On the star formation rate – brightest cluster relation: estimating the peak star formation rate in post-merger galaxies

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Accepted 2008 July 29. Received 2008 July 23; in original form 2008 June 22

ABSTRACT
We further the recent discussion on the relation between the star formation rate (SFR) of a galaxy and the luminosity of its brightest star cluster (SFR versus $M_{\text{V\,\,brightest}}$). We first show that the observed trend of SFR versus $M_{\text{V\,\,brightest}}$ is due to the brightest cluster in a galaxy being preferentially young ($\leq 15$ Myr – for a constant SFR) and hence a good tracer of the current SFR, although we give notable exceptions to this rule. Archival Hubble Space Telescope (HST) imaging of high-SFR galaxies, as well as additional galaxies/clusters from the literature, is used to further confirm the observed trend. Using a series of Monte Carlo simulations, we show that a pure power-law mass function with index $\alpha = 2$ is ruled out by the current data. Instead, we find that a Schechter function (i.e. a power law with an exponential truncation at the high-mass end) provides an excellent fit to the data. Additionally, these simulations show that bound cluster formation (in $M_\odot\,\text{yr}^{-1}$) represents only $\sim 8\pm 3$ per cent of the total star formation within a galaxy, independent of the SFR. From this, we conclude that there is only a single mode of cluster formation which operates over at least 6 orders of magnitude in the SFR. We provide a simple model of star/cluster formation feedback within dwarf galaxies (and star-forming complexes within spirals) which highlights the strong impact that a massive cluster can have on its surroundings.

Using this relation, we can extrapolate backwards in time in order to estimate the peak SFR of major merger galaxies, such as NGC 7252, 1316 and 3610. The derived SFRs for these galaxies are between a few hundred and a few thousand solar masses per year. The inferred far-infrared luminosity of the galaxies, from the extrapolated SFR, places them well within the range of ultraluminous infrared galaxies (ULIRGs) and for NGC 7252 within the hyperluminous infrared galaxy (HLIRG) regime. Thus, we provide evidence that these post-merger galaxies passed through a ULIRG/HLIRG phase and are now evolving passively.

Key words: galaxies: starburst – galaxies: star clusters.

1 INTRODUCTION
Young, massive star clusters, which often surpass the globular clusters in the Galaxy in terms of brightness, mass and density, are seen to result from intense episodes of star formation in galaxies. However, star clusters are also found in relatively quiescent, low star formation rate (SFR) galaxies, albeit at much lower masses (e.g. Larsen & Richtler 1999, Larsen & Richtler 2000). This difference in the types (mass) of clusters produced in various galactic environments has been suggested to be caused by size-of-sample effects, in which galaxies with high SFRs form proportionally more clusters, and hence are able to sample the cluster mass function out to higher masses (Larsen 2002).

This effect has been quantitatively observed through the use of the SFR versus $M_{\text{V\,\,brightest}}$ relation (Larsen 2002), where $M_{\text{V\,\,brightest}}$ is the brightest cluster in $V$-band absolute magnitude, in the sense that the most luminous clusters in galaxies with high SFRs are brighter. This trend, along with the similar log $N$ versus $M_{\text{V\,\,brightest}}$ relation (where $N$ is the number of clusters brighter than a certain magnitude limit; Whitmore 2003), has been used to argue for a universality of cluster formation, i.e. stochastic sampling from a universal underlying mass function.

Size-of-sample effects, together with cluster population synthesis models (e.g. Gieles et al. 2005), have become a common means to investigate the properties of clusters and cluster systems. For example, Hunter et al. (2003) used the relation of the most massive cluster per logarithmic age bin in the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) in order to estimate the exponent of the cluster initial mass function (IMF; $\alpha$). This
procedure was recently revisited by Gieles & Bastian (2008) who used the same relation to rule out mass-independent, long-duration (>10 Myr), cluster-disruption models. Gieles et al. (2006a) used the log $N$ versus $M_{V}^{\text{brightest}}$ relation to constrain $\alpha$, and found a value of $\sim 2.4$, which is similar (2.3) to that derived by Weidner, Kroupa & Larsen (2004) using the SFR versus $M_{V}^{\text{brightest}}$ relation. This is significantly steeper than that derived from direct measurements of the mass/luminosity function of galaxies, namely $\alpha = 2.0 \pm 0.1$ (e.g. de Grijs et al. 2003). This discrepancy will be addressed in Section 4.

Wilson et al. (2006) have tested whether the above relations still hold in the extreme environment of galaxy merger starbursts. They studied the ultraluminous infrared galaxy (ULIRG) Arp 220, and found that despite its high SFR ($\sim 240 \text{M}_\odot \text{yr}^{-1}$), being an order of magnitude higher than any of the galaxies in the previous samples, it falls nicely on the extrapolated fit to the more quiescent star-forming galaxies.

Weidner et al. (2004) used the SFR versus $M_{V}^{\text{brightest}}$ relation to constrain cluster formation scenarios, namely the time-scale over which clusters form, which they estimate to be of the order of a crossing time. They further suggest that a cluster population formation epoch (i.e. the time-scale over which statistically full population of clusters is formed) is of the order of 10 Myr. However, their analysis was based on the assumption that within a ‘cluster population formation epoch’ the brightest cluster of a galaxy is also the most massive, hence that the SFR versus $M_{V}^{\text{brightest}}$ trend is simply reflecting a relation between the SFR of a galaxy and the most massive cluster within it. Observationally, it appears that this assumption is not valid, as the brightest cluster in a galaxy tends to be young, and more massive, older clusters may appear less luminous due to stellar evolution (Gieles et al. 2006a).

In this work our goals are threefold. The first is to test the claim by Weidner et al. (2004) that the brightest cluster within a galaxy is also the most massive. This naturally leads to a discussion as to why the observed SFR versus $M_{V}^{\text{brightest}}$ relation holds. The second is to investigate the implications of the observed relation, paying particular attention to the cluster IMF, and the implied connection between the cluster and SFRs within a galaxy. Thirdly, using the observed trend, combined with a correction for stellar evolutionary fading, to estimate the SFR in a sample of post-starburst merger galaxies. This, in turn, allows us to place limits on the duration of the starburst phase of ULIRGS as well as trace their subsequent evolution.

In Section 2, we present archival observations of two ongoing galaxy mergers and a collection of data taken from the recent literature. Section 3 presents a series of Monte Carlo simulations of cluster populations in order to investigate why the observed SFR versus $M_{V}^{\text{brightest}}$ relation holds. In Section 4, we investigate the implications for the underlying cluster IMF, the relation between star and cluster formation, and use the observed relation to derive the peak SFR of post-starburst galaxies. Our conclusions are presented in Section 5.

2 OBSERVATIONS AND DATA FROM THE LITERATURE

2.1 NGC 2623

NGC 2623 is a luminous infrared galaxy which shows clear evidence of an ongoing merger, namely two long tidal tails and a large amount of ongoing star formation. It was observed with the Advanced Camera for Surveys (ACS) Wide-Field Camera (WFC) onboard the Hubble Space Telescope (HST) on 2004 June 2 (F555W; Prop. ID 9735) and 2005 November 11 (F435W, F814W; Prop. ID 10592). We obtained the reduced and calibrated drizzled images through the European Southern Observatory (ESO)/HST archive. We adopt a distance to NGC 2623 of 77.1 Mpc (assuming $H_0 = 72 \text{km s}^{-1} \text{Mpc}^{-1}$).

Aperture photometry was carried out (using a 10 pixel aperture and a background annulus from 12 to 14 pixels) on the brightest source in the F555W image and zero-points from the ACS website were applied. The brightest V-band cluster has $B$ (F435W), $V$ (F555W) and $I$ (F814W) apparent magnitudes of 20.7, 20.3 and 19.6, respectively (vegamag system). A correction for Galactic extinction was then applied ($A_V \approx 0.1$; Schlegel, Finkbeiner & Davis 1998). In order to estimate the extinction of this cluster, we employed a $B - V$ versus $V - I$ colour–colour plot. Adopting the Galactic extinction law of Savage & Mathis (1979), we find an extinction, $A_V$, of 0.3 mag was necessary in order to bring the cluster colours into agreement with the SSP models. Applying this, along with the adopted distance modulus, results in an absolute V-band magnitude of $-14.5$ for this cluster.

2.2 NGC 3256

NGC 3256 is part of the Toomre sequence of merging galaxies and has the highest current SFR and X-ray luminosity of any galaxy in the sequence. It is known to harbour an extensive cluster population which has been studied photometrically (Zepf et al. 1999) as well as spectroscopically (Trancho et al. 2007a,b). We adopt a distance of 37 Mpc (Zepf et al. 1999) and a Galactic foreground extinction of $A_V = 0.4$ mag (Schlegel et al. 1998). NGC 3256 was observed with the ACS-WFC onboard HST on 2003 November 18 (F555W; Prop. ID 9735) and 2005 November 6 (F435W, F814W – Prop. ID 10592). We obtained the images in the same manner as for NGC 2623.

We performed aperture photometry of the brightest cluster visible in the F555W image using the same techniques as above. We find that the brightest cluster has $B$ (F435W), $V$ (F555W) and $I$ (F814W) magnitudes of 16.9, 17.0 and 16.36, respectively. We have not applied any correction for intrinsic extinction. Applying the Galactic extinction and distance modulus, we find $M_V = -15.7$ for this cluster.

2.3 Additional galaxies from the literature

In Table 1, we list the $M_V$ of the brightest cluster and the estimated SFR for a sample of galaxies taken from the literature. We have focused our study on moderate-to-high SFR galaxies ($>1 \text{M}_\odot \text{yr}^{-1}$) in order to strengthen the observed trend for extrapolation to higher cluster luminosities and SFRs. References for the brightest cluster and SFR are given, where S03 refers to a SFR estimated from the infrared luminosity (taken from Sanders et al. 2003) and SFR/LIR relation of Kennicutt (1998). In the case of IRAS 19115–2124 (Väisänen et al. 2008), we used the brightest I-band cluster ($M_I = -17.5$; Väisänen, private communication) and applied a $V - I$ colour of 0.7 (typical of young clusters), in order to estimate the V-band magnitude.

The galaxy with the highest SFR in the sample is Arp 220, which was studied in detail by Wilson et al. (2006). They showed that this cluster fits the observed SFR versus $M_{V}^{\text{brightest}}$ relation quite well, even though the galaxy has a SFR that is an order of magnitude higher than any other galaxies previously used in the relation. Here
we fill in that gap and show that it is indeed a continuous relation (see Fig. 1).

In addition, we include the low-luminosity H II regions in the extreme outskirts of NGC 1533 which have recently been studied by Werk et al. (2008). These low-SFR regions (10\(^{-3.75}\) M\(_{\odot}\) yr\(^{-1}\)) are a welcome opportunity to test the low-SFR regime and also test at what physical scale (i.e. galactic, H II region, etc.) does the relation break down. The points lie at the lower-left of Fig. 1 and can be seen to follow the extrapolated relation reasonably well.

One additional caveat is that all points in Fig. 1 are in fact lower limits in the y-direction. The reason for this is that most of the studies used in the construction of Fig. 1 were based on optical studies, and hence possibly affected by extinction. Thus, it is impossible to rule out the possibility that a brighter cluster in the V band was missed due to extinction effects. However, the tight observed correlation suggests that this does not significantly bias the results.

3 THE RELATION BETWEEN THE SFR AND THE BRIGHTEST CLUSTER

The relation between the SFR of a galaxy and the brightest cluster within it is empirically based, and was originally given a statistical (i.e. size-of-sample) explanation (Larsen 2002). However, Weidner et al. (2004) suggested that the underlying cause was that a full, statistically complete cluster population was formed every \(\sim 10\) Myr, and that this rapid formation time-scale was at the basis of the observed SFR/cluster relation. For this, the authors assumed that the most massive cluster in a population is normally also the brightest.

In order to test this assertion, we performed a simple series of Monte Carlo simulations of cluster populations. We create 100 realizations of a cluster population in a galaxy. The clusters are drawn stochastically from a mass function (a power law with an index of \(-2\)) with a lower limit of 100 M\(_{\odot}\) and an upper limit drawn stochastically from a mass function (a power law with an index of \(-2\)) with a lower limit of 100 M\(_{\odot}\) and an upper limit

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**Figure 1.** The observed relation between the SFR of a galaxy and the V-band luminosity of the brightest cluster within the galaxy. Galaxies taken from Larsen (2002) are shown as filled triangles. Solid circles represent galaxies from Table 1. Filled stars represent the special cases of NGC 1569 (lower left) and NGC 7252 (upper right), where instead of the brightest cluster of the full population, we have chosen the brightest young cluster (<10 Myr). The diamond represents the third brightest cluster in NGC 34 as the first two have ages of \(\geq 150\) Myr. The best fit to the data from Weidner et al. (2004) is shown as a dashed line. Regions occupied by (ultra/hyper) luminous infrared galaxies are also shown, assuming the relation between infrared luminosity and SFR of Kennicutt (1998). The dotted line shows the expected relation for a pure power-law (\(\alpha = 2\)) case if all stars formed in bound clusters (see Section 4 for details). Expected error bars from stochastic sampling are shown in the upper left of the panel, along with assumed errors in the SFR.
of $10^{12} \, \text{M}_\odot$ (effectively no upper limit), and originally we create 5000 clusters. The clusters are then assigned ages randomly between 0 and 100 Myr [in order to simulate a constant cluster formation rate (CFR)]. We then calculate the absolute magnitude of each cluster, using the cluster’s age and mass, from simple stellar population models [Bruzual & Charlot 2003; solar metallicity, Salpter stellar IMF]. Once this is carried out for a single realization, we search the population for the brightest cluster and the most massive (which are not necessarily the same cluster) along with the corresponding clusters’ ages. The average CFR is found by dividing the total mass formed in clusters by the duration of the experiment (i.e. 100 Myr).

Fig. 2 shows the cumulative distribution of the fraction of realizations whose brightest cluster is younger than a given age (solid black line). We also show the age distribution of the most massive cluster. The 50 percentile mark is also shown, which we identify as the brightest cluster. The results shown are lower limits since we have not included any mass loss in the simulations, but only stellar evolution. Additionally, we show the cumulative distribution of the age where the most massive cluster appears as a thick dashed line. This is clearly weighted towards older ages, hence the brightest cluster is often not the most massive.

3.1 Exceptions that prove the rule – the example of NGC 7252

The above experiments assumed that the CFR of a galaxy was approximately constant during the duration of the simulations (100 Myr). However, this assumption clearly does not hold for starbursts, in which a galaxy can undergo a significant enhancement of its SFR for extended periods. To demonstrate this effect, we use the merger remnant NGC 7252 as an example. This galaxy is likely to have been produced by an equal-mass gas-rich spiral/spiral galaxy merger (Hibbard & Mihos 1995) approximately 500–1000 Myr ago (Schweizer & Seitzer 1998). NGC 7252 is an outlying point in the SFR versus $M_v^{\text{brightest}}$ relation, being significantly above the fit to the other galaxies ($\sigma > 4 \sigma$, i.e. its brightest cluster is too bright for its

\footnote{Where $\sigma$ is calculated from the difference between the observed $M_v^{\text{brightest}}$ and the best-fitting relation and error by Weidner et al. (2004).}
The SFR then dropped due to the lack of dense gas, and henceforth only smaller clusters could be formed. A schematic diagram of this process is shown in Fig. 3. In such a model, galaxies which fall to the left of the observed trend in Fig. 1 should have older brightest clusters than the average cluster used in the diagram, i.e. have ages larger than 10–20 Myr, so that enough time has passed for the clusters to have had a large influence on the surrounding ISM.

Additional evidence can be found in the young stellar clusters in this galaxy. Anders et al. (2004) have catalogued and age-dated approximately 160 clusters in NGC 1569. Using their data set, and looking at only those clusters with ages less than 10 Myr, we find that the brightest young cluster in the galaxy has $M_V = -10.31$. It is this cluster that should be used in comparison with the current SFR. In Fig. 1, we show the position of this cluster in the SFR versus $M_V^{\text{brightest}}$ diagram as the lower filled star. This cluster appears to fit the relation splendidly, hence arguing that the cluster formation process is not intrinsically different in dwarfs and spirals.

NGC 1705, the other dwarf post-starburst galaxy that lies significantly to the left of the observed relation, also has had an explosive outflow attributed to the formation of its most massive cluster which occurred $\sim 12$ Myr ago (Vázquez et al. 2004). This galaxy as well seems to have drastically reduced its SFR through the feedback associated with forming massive clusters.

However, we note that NGC 1140 appears to be $1.5\sigma - 2\sigma$ off the expected SFR versus $M_V^{\text{brightest}}$ relation. This galaxy has been classified as an amorphous galaxy (Hunter, van Woerden & Gallagher 1994), having recently undergone a strong interaction. However, it may have originally been a low-luminosity late-type spiral (Hunter et al. 1994). This galaxy has a current SFR of about $0.8 M_\odot \text{yr}^{-1}$ and a brightest cluster of $M_V = -14.8$ which has an age of 4–7 Myr (Moll et al. 2007). Due to the young age of the cluster, we would expect it to accurately reflect the current SFR in the galaxy. If this cluster/galaxy represents a statistical fluctuation or a real physical difference cannot be concluded at this time.

This conceptual model makes two predictions. The first is that there should be a few/no galaxies which lie significantly below the observed SFR versus $M_V^{\text{brightest}}$ relation (i.e. more than random sampling would predict), only above. The second is that galaxies which lie significantly above the relation should have brightest clusters which are older than the average age of clusters whose galaxies fit the relation.

### 3.3 Intense star-forming complexes within galaxies

This same effect, i.e. feedback from massive stars/clusters causing a drop in the SFR, is likely to happen within individual star-forming complexes within galaxies. For example, the dwarf/irregular starburst galaxy NGC 1705, which has a current SFR of about 0.8 $M_\odot \text{yr}^{-1}$ and a brightest cluster of $M_V = -14.8$ which has an age of 4–7 Myr (Moll et al. 2007). Due to the young age of the cluster, we would expect it to accurately reflect the current SFR in the galaxy. If this cluster/galaxy represents a statistical fluctuation or a real physical difference cannot be concluded at this time.

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regions within spiral galaxies (e.g. Shetty & Ostriker 2008), like those found in M51 or the Antennae galaxies (Bastian et al. 2005, 2006a). Here, the important length-scale is that of the GMC. Once the GMC begins to form clusters, the clusters, through radiative feedback, destroy the host GMC, and eventually halt star formation within the region/complex. Thus, we would predict older complexes to lie to the left of the observed SFR versus $M_{\text{V, brightest}}$ relation while predicting young ones (i.e. currently forming) to lie on the relation, where the SFR should be estimated over the region of interest.

4 DISCUSSION AND IMPLICATIONS

4.1 The cluster initial mass function

The SFR versus $M_{\text{V, brightest}}$ or equivalently $N_{\text{clusters}}$ versus $M_{\text{V, brightest}}$ relations have been used previously in order to constrain the IMF of clusters. Multiple studies have reported that the observed correlation is consistent with a power-law mass function with index, $\alpha = 2.3$–2.4 (Larsen 2002; Whitmore 2003; Weidner et al. 2004; Gieles et al. 2006a). This, however, is inconsistent with direct measurements of the mass function which generally find $\alpha = 2.0$ (e.g. Zhang & Fall 1999; de Grijs et al. 2003; McCrady & Graham 2007).

Gieles et al. (2006a) have suggested that instead of a power-law mass function, the underlying mass distribution of clusters is better described by a Schechter function. This gives the standard $\alpha = 2$ form on the low-mass side, but is truncated on the high-mass side above some critical value $M_\star$. This type of function is physically motivated, as GMCs (i.e. the material from which clusters form) appear to have a power-law mass function which is truncated at the high-mass end (e.g. Rosolowsky et al. 2007).

In order to test this assertion, we develop the following model. We generate 50 cluster populations for 11 CFR and stochastically sample an underlying Schechter mass function with a lower cluster mass limit of 100 $M_\odot$, a truncation mass $M_\star$, and an upper mass limit $M_m \gg M_\star$. Each population is generated with $N$ clusters which are assigned ages randomly between 0 and 100 Myr. We then calculate the absolute magnitude of each cluster, in the same way that Weidner et al. (2004) have fit the data. For each simulation, we calculate the average CFR by dividing the total mass in clusters formed in each population by the age range sampled (i.e. 100 Myr).

The top panel of Fig. 4 shows the results of the simulations for various values of $M_\star$, where the points and lines represent the mean in the logarithm of the SFR and magnitude of the 550 realizations for each value of $M_\star$. The values of $M_\star$ and the resulting slopes from linear least-square fits to the unbinned data points [i.e. in the same way that Weidner et al. (2004) have fit the data] are also shown in the figure. The bottom panel of Fig. 4 shows the same simulations but with the CFR translated into a SFR using $\Gamma = 0.08$ (the fraction of star formation which happens in bound clusters), which will be discussed in detail in Section 4.2. The dashed line in both panels is the observed relation, taken from Weidner et al. (2004), which has a slope of $-1.87$. As can be seen, low values of $M_\star(1–5 \times 10^4 M_\odot)$ do not fit the data well in the high-SFR regime, and high $M_\star$ values (i.e. pure power laws with index of $-2.0$) overpredict the magnitude of the brightest cluster for a given SFR. However, values of $M_\star$ of $1–5 \times 10^5 M_\odot$ appear to fit the observed trend quite nicely.

Weidner et al. (2004) found that the observations were best fit by $M_{\text{V, brightest}} \propto -1.87(\pm0.06) \times \text{SFR}$. This is $>8\sigma$ off that expected from the pure power law, $\alpha = 2$ case (seen as the green line with triangles in Fig. 4), hence we conclude that this is ruled out by the current data.

The rather high values of $M_\star$ which do fit the data ($1–5 \times 10^5 M_\odot$) make a direct comparison (i.e. a binned mass distribution) between a power law and a Schechter mass function extremely difficult, as the two populations only differ by a handful of the most massive clusters. An example of this is found in Whitmore, Chandar & Fall (2007) who found a lack of massive clusters at the high-mass end of the mass distribution in the Antennae galaxies compared to a pure power law with an index of $-2$, and they note that an index of $-2.0$ to $-2.2$ is required. This difference was near the Poissonian limit so no strong conclusion could be reached.

However, size-of-sample effects, like the SFR versus $M_{\text{V, brightest}}$ relation, which rely on only the brightest cluster in a sample, are
4.2 The relation between the cluster and SFRs

In order to compare our Monte Carlo cluster population simulations to the observed data, we need to apply a correction factor between the CFR and the SFR, which we define as $\Gamma \equiv \text{CFR}/\text{SFR}$. This factor enters as a horizontal scaling in Fig. 4 (i.e. the horizontal shift between the top and bottom panels). In order to equate our best-fitting simulations (in terms of the slope of the relation, i.e. a Schechter function with $M_\star = 1-5 \times 10^9 M_\odot$) to the observations, we needed to use $\Gamma = 0.08 \pm 0.03$, meaning that optically selected ‘bound’ clusters represent only 8 per cent of the total star formation of a galaxy. If we instead adopt a pure power law with index $\alpha = 2.3$, then $\Gamma = 0.2$. By ‘bound’ we refer to clusters which have survived the transition from being embedded in molecular gas to being exposed, and hence possible to be included optically selected cluster samples (see Goodwin 2008 for a recent review of this transition period). Additionally, the cluster must be compact enough so as to make it into cluster samples, for which it is often assumed that the cluster must then be gravitationally bound. Note, however, that we cannot constrain the fraction of stars which are formed in dense clusters relative to the field or loose association. We can only constrain the fraction of stars, relative to the total, which end up in bound clusters after the transition from embedded to exposed.

It is also possible to shift the other simulations on to the observed data using a conversion factor that is dependent on the SFR. However, for the pure power-law case with an index of $\alpha = 2.3$, the slope is the same as for the power-law exponent in the Schechter function. If $M_\star$ is, however, weakly correlates with the SFR (as might be expected if $M_\star$ is dependent on galaxy type), then the slope would be preserved beyond the plotted bounds in Fig. 4.

4.3 Inferring the SFR of galaxies in the past

Combining equation (2) in Weidner et al. (2004), which is shown as a dashed line in Fig. 1, and equation (4) in Kennicutt (1998), one can find the relation between the brightest cluster, the SFR and the infrared luminosity of a galaxy. However, as noted above, the brightest star cluster associated with that epoch of star formation must be used. By using the brightest cluster in a galaxy, and accounting for cluster fading due to stellar evolution using simple stellar population models, one can obtain an estimate of the SFR during the epoch of the formation of that cluster. This is similar to what has been done by Maschberger (2007); however, instead of deriving the full star formation history of a galaxy, we are interested in what was the peak SFR in that galaxy’s (recent) history.

For such a study, post-galaxy mergers are an ideal place to look, as they are known to form copious amounts of massive clusters (e.g. Schweizer 1987; Ashman & Zepf 1992). Since major mergers of galaxies are relatively rare in the local universe, one can look at the fossil remnants which are much more prevalent, in order to infer the conditions during the merger. Many nearby ($<100$ Mpc) merger remnants have had their star-cluster populations catalogued, and here we will estimate the SFR and peak $\log (L_{\text{IR}}/L_\odot)$ in order to see the prevailing conditions at the time of the cluster formation and whether these galaxies passed through a ULIRG/HILIRG phase.

Combining the observed SFR versus $M_\star^\text{brightest}$ relation and that between the SFR and far-infrared luminosity (Kennicutt 1998) results in the equations:

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = 10^{\frac{M_\star^\text{brightest}+12.14}{-1.87}},$$

(1)

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = 4.5 \times 10^{44} L_{\text{FIR}} \text{ erg s}^{-1},$$

(2)

$$M_\star^\text{brightest} + 12.14 = \log(4.5 \times 10^{44} L_{\text{FIR}}).$$

(3)

The results for seven post-merger galaxies are given in Table 2. We have used the published values of $M_\star$ and cluster age, and used the Bruzual & Charlot (2003) SSP models (solar metallicity and Salpeter stellar IMF) in order to estimate the absolute magnitude of the brightest cluster at an age of 10 Myr, $M_\star^{10\text{Myr}}$. The estimated values of $M_\star^{10\text{Myr}}$ are lower limits since we have not attempted

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2 We note that these results are largely independent of the adopted lower cluster mass limit (for which we use 100 $M_\odot$), since the CFR is determined after each population has been constructed (total mass in clusters divided by the duration of the experiment). Hence, for a given number of clusters generated, decreasing the lower limit decreases the CFR and decreases the expected $M_\star^\text{brightest}$, hence shifting the curves along their slopes.

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to correct for mass loss due to tidal/dynamical effects, which are expected to be relatively small since the mass loss is inversely related to cluster mass (e.g. Baumgardt & Makino 2003; Lamers et al. 2005).

Additionally, the peak $L_{IR}$ values quoted here are also lower limits since they do not consider any active galactic nuclei (AGN) component which may have been present. It has been noted (e.g. Veilleux, Sanders & Kim 1999) that the fraction of galaxies with a clear AGN component increases with increasing luminosity. However, Verma et al. (2002) note that in their sample of four hyperluminous infrared galaxies (HLIRGs), three needed substantial fraction of the LIRG to come from an obscured starburst (from 30 to 75 per cent of the total LIR luminosity).

NGC 7252 stands out among the others in its estimated SFR ($>4000 M_\odot$ yr$^{-1}$) and its peak luminosity would clearly place it in the range of HLIRGs. Verma et al. (2002) have decomposed the infrared spectra of two HLIRGs into their starburst and AGN components, and have estimated SFRs above 3000 $M_\odot$ yr$^{-1}$. If, instead of W3, we used the second brightest cluster in the NGC 7252, W30, the implied SFR and peak $L_{IR}$ would be $\sim 600 M_\odot$ yr$^{-1}$ and $10^{12.5} L_\odot$, respectively. While still well within the ULIRG category, this shows the sensitivity and limitations of the method used here. One possibility to decrease this sensitivity would be to use, the, say, three or five brightest clusters, which would reduce the sampling scatter.

Young clusters do not form in isolation but are often, instead, found in cluster complexes (e.g. Bastian et al. 2005; Bastian et al. 2006a). Within these complexes, cluster merging may be an important mechanism in building massive clusters (e.g. Fellhauer & Kroupa 2002; Kissler-Patig, Jordán & Bastian 2006). Through merging, it is possible to raise a galaxy in the SFR versus $M_{\text{V}}$ (SFR) relation, as the brightness of the most luminous cluster would increase through cluster mergers, but the SFR would remain unchanged. We do not expect this to bias our results substantially, as the SFR versus $M_{\text{V}}$ relation is empirically derived, and this effect may already be included. However, if a significant amount of merging happens after the first 15–20 Myr of a cluster’s life, the current (stellar evolutionary corrected) magnitudes would be overestimates leading to high SFR and $L_{IR}$ derivations.

4.4 Duration of the LIRG/ULIRG phase

One galaxy, NGC 34, stands out as unique in the sample assembled here. It is currently a LIRG with a far-IR luminosity of $10^{11.44} L_\odot$, which translates to a SFR of 75–90 $M_\odot$ yr$^{-1}$ (S03; Prouton et al. 2004). However, it appears to have had a higher SFR in the past. Schweizer & Seitzer (2007) have obtained spectroscopic ages of the two brightest clusters ($M_{\text{V}}$ = −15.36) in the galaxy, and have derived ages of $\sim 150$ Myr (although they note that cluster 2 may be nearly four times older). Correcting for evolutionary fading and applying equations (1)–(3) give an absolute $V$-band magnitude at 10 Myr, peak SFR and peak $L_{IR}$ of −17.3 mag, $\sim 600 M_\odot$ yr$^{-1}$ and $10^{12.5} L_\odot$, respectively. Therefore, we can infer that the SFR and $L_{IR}$ have both been declining for the past 150 Myr to the current levels, and that this time-scale is a lower limit to the duration of the LIRG/ULIRG phase. If cluster 2 is indeed four times older, then the ULIRG duration for this galaxy is at least $\sim 600$ Myr, or if the SFR has not been continuous, then NGC 34 has gone through multiple ULIRG phases.

5 CONCLUSIONS

Using the empirically derived relation between the SFR and the luminosity of the brightest star cluster within the galaxy (Larsen 2002), we have investigated the conditions (SFR and infrared luminosity) that were present during the peak star-forming epoch of galactic mergers. We began with a series of simple Monte Carlo simulations of cluster populations with different assumptions on the underlying cluster mass function, and showed that, independent of the model construction, the youngest clusters (<10 Myr) were predominantly the brightest. This, along with size-of-sample effects, can explain the observed SFR versus $M_{\text{V}}$ (SFR) relation, as the young clusters should be a good representation of the current SFR.

Using data from the literature as well as archival HST imaging, we have further tested the high-SFR regime of the relation. We found, in agreement with the results of Wilson et al. (2006), that the relation continues to hold up to SFRs of a few hundred solar masses per year.

We have also presented a schematic model (following on Weidner et al. 2004) to explain why some dwarf (post) starburst galaxies lie on the left of the observed relation. The basic model is that the formation of a massive cluster is enough to disturb a substantial part of the galaxy, and cause an ISM blowout (as seen in NGC 1569) which effectively terminates further star formation. This same process is expected to take place within star-forming complexes in spiral galaxies.

By generating a large sample of Monte Carlo simulations of cluster populations with varying underlying IMFs and CFR, we have shown that the observed SFR versus $M_{\text{V}}$ (SFR) relation is best fitted by a Schechter mass function with $M_\star = 1.5 \times 10^6 M_\odot$. This rather high value of $M_\star$ makes it extremely difficult to detect a difference between a pure power law or a Schechter-type mass function directly (i.e. through binned cluster mass distributions).

Table 2. The properties of galactic merger remnants.

| Galaxy | Cluster ID | $M_{\text{V}}$ (mag) | Age (Myr) | Peak SFR (M$_\odot$ yr$^{-1}$) | Peak log ($L_{IR}$) (L$_\odot$) |
|--------|------------|---------------------|-----------|-------------------------------|-------------------------------|
| NGC 7252 | W3 | −16.2 | −18.9 | 400 | 4131 | 13.4 |
| NGC 7252 | W30 | −14.6 | −17.3 | 400 | 576 | 12.5 |
| NGC 1316 | GI14 | −13.0 | −17.6 | 3000 | 853 | 12.7 |
| NGC 3921 | S1 | −12.5 | −15.3 | 450 | 50 | 11.5 |
| NGC 3610 | 1 | −11.6 | −16.5 | 4000 | 218 | 12.1 |
| NGC 1700 | 1 | −10.9 | −15.8 | 4000 | 91 | 11.7 |
| NGC 34 | 1 | −15.4 | −17.3 | 150 | 601 | 12.5 |
| NGC 3597 | − | −13.2 | −16.4 | 200 | 57 | 11.5 |

*This is the second brightness cluster in the galaxy, given here as an example of the uncertainties in the method.*
However, size-of-sample effects which rely heavily on the most massive or brightest object in a sample are much more sensitive to small differences between these two functions at the high-mass end. We find that the data are inconsistent with the pure power law, $\alpha = 2$ case at the $>8r$ level.

Using this set of simulations, we also showed that a constant fraction of star formation goes into clusters. This fraction, which we term $\Gamma$, is $0.08 \pm 0.03$, meaning that optically selected clusters represent only 8 per cent of the total star formation in a galaxy. This is similar to that found for the solar neighbourhood by Lada & Lada (2003) and Lamers & Gieles (2008), and it is also in fair agreement with that derived for the SMC, namely 2–4 per cent (Gieles & Bastian 2008). $\Gamma$ appears to be independent of the SFR over 6 orders of magnitude. From this, we conclude that cluster formation does not have ‘multiple modes’ and that the cluster formation history of a galaxy should accurately reflect its star formation history (once a proper accounting of the CFR and variance in the stellar fields are taken into account).

Using the fit to the SFR versus $M^\text{bright}_{\text{host}}$ relation by Weidner et al. (2004), and extrapolating to higher SFRs, we have estimated the peak SFR and infrared luminosity of seven (post-starburst) galactic mergers by estimating the absolute magnitude of the brightest star cluster when corrected for stellar evolutionary fading. We estimate SFRs between 50 and $>4000 M_{\odot}$ yr$^{-1}$ and infrared luminosities between $10^{11.5}$ and $10^{14.4} L_{\odot}$. These are lower limits as we have not corrected for cluster mass loss (fading) due to tidal fields and internal dynamics. Additionally, the infrared luminosities are also lower limits as they do not take into consideration any additional contribution to the $L_\text{IR}$ by an AGN component. These results further demonstrate that many mergers pass through a LIRG/ULIRG/HLIRG phase during their evolution.

NGC 34, which currently has a high SFR ($>75 M_{\odot}$ yr$^{-1}$), also hosts a population of bright massive clusters with ages of ~150–600 Myr (Schweizer & Seitzer 2007). Using these clusters, we have estimated a peak SFR of ~600 $M_{\odot}$ yr$^{-1}$, which corresponds to an infrared luminosity of $10^{12.5} L_{\odot}$, well within the ULIRG regime. Thus, we have placed a lower limit to the duration of the LIRG/ULIRG phase of 150 Myr for this galaxy.

ACKNOWLEDGMENTS

NB thanks Mark Gieles for helpful discussions and for providing the stochastic power-law and Schechter function sampling programmes, used throughout this work. François Schweizer, Cathie Clarke, Thomas Maschberger and John Hibbard are gratefully acknowledged for interesting and helpful discussions. This paper is based in part on observations with the NASA/ESA HST which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS5-26555.

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