
<td>74.85</td>
<td>22.9 ± 2.8</td>
</tr>
<tr>
<td>NGC 5236 (M83)$^b$</td>
<td>0.3867</td>
<td>0.7077</td>
<td>26.7 ± 2.3</td>
</tr>
<tr>
<td>NGC 6946$^b$</td>
<td>0.1725</td>
<td>37.49</td>
<td>12.5 ± 1.8</td>
</tr>
<tr>
<td>LMC</td>
<td>0.1201</td>
<td>79</td>
<td>5.8 ± 0.5</td>
</tr>
<tr>
<td>SMC</td>
<td>0.0426</td>
<td>58.55</td>
<td>4.2 ± 0.2</td>
</tr>
<tr>
<td>Milky Way</td>
<td>0.1508</td>
<td>12.56</td>
<td>7.0 ± 1.0</td>
</tr>
</tbody>
</table>

Given the range of values we can calculate for $\Gamma$ based on the Anders et al. (2007) data set and the extremely shallow mass function of young clusters in this sample combined with the range in quoted SFRs for the Antennae we do not publish a value for this system. It serves as a reminder of how difficult these calculations can be and how dependent they are on accurate knowledge of the SFR.

5 THE VARIATION OF $\Gamma$ WITH SFR

In Table 4 we present all the information used hereafter, including the values of $\Gamma$, SFR and area over which these quantities were measured. The superscript ‘$^p$’ after the galaxy names indicates that only a partial area of the galaxy was used to derive these results, as described in the previous sections. At this point it is worth noting that because results have been obtained from various data sets the methodology used differs between results. Overall the consistency of results is thought to be robust as measurements of $\Gamma$ are based on the brightest and easiest clusters to detect which should give consistent results. It is harder to estimate the errors associated with $\Gamma$ based on other data sets. Results shown in Fig. 11 for galaxies other than NGC 3256 and the Milky Way only include errors associated with the uncertainty in the fraction of mass expected above whatever lower mass limit was used. Errors due to uncertainties in the metallicity and SSP fitting have not been estimated as this is difficult without reprocessing the entire data set.

Fig. 11 shows the relation between the SFR density ($\Sigma_{\text{SFR}}$) and $\Gamma$ for all galaxies discussed in this paper. In addition we plot results for three galaxies from Gieles (2009a) in which CFRs (and subsequently $\Gamma$) are calculated via comparison with empirical luminosity functions. It is immediately obvious that $\Gamma$ increases with the SFR density. Over three orders of magnitude a power-law relationship holds and the dot–dashed line shows a least-squares fit to the data of the form, $\Gamma \propto \Sigma_{\text{SFR}}^{0.03}$.

$$\Gamma \propto \Sigma_{\text{SFR}}^{0.03} (M_\odot \text{ yr}^{-1} \text{ kpc}^{-2})$$
From this equation we can predict at what density we might expect to see all stars in clusters, effectively a $\Gamma$ of 100 per cent, this would occur at a SFR density of $7.5 \times 10^3 M_\odot$ yr$^{-1}$ kpc$^{-2}$, a rather high value. Interestingly we can integrate this value over the time it takes a cluster to form, assuming this takes roughly 3 Myr we expect $2.25 \times 10^3 M_\odot$ pc$^{-2}$, which is approximately the density of a typical cluster.

Although the results taken from Gieles (2009a) are not calculated in the same manner as we have for other data sets these points fit the trend quite well, particularly at low SFR densities. It should be noted that our calculation of the best-fitting power law does not include these additional data points, given the different method used to determine these results, they are shown here to demonstrate the consistency of our results.

We have investigated whether the observed correlation (equation 3) could be due to a systematic effect, namely if the mass function index varied with environment. Assuming the LMC cluster distribution is well approximated with $\alpha = 2$, an index of $\alpha \sim 1.2$ would be required in order to bring the results of NGC 3256 into agreement with the LMC. This kind of gross deviation is ruled out by our direct observations of the cluster population (e.g. Fig. 4).

A similar conclusion (that more stars are formed in bound clusters with increasing SFR density) has been reached based on the fraction of light observed in clusters relative to the host galaxy. Specifically, Meurer et al. (1995) and Zepf et al. (1999) found this for merging/starburst galaxies and Larsen & Richler (2000) and Larsen (2004) found this for a larger sample that includes starburst and quiescent galaxies. While measuring the fraction of light in clusters is significantly easier than deriving $\Gamma$, hence suitable for construction of large surveys, it is affected by the star formation history of the galaxy and possibly by differential extinction effects. The exact relation between $\Gamma$ and the fraction of light observed in clusters will be modelled in a future paper.

Kennicutt (1999) investigated a global Schmidt–Kennicutt law across galaxies, correlating the SFR density to the surface gas density. As $\Gamma$ appears to follow a power-law relationship with the SFR density using the Schmidt–Kennicutt law defined in Kennicutt (1998b) we can construct a relation between $\Gamma$ and the surface gas density, shown in equation (4):

$$\Gamma \text{(per cent)} = (4.1 \pm 1.9) \Sigma_{gas}^{0.34\pm0.07} \ (M_\odot \text{ pc}^{-2}).$$  \hspace{1cm} (4)

We show the derived surface gas density corresponding to a given SFR density on the top axis of Fig. 11. Although our data only chart the value of $\Gamma$ for gas densities in the range $1–300 M_\odot$ pc$^{-2}$ it is insightful to interpret this relation to the more extreme star-forming environments. Arp220 represents one of the most active star-forming galaxies found (Wilson et al. 2006), with a global SFR of $240 M_\odot$ yr$^{-1}$ based on the far-IR luminosity of Sanders et al. (2003) and the calibration of Kennicutt (1998a). Assuming that Arp220 occupies an area of roughly 1 kpc$^2$ (Anantharamaiah et al. 2000) and thus has a surface area of 1 kpc$^2$ on the sky we can derive the SFR density is approximately $240 M_\odot$ yr$^{-1}$ kpc$^{-2}$. Such a high SFR density translates to a value of $\Gamma$ of roughly 85 per cent using equation (3), indicating that almost all the star clusters in Arp220 would be expected to survive the embedded phase, and the CMF would be almost identical to the true underlying initial CMF. Hence, there are regions where we would expect most/all young stars to be found in clusters.

6 CONCLUSIONS

Over the course of this paper we have shown that it is possible to accurately measure the fraction of stars found within young clusters, a parameter we have termed $\Gamma$. This is achieved by obtaining ages and masses for the cluster population of NGC 3256 through multiple waveband photometry and comparison with SSP models. We have also been able to calculate $\Gamma$ for several other galaxies using published cluster populations. We examined how $\Gamma$ varies with the SFR of the host galaxy and we summarize our conclusions in the following.

(i) The cluster formation history of NGC 3256 shows an increase in the SFR over the last 100 Myr, most likely caused by the ongoing merger of the two progenitor spiral galaxies. The CMF for NGC 3256 is best described by a power law with slope $\alpha = 1.85 \pm 0.12$.

(ii) $\Gamma$ may be calculated directly if an accurate cluster population is known; however, there are several possible sources of error in making these calculations. The effect of SSP fitting must be taken into account and an unknown metallicity may produce additional uncertainties. Selection effects may also alter the value of $\Gamma$ but this can be estimated. The calculated $\Gamma$ does depend on the form of the cluster mass function used, we assume a simple power-law function with slope $\alpha = 2.0$. We have shown that a Schechter function produces similar but higher values; however, this effect is small if the $M_*$ is high ($M_* > 10^6 M_\odot$).

(iii) We found a weak positive correlation of $\Gamma$ with the total SFR. We find a strong relation between $\Gamma$ and the SFR density, which we have written as a power-law type relation, $\Gamma$ (per cent) = $(25 \pm 6.0) \Sigma_{SFR}^{0.22\pm0.05} \ (M_\odot$ yr$^{-1}$ kpc$^{-2}$). This is similar to that found by Larsen & Richler (2000) for the fraction of $U$-band light in clusters relative to the total galaxy. This result can also be interpreted as a correlation with the surface gas density through the Schmidt–Kennicutt law (Kennicutt 1998b). This implies that either clusters born in high density environments are more resistant to disruption in the embedded phase, or the environment changes the fraction of stars born in clusters.

Measuring $\Gamma$ is not trivial and it does have several sources of error which must be taken into account. However, it is possible to
make these calculations which may be further refined with consistent measurements using the same instruments, detection methods and cluster fitting models. This paper is intended to show that if all sources of uncertainty are taken into account and measured then calculating $\Gamma$ is possible. Future work, including larger homogenous samples and deeper observations to constrain the form of the cluster mass function to lower masses, will be needed to conclusively investigate the intriguing relation between $\Gamma$ and the SFR density of the host galaxy.

**ACKNOWLEDGMENTS**

We thank Søren Larsen and Mark Gieles for valuable discussions and suggestions. NB is supported by an STFC Advanced Fellowship.

**REFERENCES**

Kennicutt R. C., Jr, 1998a, ARA&A, 36, 189
Savage B. D., Mathis J. S., 1979, ARA&A, 17, 73

**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this paper:

**Table 5.** Cluster photometry and parameters for the 276 good cluster fits.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a TeX/\LaTeX file prepared by the author.