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Survival of star-forming giant clumps in high-redshift galaxies

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ABSTRACT

We investigate the effects of radiation pressure from stars on the survival of the star-forming giant clumps in high-redshift massive disc galaxies, during the most active phase of galaxy formation. The clumps, typically of mass $\sim10^8$–10^9 M$_\odot$ and radius ∼0.5–1 kpc, are formed in the turbulent gas-rich discs by violent gravitational instability and then migrate into a central bulge in ∼10 dynamical times. We show that the survival or disruption of these clumps under the influence of stellar feedback depends critically on the rate at which they form stars. If they convert a few per cent of their gas mass to stars per free-fall time, as observed for all local star-forming systems and implied by the Kennicutt–Schmidt law, they cannot be disrupted. Only if clumps convert most of their mass to stars in a few free-fall times can feedback produce significant gas expulsion. We consider whether such rapid star formation is likely in high-redshift giant clumps.

Key words: galaxies: formation – galaxies: ISM – galaxies: star clusters: general – galaxies: star formation – ISM: clouds – stars: formation.

1 INTRODUCTION

A significant fraction of the massive galaxies, $\sim10^{11}$ M$_\odot$ in baryons, during the period from $z = 1.5$ to 3 when star formation is at its peak and most stellar mass is assembled (Hopkins & Beacom 2006; Magnelli et al. 2009), form stars at high star formation rates (SFRs) of $\sim100\,\mathrm{M_\odot\,yr^{-1}}$. Many of these are turbulent, gas-rich, extended rotating discs in which much of the star formation takes place in a few *giant clumps* (Cowie, Hu & Songaila 1995; van den Bergh et al. 1996; Elmegreen, Elmegreen & Hirst 2004a; Elmegreen et al. 2005, 2007). Based on this morphology, they were first termed 'chain' or 'clump-cluster' galaxies. In a typical galaxy of this type, 10–40 per cent of the ultraviolet rest-frame light is emitted from a few clumps of characteristic size ∼1 kpc that form stars at tens of $\mathrm{M_\odot\,yr^{-1}}$ each (Elmegreen, Elmegreen & Sheets 2004b; Elmegreen et al. 2005; Förster Schreiber et al. 2006; Genzel et al. 2008). These clumps are much more massive than the star-forming complexes in local galaxies. The star formation in these clumps, and their survival subject to stellar feedback, are central to our understanding of galaxy formation.

Kinematically, most of the galaxies that host the clumps are thick rotating discs, with high velocity dispersions of $\sigma = 20$–$80\,\mathrm{s^{-1}}$ (one dimensional), compared to $\sigma \simeq 10\,\mathrm{s^{-1}}$ is present-day discs; they have rotation to dispersion ratios of $V/\sigma \sim 1$–7 (Cresci et al. 2009). Estimates of the total gas fraction in star-forming galaxies, based on CO measurements, range from 0.2 to 0.8, with an average of ∼0.4–0.6 (Daddi et al. 2008; Tacconi et al. 2008; Daddi et al. 2009), systematically higher than the typical gas fraction in today's discs. These properties are generally incompatible with these systems being ongoing major mergers or remnants of such mergers (Bournaud et al. 2008; Shapiro et al. 2008; Bournaud & Elmegreen 2009; Dekel et al. 2009a; Dekel, Sari & Ceverino 2009b), though there may be counter examples (Robertson & Bullock 2008).

Instead, giant clumps form through a scenario, summarized by Dekel et al. (2009b), in which massive galaxies at $z \sim 2$–3 are fed by a few narrow and partly clumpy streams of cold gas ($\sim10^4$ K) that flow along the dark matter filaments of the cosmic web (e.g. Hahn et al. 2007) and penetrate deep into the centres of the massive dark matter haloes of $\sim10^{12}$ M$_\odot$ (Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006; Ocvirk, Pichon & Teyssier 2008; Dekel et al. 2009a). Indeed, the existence of these streams is an *inevitable* prediction of the standard Lambda cold dark matter (ΛCDM) cosmology. They may produce the structures we observe as Lyman α blobs (Furlanetto et al. 2005; Dijkstra & Loeb 2009; Goerdt et al. 2009). The angular momentum they carry leads the accreted material to form a disc of radius $R_\mathrm{d} \sim 10$ kpc. The continuous intense input of gas at the level of $\sim100\,\mathrm{M_\odot\,yr^{-1}}$ maintains a high gas surface density Σ, which drives a violent gravitational instability with a Toomre Q parameter below unity, $Q \simeq \sigma\Omega/(\pi G\Sigma) < 1$, where σ is the one-dimensional velocity dispersion and Ω is the angular velocity associated with the potential well (Toomre 1964). The disc instability is self-regulated at $Q \lesssim 1$ by the gravitational interactions in the perturbed disc, which keep the disc thick and with a high velocity dispersion. The disc forms strong, transient spiral features that fragment to produce 5–10 bound clumps, that

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together comprise ~20 per cent of the disc mass. The largest clumps have characteristic radii $R \simeq 7G\Sigma/\Omega^2 \sim 1$ kpc, and characteristic masses of a few per cent of the disc mass, $M \sim 10^9\,\mathrm{M_{\odot}}$. A spectrum of smaller clumps with somewhat lower masses forms as well. The clumps' large masses cause them to migrate to the centre of the disc on a short time-scale of ~10 disc crossing times, where they merge into a central bulge (Noguchi 1999; Immeli et al. 2004a,b; Bournaud, Elmegreen & Elmegreen 2007; Agertz, Teyssier & Moore 2009; Ceverino, Dekel & Bournaud 2010). This violent instability phase can last for more than a Gyr, during which the mass flow from the disc to the bulge is replenished by fresh accretion, keeping the mass within the disc radius divided quite evenly between disc, bulge and dark matter components.

While this scenario of clump formation and migration to build up bulges is appealing, it relies on the ability of clumps to survive for ~10 disc dynamical times, i.e. a few hundred Myr, while the gas in them turns into stars on a comparable time-scale (Genzel et al. 2008; Ceverino et al. 2010; Dekel et al. 2009b). However, at the SFR of a few tens of solar masses per year in the clumps, it is possible that they might be disrupted by stellar feedback on considerably shorter time-scales. Murray, Quataert & Thompson (2010) argue for exactly this scenario. In their models, clumps disrupt after ~1 dynamical time, during which they turn only ~30 per cent of their mass into stars. In this picture clumps would not survive long enough to migrate, and bulges would instead need to be built up by mergers. While this scenario seems difficult to reconcile with the estimated ages of a few hundred Myr for the oldest stellar populations in some clumps (Elmegreen et al. 2009a; Förster Schreiber et al. 2009), there is sufficient uncertainty in both the observational estimates of clump ages and the theoretical modelling of clump evolution and disruption to merit a re-investigation of the problem, which we provide in this paper.

The outline of the paper is as follows. In Section 2 we derive the expected gas ejection fraction as a function of SFR efficiency. In Section 3 we address the observational estimates of the SFR efficiency. In Section 4 we discuss some of the issues raised by our results and compare to previous work. We summarize our conclusions in Section 5.

2 RADIATIVE FEEDBACK AND CLUMP SURVIVAL

Consider a uniform-density giant gas clump of mass M, radius R and surface density $\Sigma = M/(\pi R^2)$. It forms stars at a rate $\dot{M}_*$, and the stars formed within it have a combined luminosity L. (We defer discussing the effect of subclumping within giant clumps to Section 3.3 since it does not change the qualitative result.) Characteristic numbers to keep in mind for the largest, best observed clumps, found in galaxies with baryonic masses $\sim 10^{11}\,\mathrm{M_{\odot}}$, are $M \simeq 10^9\,\mathrm{M_{\odot}}$, $R \simeq 1$ kpc and $\Sigma \simeq 0.1$ g cm^{-1}. Clumps in the $\sim 10^{10}\,\mathrm{M_{\odot}}$ galaxies, which are more common, have masses $\sim 10^8\,\mathrm{M_{\odot}}$ and sizes that are at or below the resolution limit of present observations. We will assume that they have surface densities comparable to those their larger cousins; they cannot be much smaller since the mean column densities of the galactic discs as a whole is $\Sigma \sim 0.05$ g cm^{-2}. We wish to evaluate the fraction e of clump mass that will be ejected by stellar feedback and the fraction $\mathcal{E} = 1 - e$ that is transformed into stars because this is the critical parameter that determines whether the clump will form a bound stellar system. Both N-body simulations and analytic models (e.g. Hills 1980; Kroupa 2001; Kroupa & Boily 2002; Baumgardt & Kroupa 2007) indicate that if $\mathcal{E} \gtrsim 0.5$, then most of the stellar mass will remain bound, while if $\mathcal{E} \lesssim 0.3$ then no bound stellar system will be left. Small portions of the clump where $\mathcal{E}$ was locally higher may form bound clusters, but these will be orders of magnitude smaller than the initial clump.

Several common feedback mechanisms are not important for giant clumps in the relevant mass range. First, supernova feedback is unlikely to be effective in ejecting mass from these giant clumps, due to cooling and leakage of hot gas (Dekel et al. 2009b; Krumholz & Matzner 2009; Murray et al. 2010). Secondly, the pressure of warm ($\sim 10^4$ K) ionized gas is ineffective because the escape velocity from the clump is larger than the gas sound speed of ~10 km s^{-1}. Thirdly, protostellar outflows are unable to eject mass because they do not provide enough momentum (Fall, Krumholz & Matzner 2010). Instead, the dominant feedback mechanism is likely to be radiation pressure from newly formed stars, which creates a radiation-dominated H II region. The expansion of such a region follows a similarity solution (Krumholz & Matzner 2009), and Fall et al. (2010) use this solution to show that all the remaining gas will be ejected once the fraction of gas mass transformed into stars reaches a value

$$\mathcal{E} = \frac{M_*}{M} = \frac{\Sigma}{\Sigma + \Sigma_{\rm crit}}, \qquad (1)$$

where

$$\Sigma_{\rm crit} = \frac{5\eta f_{\rm trap}\,\langle L/M_*\rangle}{\pi\alpha_{\rm crit} G c}, \qquad (2)$$

η is a constant of the order of unity that depends on the density distribution within the clump, $\langle L/M_*\rangle$ is the light-to-mass ratio of the stellar population, $f_{\rm trap}$ represents the factor by which the radiation force is enhanced by trapping of reradiated infrared light within the expanding shell, and $\alpha_{\rm crit}$ is a parameter of the order of unity that describes the critical velocity required to eject mass from the cloud. Fall et al. (2010) assume fiducial values of $\eta = 2/3$ and $f_{\rm trap} = \alpha_{\rm crit} = 2$ for the local star-forming regions, and we adopt the same values here since there is no obvious reason for them to be systematically different in the case of giant clumps at redshift 2. We refer to $\mathcal{E}$ as the final star fraction.[1]

To determine the light-to-mass ratio, we must deal with the complication that the characteristic crossing time of a giant clump is rather long, $t_{\rm cr} = R/\sqrt{GM/R} = 15 M_9^{-1/2} R_1^{3/2}$ Myr, where $M_9 = M/(10^9\,\mathrm{M_{\odot}})$ and $R_1 = R/(1\,\mathrm{kpc})$. Depending on the exact values of M and R, this can be either greater than or less than the main-sequence lifetime of massive stars. Thus we can assume neither a single burst, so that all stars are coeval, nor a continuous star formation, so that the population is in equilibrium between new stars forming and old ones evolving off the main sequence. However, we can treat these scenarios as two limiting cases, which must bracket any real stellar population. Krumholz & Tan (2007) point out that in stellar populations younger than 3 Myr, where no stars have left the main sequence yet, the light-to-mass ratio has a constant value, Ψ, for which we adopt $\Psi \approx 2200$ erg s^{-1} g^{-1} (Fall et al. 2010). Once a stellar population is old enough to reach statistical equilibrium between star formation and star death, it instead has a nearly constant luminosity-to-SFR ratio, Φ, which we take to be $\Phi \approx 6.1\times 10^{17}$ erg g^{-1} (Krumholz & Tan 2007). For any realistic stellar population whose light is dominated by young, massive stars as opposed to old ones, the luminosity is roughly equal to the smaller of these

[1] Note that this is sometimes referred to as star formation efficiency as well, but we avoid the term efficiency because it does not have a standard meaning, and different authors use it for different concepts.

two limits, and for simplicity we simply take the light-to-mass ratio to be

$$\left\langle \frac{L}{M_*} \right\rangle = \min\left(\Psi, \Phi\frac{\dot{M}_*}{M_*}\right). \tag{3}$$

We refer to the first case as the 'young stars' limit and the second as the 'old stars' limit since they represent the opposite extremes of stellar populations that have undergone no evolution and populations that are old enough to have reached equilibrium between star formation and stellar evolution.

Substituting these two light-to-mass estimates into equation (1) gives

$$\mathcal{E} = \max\left[\left(1+\frac{\Sigma_{\rm crit,y}}{\Sigma}\right)^{-1}, 1-\frac{\Sigma_{\rm crit,y}}{\Sigma}\left(\frac{\Phi}{\Psi t_{\rm dep}}\right)\right], \tag{4}$$

where

$$\Sigma_{\rm crit,y} = \frac{5\eta f_{\rm trap}\Psi}{\pi\alpha_{\rm crit}Gc} \approx 1.2 \text{ g cm}^{-2} \tag{5}$$

is the critical density evaluated in the young stars limit and $t_{\rm dep} = M/\dot{M}_*$ is the depletion time, i.e. the time that would be required to convert all of the gas into stars. The numerical evaluation in equation (5) is for the fiducial parameters of Fall et al. (2010). Note that this expression is a maximum rather than a minimum because $\mathcal{E}$ is a decreasing function of $\langle L/M_*\rangle$.

Following Krumholz & McKee (2005), we define the dimensionless SFR efficiency as the ratio between the free-fall time and the depletion time,[2] namely

$$\epsilon_{\rm ff} = \frac{\dot{M}_*}{M/t_{\rm ff}}. \tag{6}$$

Krumholz & Tan (2007) show that $\epsilon_{\rm ff} \simeq 0.01$ across a very broad range of densities, size scales and environments. Here we define the free-fall time as $t_{\rm ff} = \sqrt{3\pi/(32G\rho)}$, where ρ is the gas density. We discuss in Section 3 below whether this value of $\epsilon_{\rm ff}$ applies in high-z giant clumps. If we adopt it for now and make this substitution in equation (4), we find that

$$\mathcal{E} = \max\left[\left(1+\frac{\Sigma_{\rm crit,y}}{\Sigma}\right)^{-1}, 1-\frac{\epsilon_{\rm ff}\sqrt{8G}\,\Sigma_{\rm crit,y}\Phi}{(\pi\Sigma M)^{1/4}\Psi}\right] \tag{7}$$

$$\simeq \max\left[\left(1+\frac{12}{\Sigma_{-1}}\right)^{-1}, 1-\frac{0.086}{(\Sigma_{-1}M_9)^{1/4}}\epsilon_{\rm ff,-2}\right], \tag{8}$$

where $\Sigma_{-1} = \Sigma/(0.1 \text{ g cm}^{-2})$, $\epsilon_{\rm ff,-2} = \epsilon_{\rm ff}/100$, and the numerical evaluation uses the fiducial parameters from Fall et al. (2010). We use equation (8) to plot $\mathcal{E}$ as a function of $\epsilon_{\rm ff}$ in Fig. 1.

What does this result imply for the survival of high-z giant clumps? We note that the second term in brackets in equation (8), corresponding to the case of a stellar population older than ∼3 Myr, is generally the one that applies for giant clumps. This reflects the fact that the crossing time for our fiducial values of the parameters is 15 Myr, which is significantly larger than 3 Myr. The young stellar population limit applies only if the SFR efficiency is much higher than is observed in any star-forming systems anywhere in the local universe, $\epsilon_{\rm ff,-2} \gtrsim 10$, or if the star-forming systems are significantly less massive or much more dense. This makes high-z giant clumps very different from Galactic star clusters or even superstar clusters, such as those found in local starburst galaxies, e.g. the Antennae or M82. These have lower masses and higher surface densities, with crossing times ∼0.1 Myr (e.g. McCrady & Graham 2007), placing them firmly in the young stars limit. Indeed, the first term in the brackets is identical to that derived by Fall et al. (2010) for local star-forming clumps.[3]

[2]Note that the rate efficiency $\epsilon_{\rm ff}$ that we have defined here is distinct both from the SFR, which has units of $M_\odot$ yr^{-1} and is not normalized by the ratio of mass over free-fall time, and the final stellar mass fraction $\mathcal{E}$, which is dimensionless but does not carry any information about the SFR.

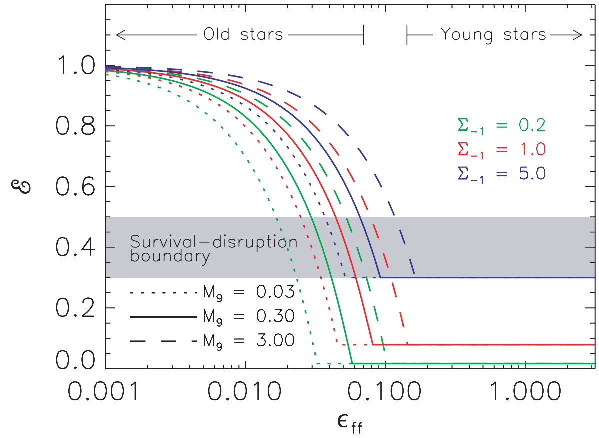

Figure 1. Final stellar fraction $\mathcal{E}$ as a function of star formation rate efficiency $\epsilon_{\rm ff}$, computed from equation (7). We show results for giant clump surface densities Σ_{-1} = 0.2, 1.0 and 5.0 (green, red and blue lines, as indicated), and for giant clump masses M_9 = 0.03, 0.3 and 3.0 (dotted, solid and dashed lines, as indicated). The arrows schematically indicate the region around $\epsilon_{\rm ff} = 0.1$ where we change from the old stars limit (low $\epsilon_{\rm ff}$) to the young stars limit (high $\epsilon_{\rm ff}$). The grey region from $\mathcal{E}$ = 0.3–0.5 indicates the rough boundary between stellar fractions $\mathcal{E} \lesssim 0.3$, for which no bound stellar system will remain, and $\mathcal{E} \gtrsim 0.5$, for which a majority of the stellar mass will remain bound.

We conclude that unless $\epsilon_{\rm ff,-2} \gg 1$ for giant clumps, as opposed to ∼1 for the local star-forming systems, star-forming clumps with masses ∼10^8–10^9 $M_\odot$ and surface densities ∼0.1 g cm^{-2} cannot be disrupted by radiation pressure – so they end up converting most of their mass to stars. Thus, the *expulsion fraction* relevant for high-z giant clumps, as derived in the old stars limit, is

$$e = 1 - \mathcal{E} = 0.086\Sigma_{-1}^{-1/4}M_9^{-1/4}\epsilon_{\rm ff,-2}. \tag{9}$$

Since $\mathcal{E} \gtrsim 0.5$, we expect the resulting stellar systems to remain gravitationally bound. Clumps with $\Sigma_{-1} = 1$ have $\mathcal{E} < 0.5$ and suffer significant disruption only if their masses are below ∼10^6 $M_\odot$, and they reach $\mathcal{E} < 0.3$ and undergo complete disruption only at masses $\lesssim 2 \times 10^5$ $M_\odot$. Thus the observed ∼10^8–10^9 $M_\odot$ giant clumps in high-z galaxies should survive disruption unless $\epsilon_{\rm ff,-2} \gg 1$. Even if we are maximally conservative and assume that the smaller clumps have $\Sigma_{-1} = 0.5$, i.e. that their surface densities do not exceed the mean surface densities of their host galaxies, our estimated maximum mass for disruption only increases by a factor of 2.

3 THE STAR FORMATION RATE EFFICIENCY IN HIGH-z CLUMPS

Equation (9) shows that the most important parameter in determining the survival of giant clumps is how quickly, normalized to

[3]To get numerical agreement in the coefficient of Σ_{-1}, we must adjust k by a factor of $\sqrt{0.4}$ to account for measuring the escape velocity at the surface instead of at the half-mass radius.

their free-fall times, they turn themselves into stars. Only if they do so with a very high rate efficiency, $\epsilon_{\rm ff,-2} \gtrsim 10$, do we expect significant gas expulsion. In the local universe, one measures $\epsilon_{\rm ff}$ by determining the SFR of an object or a population of objects, and comparing this to the objects' gas mass divided by the free-fall time computed for their density. This procedure was first applied by Zuckerman & Evans (1974) to the population of giant molecular clouds in the Milky Way, and has subsequently been extended to other objects by Krumholz & Tan (2007) and Evans et al. (2009). These measurements give $\epsilon_{\rm ff,-2} \sim 1$ over a very wide range of star-forming environments, from small star clusters in the Milky Way to entire starburst galaxies. The results are subject to considerable uncertainty, but values $\epsilon_{\rm ff,-2} \gtrsim 10$ are strongly excluded by the data. However, we lack comparable data for star formation at high redshifts. In this section, we therefore turn to the question of the likely value of $\epsilon_{\rm ff}$ in high-z giant clumps.

3.1 Estimates of $\epsilon_{\rm ff}$ from Observations of Giant Clumps

Unfortunately, we cannot easily apply the direct measurement procedure used to determine $\epsilon_{\rm ff}$ in the local universe to the high-z clumps because, while we can evaluate SFRs using Hα luminosities, we are limited in our ability to measure the corresponding gas properties.

For example, Elmegreen et al. (2009b) use stellar population synthesis to estimate masses and ages for the stellar populations seen in giant clumps in high-z galaxies, and they then compare the ages τ to the clump dynamical times, defined as $t_{\rm dyn} \equiv (G\rho)^{-1/2} \approx 0.5 t_{\rm ff}$, where ρ is taken to be the *stellar* mass density. They find typical values $\tau/t_{\rm dyn} \sim$ 1–10, corresponding to $\tau/t_{\rm ff} \sim$ 2–20, with a factor of $\sim$10 scatter. It is tempting to identify τ with $t_{\rm dep}$ and simply estimate $\epsilon_{\rm ff} \sim t_{\rm ff}/\tau \sim$ 0.05–0.5, but this is likely to be a significant overestimate. Based on dynamical mass estimates, Genzel et al. (2008) estimate that gas comprises 10–30 per cent of the total mass within the disc radius. Estimates based on direct CO measurements indicate gas fractions of 45–60 per cent at $z \sim 2$ (Daddi et al. 2009; Tacconi et al. 2010). It is likely to be an even larger fraction of the mass within the dense, rapidly star-forming giant clumps, which are self-gravitating and lack a dark matter component. If the stars measured by Elmegreen et al. comprise only a small fraction f_* of the total mass in clump, then $\epsilon_{\rm ff}$ will be reduced by a factor of roughly $f_*^{1.5}$ relative to the previous estimate – one power of f_* to account for the gas that has not yet formed stars, and another factor of $f_*^{0.5}$ because the free-fall time will be shorter than the value Elmegreen et al. estimate based on the stars alone. To give a sense of the possible magnitude of the error, note that Murray et al. (2010) estimate $f_* = 0.2$ for a giant clump in BX 482 (and we argue in Section 4.2 that f_* is probably even smaller), and this value of f_* would be sufficient to lower the estimate of $\epsilon_{\rm ff}$ by a factor of 10, to 5×10^{-3} to 5×10^{-2}. A secondary worry is that, as Elmegreen et al. point out, since the clumps are selected using rest-frame blue light there is a strong bias against selecting older, redder clumps, causing an underestimate of τ. In general, τ is expected to be an underestimate of $t_{\rm dep}$ because the former refers only to the stars that have already formed.

Given this problem, many observers have attempted to estimate gas masses via the 'inverse' Kennicutt (1998) law, namely by measuring the SFR surface density and then assuming that the gas surface density has the value required for the object to obey the Kennicutt law (e.g. Genzel et al. 2006, 2008). Unfortunately this procedure does not yield an independent estimate of $\epsilon_{\rm ff}$. The Kennicutt relation is

$$\dot{\Sigma}_* = A \Sigma_{-1}^{1.4}, \tag{10}$$

with $A \simeq 1.4\,{\rm M_\odot\,yr^{-1}\,kpc^{-2}}$. Thus if the scaleheight of the galaxy is h, then the mid-plane gas density is $\rho = \Sigma/h$, the free-fall time is $t_{\rm ff} = \sqrt{3\pi h/(32 G \Sigma)}$, and we have

$$\epsilon_{\rm ff,-2} = 100 \frac{\dot{\Sigma}_*}{\Sigma/t_{\rm ff}} = 3.4\, A_{1.4}\, h_0^{0.5} \Sigma_{-1}^{-0.1}, \tag{11}$$

where $h_0 = h/{\rm kpc}$ and $A_{1.4} = A/(1.4\,{\rm M_\odot\,yr^{-1}\,kpc^{-2}})$. The true value of $\epsilon_{\rm ff}$ is almost certainly a bit smaller than this since star-forming clouds have densities higher than the mean mid-plane density, and thus smaller free-fall times. None the less, this calculation illustrates a crucial point: to the extent that galactic scaleheights do not have a very large range of variation (and the dependence is only to the 0.5 power), the statement that $\epsilon_{\rm ff,-2} \sim 1$ is roughly equivalent to the Kennicutt law. (See Krumholz & McKee 2005 and Schaye & Dalla Vecchia 2008 for a more detailed discussion of the relationship between volumetric and areal star formation laws.) Thus, no measurement of the gas surface density that assumes the Kennicutt law a priori can produce a value of $\epsilon_{\rm ff,-2}$ significantly different from this. Any measurement of $\epsilon_{\rm ff,-2}$ that did yield a significantly larger value would necessarily place the galaxy well off the Kennicutt relation.

3.2 Estimates of $\epsilon_{\rm ff}$ from Observations of Clump Host Galaxies

Given the difficulties of estimating $\epsilon_{\rm ff}$ in giant clumps directly, we instead turn to indirect inferences, based on the more robust measurements of the overall disc properties. We first note that the observed correlation between total gas mass and total SFR in high-z galaxies (e.g. Carilli et al. 2005; Greve et al. 2005; Gao et al. 2007) is consistent with these galaxies having the same value of $\epsilon_{\rm ff}$ as local star-forming systems (Krumholz & Thompson 2007; Narayanan, Cox & Hernquist 2008a; Narayanan et al. 2008b). Bothwell et al. (2009) have claimed to detect a deviation from a universal star formation law in spatially resolved observations of three $z \sim 2$ systems. However, Bothwell et al. obtain this result only because they choose a non-standard conversion factor between CO luminosity and mass, which leads them to conclude that the gas fraction in these systems is only $\sim$5–10 per cent, much lower than in typical star-forming galaxies at $z \sim 2$, and on the low side even for local star-forming galaxies. Tacconi et al. (2010), using a standard conversion factor, conclude instead that these galaxies have molecular gas fractions of 35–45 per cent. This is consistent with the star formation law and the value of $\epsilon_{\rm ff}$ at $z \sim 2$ being the same as in the local universe.

We can also approach the problem more theoretically. The high-z clump discs with which we are concerned have SFR $\dot{M}_* \sim 100\,{\rm M_\odot\,yr^{-1}}$, baryonic mass $M_{\rm d} \sim 10^{11}\,{\rm M_\odot}$ and disc radius $R_{\rm d} \sim 10$ kpc. We first express the relevant quantities in equation (9) as a function of the clump mass M, surface density Σ and SFR $\dot{M}_*$. The free-fall time (which is $\sqrt{5}/2$ times the crossing time R/V), expressed in 10^6 yr, is

$$t_{\rm ff,6} \equiv \sqrt{\frac{3\pi}{32 G\rho}} = 16.7 M_9^{-1/2} R_1^{3/2} = 12.3 M_9^{1/4} \Sigma_{-1}^{-3/4}. \tag{12}$$

Then

$$\epsilon_{\rm ff,-2} \equiv \frac{\dot{M}_*}{M/t_{\rm ff}} = 12.3 \dot{M}_{*10} \Sigma_{-1}^{-3/4} M_9^{-3/4}, \tag{13}$$

where $\dot{M}_{*10}$ is the SFR in a clump in $10\,{\rm M_\odot\,yr^{-1}}$.

Now let us express the clump quantities in terms of the disc mass, surface density and total SFR. The disc surface density is

$$\Sigma_{\mathrm{d},-1} = 0.663 M_{\mathrm{d},11} R_{\mathrm{d},10}^{-2}, \tag{14}$$

where $R_{\mathrm{d},10}$ is the disc radius measured in units of 10 kpc. The virialized clumps can be assumed to have collapsed by at least a factor of 2 in radius, so the clump surface density is $s \equiv 4s_4$ times larger than that of the disc, or

$$\Sigma_{-1} = 2.65 s_4 M_{\mathrm{d},11} R_{\mathrm{d},10}^{-2}, \tag{15}$$

with $s_4 \geq 1$.

Assume that a fraction α ($\simeq$0.2) of the disc mass is in N ($\sim$10) identical clumps and a fraction β ($\simeq$0.5) of the SFR is in the clumps (Ceverino et al. 2010; Dekel et al. 2009b). Then

$$\dot{M}_{*,10} = 0.5 \beta_{0.5} N_{10}^{-1} \dot{M}_{\mathrm{d}*,100} \tag{16}$$

and

$$M_9 = 2\alpha_{0.2} N_{10}^{-1} M_{\mathrm{d},11}. \tag{17}$$

Substituting the last three expressions in equation (13) we obtain in terms of the disc quantities

$$\epsilon_{\mathrm{ff},-2} = 1.75 s_4^{-3/4} \beta_{0.5} \alpha_{0.2}^{-3/4} N_{10}^{-1/4} \dot{M}_{\mathrm{d}*,100} M_{\mathrm{d},11}^{-3/2} R_{\mathrm{d},10}^{3/2}. \tag{18}$$

Note the very weak dependence on N. We see that the most straightforward observational estimates for the massive clumpy discs at $z \sim 2$ (e.g. the BzK galaxies, Genzel et al. 2008) yield $\epsilon_{\mathrm{ff},-2} \simeq 1.75$ and $e \sim 0.1$, i.e. no significant expulsion.

This estimate is based on the observed properties of galaxies over a relatively narrow range of galaxy masses and redshifts, but using simple theoretical arguments we can deduce how the results are likely to scale to other galaxies for which we currently lack direct observations. For a self-gravitating disc, the circular velocity is roughly $V_{\mathrm{d},200}^2 \simeq M_{\mathrm{d},11}/R_{\mathrm{d},10}$, so $\epsilon_{\mathrm{ff},-2} \propto \dot{M}_{\mathrm{d}*} V_{\mathrm{d}}^{-3}$, namely

$$\epsilon_{\mathrm{ff},-2} \propto \frac{\dot{M}_{\mathrm{d}*}}{M_{\mathrm{vir}}}. \tag{19}$$

A constant $\epsilon_{\mathrm{ff},-2}$ ($\sim$1) is consistent with the SFR being a constant fraction of the baryon accretion rate because the latter is roughly proportional to halo mass (Neistein, van den Bosch & Dekel 2006; Birnboim, Dekel & Neistein 2007):

$$\dot{M}_{\mathrm{d}*} \sim \dot{M} \propto M_{\mathrm{vir}}. \tag{20}$$

The fact that the SFR follows the accretion rate is a natural result of the fact that the SFR is proportional to the mass of the available gas (Bouche et al. 2009; Dutton, van den Bosch & Dekel 2009), and is consistent with the finding from simulations when compared to observed SFR (Dekel et al. 2009a). We learn that e is only weakly dependent on M.

The redshift dependence at a given halo mass, using $V^3 \propto M_{\mathrm{v}}(1+z)^{3/2}$ and $\dot{M} \propto (1+z)^2$, is

$$\epsilon_{\mathrm{ff},-2} \propto s^{-3/4}(1+z)^{1/2}. \tag{21}$$

The system can adjust the SFR to match the rate of gas supply by accretion with $\epsilon_{\mathrm{ff},-2} \sim 1$ at all times by slight variations in the contraction factor s. At higher redshift, the clumps should contract a bit further and form stars at a somewhat higher surface density.

3.3 Subresolution clumping

Our discussion of clump survival in the preceding sections is based on the assumption that giant clumps represent single star-forming molecular clouds, although we of course expect them to possess significant substructure, as do local molecular clouds. These substructures are unresolved by current observations and by simulations. Here we discuss how their presence affects our conclusions.

First note that, for this purpose, we do not care whether any subclumps within the giant clumps themselves survive star formation feedback and form bound stellar clusters. To see why, consider an extreme case in which all the subclumps within the giant clump expel most of their gas, and thus do not leave behind bound remnants. This is what we might expect to happen if all the subclumps had surface densities similar to that of their parent giant clump, but had masses well below the $\sim 10^5$–$10^6\,\mathrm{M}_\odot$ minimum survival mass that we computed in Section 2. In this case the subclumps would all form stars, expel their gas and disperse, but both the stars and the expelled gas would still remain trapped within the much larger gravitational potential well of the giant clump. They could escape from this potential well only if the giant clump as a whole were disrupted by gas expulsion, which we have already shown in Section 2 will happen only if ϵ_{ff} is much larger than the expected value. Thus the end result of this scenario would be a bound giant star cluster without any bound subclusters inside it.

At the opposite extreme, suppose that all the subclumps were to remain bound and undergo negligible gas expulsion. We might expect this scenario if the subclumps all had surface densities much higher than that of their parent giant clump. In this case the subclumps would convert most of their mass to stars, forming bound clusters. All the bound clusters would irradiate the remaining mass in the giant clump, imparting momentum to it. If the stars imparted enough momentum, this gas would be expelled. Assuming most of the mass were in the interclump medium, as is the case for local molecular clouds, this expulsion would unbind the giant clump, producing many small individually bound clusters that are not bound to one another. Conversely, if the imparted momentum were not sufficient to unbind the giant clump, as we expect, the result would be a giant star cluster consisting of many smaller bound clusters, all gravitationally bound to one another.

In either extreme scenario, whether or not subclumps survive does not make any difference to whether a giant clump as a whole survives. This is dictated solely by the expulsion fraction from the giant clump. However, subclumping still could make a difference for giant clump survival by raising the value of ϵ_{ff}. In this case the subclumps would still have $\epsilon_{\mathrm{ff},-2} \sim 1$, but the giant clump would have $\epsilon_{\mathrm{ff},-2} \gg 1$ because it would have the same SFR but a much lower mean density, and thus a longer free-fall time.

To see whether this is likely to happen, we first note that the turbulent motions within a giant clump are likely to break it up into smaller subclumps, much as local molecular clouds are broken up into clumpy, filamentary structures by turbulence. In such a configuration, a majority of the mass is at a density higher than the volumetric mean density $\bar{\rho}$ that we have computed, and would therefore have a shorter free-fall time and a higher SFR. Quantitatively, we have computed the SFR as $\dot{M}_* = \epsilon_{\mathrm{ff}} M/t_{\mathrm{ff}}(\bar{\rho})$, where M is the total mass of the giant clump, $\bar{\rho}$ is its volume-averaged density, and t_{ff} is the free-fall time computed at that density. However, if most of the mass is at a density $\rho > \bar{\rho}$, the appropriate mass might be the mass $M(>\rho)$ above that higher density, and the appropriate time-scale might be $t_{\mathrm{ff}}(\rho)$ computed for that density. While one might worry that this could be a significant effect, Krumholz & Thompson (2007) point out that it is in reality quite small. Turbulent systems generally have lognormal density distributions. For such a distribution, the fraction of the cloud mass with density greater than

ρ is given by

$$\frac{M(>\rho)}{M} = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{-2\ln x + \sigma_\rho^2}{2^{3/2}\sigma_\rho}\right)\right], \quad (22)$$

where $x = \rho/\bar{\rho}$, $\bar{\rho}$ is the volumetric mean density and σ_ρ is the dispersion of the density distribution. This is related to the Mach number $\mathcal{M}$ of the turbulence by $\sigma_\rho^2 \approx \ln(1 + \gamma\mathcal{M}^2)$, where γ is a constant of the order of unity (Padoan & Nordlund 2002; Federrath, Klessen & Schmidt 2008). For $\sigma_\rho = 2.5$–3, the range of values expected for the Mach numbers found in giant clumps, the quantity $M(>\rho)/t_{\mathrm{ff}}(\rho)$ varies by only a factor of a few over a range of densities $\rho/\bar{\rho} \approx 10^{-1}$ to 10^5. Thus even if most of the mass is at a density vastly larger than the mean density we have used, as long as the mass distribution follows the lognormal form expected for supersonic turbulence, the SFR will not be modified significantly from our estimate using the volume-averaged density.

4 DISCUSSION

4.1 Turbulence and energy balance in giant clumps

Our finding that the fraction of gas ejected from giant clumps depends critically on their dimensionless SFR efficiency ϵ_{ff} naturally leads to the question of how this quantity is set, and whether the physical processes responsible for setting $\epsilon_{\mathrm{ff},-2} \sim 1$ in the local universe might determine a different value in high-redshift clumps. Krumholz & McKee (2005) show that, as long as the gas in a molecular cloud is supersonically turbulent with a velocity dispersion comparable to the cloud's virial velocity, as is observed to be the case in all molecular clouds in the local universe, $\epsilon_{\mathrm{ff},-2} \sim 1$ is the inevitable consequence. In contrast, in the absence of supersonic turbulence, simulations find that clouds undergo a rapid global collapse in which they convert all their mass into stars in roughly a dynamical time, i.e. $\epsilon_{\mathrm{ff},-2} \sim 100$ (e.g. Nakamura & Li 2007; Wang et al. 2010).[4] Thus, a value of $\epsilon_{\mathrm{ff},-2} \sim 1$ may be expected in high-z giant clumps only if they maintain the level of turbulence required to avoid rapid, global collapse.

Whether the turbulence can actually be maintained is somewhat less clear. Simulations show that supersonic turbulence decays in roughly one cloud-crossing time (e.g. Mac Low et al. 1998; Stone, Ostriker & Gammie 1998; Mac Low 1999), so global collapse can be avoided only if this energy is replaced on a comparable time-scale. In local, low-mass star-forming clouds ($\lesssim 10^4\,\mathrm{M}_\odot$), observations (Quillen et al. 2005), simulations (Nakamura & Li 2007; Wang et al. 2010) and analytic theory (Matzner 2007) all suggest that protostellar outflows can supply the necessary energy. In local giant molecular clouds with masses of $\sim 10^4$–$10^6\,\mathrm{M}_\odot$, H II regions driven by the pressure of photoionized gas are likely to be able to supply the necessary energy (Matzner 2002; Krumholz, Matzner & McKee 2006). However, neither of these mechanisms is effective for clumps with $M_9 \sim 1$ and $\Sigma_{-1} \sim 1$ because they do not provide enough momentum input and because they are overwhelmed by radiation pressure (see fig. 2 of Fall et al. 2010).

Supernova feedback (Dekel & Silk 1986) does not appear to be a likely candidate to drive the turbulence either. Supernovae do not provide enough power to drive the observed level of turbulence (Dekel et al. 2009a), and analytic calculations (Harper-Clark & Murray 2009; Krumholz & Matzner 2009), numerical simulations of isolated disc galaxies (Tasker & Bryan 2008; Joung, Mac Low & Bryan 2009) and numerical simulations of galaxies in cosmological context (Ceverino & Klypin 2009) all indicate that supernova-heated gas is likely to escape through low-density holes in the molecular gas without driving much turbulence.

Contrary to this conclusion, Lehnert et al. (2009) use the observed correlation between Hα surface brightness and linewidth in $z \sim 2$ galaxies to argue that supernova feedback is responsible for driving the turbulence, based in part on simulations by Dib, Bell & Burkert (2006), who obtain a scaling relation between velocity dispersion and supernova rate in numerical simulations. However, the efficiency with which supernova energy is coupled to the interstellar medium (ISM) is a free parameter in both Lehnert et al. analysis and in Dib et al. simulations, and their results are consistent with the data only if it is ~25 per cent, whereas in the dense environments found in high-redshift galaxies it is expected to be far lower (Thompson, Quataert & Murray 2005). This conclusion is confirmed by the more recent simulations, which do not need to assume an efficiency because they have sufficient resolution to resolve the multiphase structure of the ISM. Finally, we note that the correlation between Hα surface brightness and linewidth observed by Lehnert et al. has a more prosaic explanation: in a marginally stable galactic disc of constant circular velocity, the velocity dispersion is proportional to the gas surface density since $Q = \kappa\sigma/(\pi G\Sigma) = 1$. Thus higher velocity dispersions correspond to higher surface densities, which in turn produce higher SFRs in accordance with the standard Kennicutt (1998) relation. This naturally explains the observed correlation.

Radiation pressure is another mechanism to consider. If radiation pressure is not able to drive mass out of the clump, as found above for $\epsilon_{\mathrm{ff}} \sim 0.01$, this suggests that it might not be able to drive turbulence to the required virial level either since the virial and escape velocities only differ by a factor of $\sqrt{2}$. However, it is unclear whether this conclusion is warranted. Radiation pressure cannot drive material out of a clump not because stars do not accelerate material enough, but because they evolve off the main sequence before they are actually able to eject matter. As a result, they produce expanding shells whose velocities greatly exceed the escape velocity. They simply fail to drive mass out because the clump because the driving sources turn off before the shells actually escape from the cluster. It is unclear if the expanding shells might provide enough energy to maintain the turbulence; this problem will require further modelling.

We are left with the possibility that the turbulence is driven by gravity. The driving source *cannot* be the collapse of the clump itself; although such a collapse does produce turbulence, it does so at the price of reducing the crossing time, raising the rate of energy loss. Consequently, the collapse becomes a runaway process, and all the gas quickly converts to stars. However, as shown by Dekel et al. (2009a), the gravitational migration of the clumps *through* the galactic disc does provide enough power to maintain the turbulence within them. The main uncertainty in this model is how much of that power will go into driving internal motions within the clump, rather than motions in the external galactic disc. This depends on how the clumps are torqued by one another and by the disc. However, there is suggestive evidence from simulations of giant clumps that this mechanism might be viable. The simulations of clumpy galaxies that have been done to date (e.g. Bournaud, Elmegreen & Elmegreen 2007; Elmegreen, Bournaud & Elmegreen 2008; Agertz, Teyssier & Moore 2009; Ceverino, Dekel & Bournaud 2010) either include no feedback or include only supernova feedback (which is

[4] This can be avoided if clouds are magnetically subcritical (e.g. Nakamura & Li 2008), but magnetic fields in the early universe are likely to be weaker than those in the local universe, and even in the local universe clouds do not appear to be subcritical in typical clouds (Crutcher, Hakobian & Troland 2009).

ineffective). If the giant clumps formed in these simulations did lose their turbulence and undergo global collapse, then, depending on the details of the simulation method, either they would convert all of their mass into stars, or all of the mass within them would collapse to the maximum density allowed by the imposed numerical pressure floor. This collapse would happen on the crossing time-scale of a clump, which is much less than the time required for the clumps to migrate to the galactic centre. However, such collapses are not observed in the simulations. This strongly suggests that, even in the absence of feedback, gravitational power is sufficient to maintain the turbulence.

We conclude that the generation of turbulence in the giant clumps is an important open issue, to be addressed by further studies including simulations of higher resolution.

4.2 Comparison to previous work

Our conclusion that giant clumps are not likely to be disrupted by feedback is in contrast with the findings of Murray et al. (2010) for the giant clump in the galaxy Q2346−BX 482 (Genzel et al. 2008), and this difference merits discussion. Based on the Hα luminosity of the clump, Murray et al. estimate a total bolometric luminosity of $L = 4 \times 10^{11}\,\mathrm{L}_\odot$, which corresponds to a SFR of $34\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ in the old stars limit, or a stellar mass of $2.6 \times 10^8\,\mathrm{M}_\odot$ in the young stars limit, which Murray et al. assume. If these stars are indeed young, then the SFR could be higher than $34\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, but it could not be any lower.

While the estimate of the SFR is relatively straightforward, inferring the gas mass is much less so. Murray et al. (2010) take it to be $10^9\,\mathrm{M}_\odot$ based on an order-of-magnitude estimate for the Toomre mass in the galaxy. This choice is crucial to their result. The clump radius is $r = 925$ pc, so if we adopt this radius, the mean density free-fall time is 15 Myr, so $\epsilon_{\mathrm{ff},-2} \simeq 50$. Using this value in equation (8), together with the corresponding surface density and mass $\Sigma_{-1} = 0.8$ and $M_9 = 1$, tells us that we are in the young stars limit and that $\mathcal{E} = 0.06$ – fully consistent with the conclusion of Murray et al. that only a relatively small fraction of the gas mass turns into stars, and that this is sufficient to expel the remaining gas. Murray et al. derive a slightly higher value $\mathcal{E} \sim 1/3$ because their criterion for ejection amounts to adopting $\alpha_{\mathrm{crit}} \sim 10$.

However, this conclusion depends crucially on having a low estimate of the gas mass, and a correspondingly high estimate for $\epsilon_{\mathrm{ff},-2}$. Indeed, if the value of $\epsilon_{\mathrm{ff},-2} \simeq 50$ were accurate, this clump would have the highest SFR efficiency of any known system. It is therefore useful to consider alternative methods for estimating the mass. If we were to adopt the inverse Kennicutt method, the observed SFR per unit area $\dot{\Sigma}_* \simeq 13\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-1}$, together with equation (10), gives a gas surface density of $\Sigma_{-1} \simeq 5$ (or $2300\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}$). The corresponding gas mass is $6 \times 10^9\,\mathrm{M}_\odot$, and recomputing ϵ_{ff} for this mass gives $\epsilon_{\mathrm{ff},-2} \simeq 3$, consistent with the point we made earlier that the Kennicutt law is in practice equivalent to having $\epsilon_{\mathrm{ff},-2} \sim 1$. With this mass we would predict $\mathcal{E} \simeq 0.9$, i.e. essentially no gas expulsion. One would expect similar results from the models of Murray et al. because the effect of this mass increase would be to increase the gravitational force by a factor of 40 while leaving the radiative force unchanged. Thus while the models of Murray et al. suggest that the clump in BX 482 has stopped forming stars and all the remaining gas has just been expelled, according to our estimate this clump can be only part of the way through its life and may continue to form stars.

Murray et al. (2010) also suggest another method of estimating the gas mass. Based on the Hα luminosity, if one assumes that the clump is filled with uniform-density gas, then ionization balance requires that this gas have a density of hydrogen nuclei

$$n_{\mathrm{H}} = \sqrt{\frac{3S}{4\pi r^3 \alpha^{(B)}} \left(\frac{4X}{3X+1}\right)}, \tag{23}$$

where X is the hydrogen mass fraction and this expression assumes that He is singly ionized. If, following Murray et al. (2010), we adopt the young stars limit, then the ionizing luminosity is $S = 6.3 \times 10^{46}(M_*/\mathrm{M}_\odot) = 1.6 \times 10^{55}$ photons s^{-1} (Murray & Rahman 2010).[5] Combining this with the case B recombination coefficient $\alpha^{(B)} = 3.46 \times 10^{-13}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ and the solar hydrogen mass fraction $X = 0.71$ (mean mass per H nucleus of $1.4 m_{\mathrm{H}}$) gives $n_{\mathrm{H}} = 21\,\mathrm{cm}^{-3}$, corresponding to a mass of $2.4 \times 10^9\,\mathrm{M}_\odot$ and $\epsilon_{\mathrm{ff},-2} = 14$. Plugging this mass, surface density and value of $\epsilon_{\mathrm{ff},-2}$ into equation (8) gives $\mathcal{E} \simeq 0.2$, i.e. the star fraction is more than three times what we would obtain using Murray et al. mass of $M = 1 \times 10^9\,\mathrm{M}_\odot$. Adopting $\alpha_{\mathrm{crit}} = 10$ to shift our fiducial parameters closer to those used in Murray et al. would give $\mathcal{E} \simeq 0.8$, no significant gas expulsion. We emphasize that these calculations are lower limits on the gas mass and upper limits on the fraction of mass ejected because this mass estimate includes only ionized gas. However, models of both classical gas pressure-driven H II regions and ones driven by radiation pressure (Krumholz & Matzner 2009; Murray et al. 2010) suggest that the ionized gas mass in the H II region interior is significantly smaller than the mass of neutral gas swept up in the shell around it. Including this mass would lower $\epsilon_{\mathrm{ff},-2}$ and increase $\mathcal{E}$ even further.

In summary, our conclusions differ from those of Murray et al. (2010) not because of any difference in the physics of radiation feedback, but because they have used an estimated gas mass that produces an extraordinarily high value of ϵ_{ff}.

5 CONCLUSIONS

Our main result in this paper, summarized in equation (9) and Fig. 1, is that the survival or disruption of giant star-forming clumps in high-z galaxies depends critically on the rate at which they turn into stars. We find that as long as the high-redshift clumps convert their gas mass into stars at a rate of one to a few per cent of the mass per free-fall time, $\epsilon_{\mathrm{ff}} \sim 0.01$, as is observed in low-redshift star-forming systems from small galactic clusters to ultraluminous infrared galaxies, the clumps retain most of their gas and turn it into stars. As a result, they remain bound as they migrate into the galactic centre on time-scales of ∼2 disc orbital times. A significant fraction of the clump gas could be ejected on a free-fall time-scale before turning into stars only if clumps can convert $\gtrsim$10 per cent of their gas mass into stars in a free-fall time, forming stars much faster than any other star-forming system known. We argue the current high-z data is consistent with the standard SFR rate efficiencies at the level of one to a few per cent, with no significant evidence for a change in the star formation process in high-z star-forming galaxies. Nevertheless, this is clearly an interesting issue to explore with more direct observational estimates of the gas mass in these galaxies.

It is possible to check our theoretical arguments for clump survival with a number of possible observations. First, clumps can be disrupted by radiation pressure only if a majority of their gas is expelled, and the resulting massive radiation-driven outflows from

[5] The ionizing luminosity is somewhat lower in the old stars limit: $S = 2.5 \times 10^{53}(\dot{M}_*/\mathrm{M}_\odot\,\mathrm{yr}^{-1}) = 8.5 \times 10^{54}$ photons s^{-1}.

clumps may be observable as systematic blueshifts at the clump locations. A preliminary search for such a phenomenon have yielded a null result (K. Shapiro, private communication), but further investigations of the kinematics in and around the clumps are worthwhile. It is possible that sufficient extinction could hide the blueshifted signature, but we note that, if the gas surface densities are relatively low as, e.g. Murray et al. (2010) propose, the extinction is relatively mild.

Secondly, stellar populations in high-redshift clumps can provide independent observational tests that could help distinguish between the two scenarios of clump survival or disruption. One such test involves the age spread of stars in actively star-forming clumps. If radiative feedback disrupts the clumps after one or a few free-fall times, the spread of stellar ages in each clump should not exceed $\sim$50 Myr. If clumps survive, on the other hand, then the age spreads may reach $\gtrsim$100 Myr, with a high and roughly constant SFR during the lifetime of the clump. There is preliminary observational evidence in favour of the latter (Elmegreen et al. 2009b; Förster Schreiber et al. 2009), but this should be explored further. In this case, migration towards the bulge will produce an age gradient, so that clumps closer to the bulge have systematically larger age spreads than those further out in the disc.

A third test is associated with the properties of massive star clusters in the disc that are not actively forming stars. Clusters with masses $\gtrsim 10^7$ $M_{\odot}$ can only be made in giant clumps, not in the rest of the disc, where molecular clouds are smaller. If clumps undergo rapid disruption by feedback, most of the clusters are likely to dissolve as is the case for local star formation (e.g. Fall, Chandar & Whitmore 2009), but the few clusters that may survive will remain in the disc near their formation radii. None will migrate into the bulge since the migration time varies as M^2 (Dekel et al. 2009b), and the masses of the clusters are much smaller than those of their parent gas clumps. In contrast, if gas clumps survive feedback and convert most of their mass to stars, the resulting massive objects will rapidly migrate towards the galactic centre. They will lose $\sim$50 per cent of their mass due to tidal stripping (Bournaud et al. 2007), possibly including some massive subclusters, but they will deliver the rest of their mass to the bulge. Thus, if giant clumps do not survive, we expect to see a few massive clusters in the disc and none in the bulge. If, on the other hand, our model is correct, then there should be comparable masses of disc and bulge clusters. Those bulge clusters that survive today may correspond to the metal-rich globular cluster population seen in present-day galactic bulges (Brodie & Strader 2006; Shapiro, Genzel & Förster Schreiber 2010; Romanowsky et al., in preparation).

Even though we have concluded that the high-z giant clumps are expected to survive radiative stellar feedback, we do emphasize the important role that this process is likely to play in galaxy formation. For example, it can provide some of the pressure support needed in these giant clumps, it can drive non-negligible winds out of them, and it is likely to disrupt the less massive clumps where stars form at later redshifts. In many circumstances, this mode of feedback is expected to be more important than supernova feedback, as it pushes away the cold dense gas while the latter mostly affects the hot dilute gas. We thus highlight the need for incorporating radiative stellar feedback in hydrodynamical simulations as well as in semi-analytic models of galaxy evolution.

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