Star-forming galaxies at $z \sim 2$ and the formation of the metal-rich globular cluster population

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ABSTRACT
We examine whether the super star-forming (super-SF) clumps ($R \sim 1–3$ kpc; $M \sim 10^8–10^9 \, M_\odot$) now known to be a key component of star-forming galaxies at $z \sim 2$ could be the formation sites of the locally observed old globular cluster (GC) population. We find that the stellar populations of these super-SF clumps are excellent matches to those of local metal-rich GCs. Moreover, this GC population is known to be associated with the bulges/thick discs of galaxies, and we show that its spatial distribution and kinematics are consistent with the current understanding of the assembly of bulges and thick discs from super-SF clumps at high redshift. Finally, with the assumption that star formation in these clumps proceeds as a scaled-up version of local star formation in molecular clouds, this formation scenario reproduces the observed numbers and mass spectra of metal-rich GCs. The resulting link between the turbulent and clumpy discs observed in high-redshift galaxies and a local GC population provides a plausible co-evolutionary scenario for several of the major components of a galaxy: the bulge, the thick disc and one of the GC populations.

Key words: globular clusters: general – galaxies: evolution – galaxies: high-redshift.

1 INTRODUCTION
The Universe at $z \sim 2$ is now known to be an important epoch in the galaxy formation, during which the cosmic star formation rate (SFR) density peaks as galaxies undergo rapid growth (e.g. Rudnick et al. 2003). Much of this activity occurs in massive, rapidly star-forming galaxies (SFGs) ($M_* \sim 10^{10}–10^{11} \, M_\odot$, SFR $\sim 10–200 \, M_\odot$ yr$^{-1}$; Reddy et al. 2005) identified via their rest-frame optical and near-infrared colours. Comparisons of the observed properties of this population (clustering, dynamical masses, SFRs) with dark matter halo properties in cosmological simulations imply that these galaxies will evolve into local bulge-dominated spiral, lenticular and low-mass elliptical galaxies, increasing in halo mass by a factor of 3 between $z \sim 2$ and 0 (Conroy et al. 2008; Genel et al. 2008). For the majority of the population, this evolution will occur in a ‘smooth’ fashion, via accretion and minor mergers, with an average of 0–1 major mergers during this interval (Genel et al. 2008). This smooth yet rapid mass growth, coupled with the lack of disruption by major mergers, renders these galaxies a natural population in which important structures in local galaxies may be assembled and thus a critical population to study.

Detailed dynamical and morphological observations of this galaxy population have revealed that a substantial fraction is characterized by large ($\sim 5–10$ kpc), regularly rotating, thick discs ($h_1 \sim 1$ kpc, $v/\sigma \sim 2–6$; Elmegreen & Elmegreen 2005; Förster Schreiber et al. 2006, 2009; Cresci et al. 2009; Elmegreen et al. 2009). These galaxies are each populated by 5–10 super star-forming (super-SF) clumps ($R \sim 1–3$ kpc), which collectively account for $\sim 30$ per cent of the total baryonic mass in each galaxy (Cowie, Hu & Songaila 1995; van den Bergh et al. 1996; Elmegreen & Elmegreen 2005; Genzel et al. 2008; Elmegreen et al. 2009). The masses of individual super-SF clumps are limited at the upper end by the ‘Toomre’ mass, the characteristic scale of these marginally stable ($Q \sim 1$) rotating galaxies, $M_2 \sim 2.5 \times 10^8 \, M_\odot$, and are believed to have typical masses $M \sim 10^9 \, M_\odot$ (Genzel et al. 2008; Elmegreen et al. 2009; Dekel, Sari & Ceverino 2009). Simulations suggest that these clumps form naturally in gas-rich turbulent discs and that dynamical friction will cause them to spiral in to the centre of the host galaxy on time-scales $\lesssim 1$ Gyr and form a nascent bulge (Noguchi 1999; Immeli et al. 2004; Bournaud, Elmegreen & Elmegreen 2007), leaving a fraction of their mass behind in a thin star-forming disc and a quiescent thick disc (Bournaud, Elmegreen & Martig 2009). Similar conclusions are reached from observations of galaxies in this ‘gas-rich clump-driven phase’ (Genzel et al. 2008; Elmegreen, Bournaud & Elmegreen 2008a), which we will refer to here as $z \sim 2$ star-forming galaxies ($z2$SFGs).

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Could this phase of galaxy evolution also be associated with the formation of globular clusters (GCs)? The high masses ($M_\star \sim 10^4$–$10^7 M_\odot$) and densities ($\rho_{\text{central}} \sim 8 \times 10^3 M_\odot$ pc$^{-3}$) of GCs require exceptionally massive and/or dense giant molecular clouds (GMCs); the super-SF clumps found in zSFGs are thus good candidates for this process. Indeed the average properties of the super-SF clumps ($R \sim 1$–$10$ kpc; $M \sim 10^8 M_\odot$) are very consistent with the predictions of Harris & Pudritz (1994) and McLaughlin & Pudritz (1996), who concluded that ‘super GMCs’ in the early Universe ($R \sim 1$ kpc; $M \sim 10^8 M_\odot$) are likely formation sites for GCs (see Section 3 for a discussion of other proposed GC formation mechanisms). Subsequently, Elmegreen & Efremov (1997) showed that such super GMCs/super-SF clumps are naturally formed in an interstellar medium characterized by high turbulent velocities and gas surface densities. Likewise, Escala & Larson (2008) showed that gas-rich disc galaxies would have large Jeans masses and could create the requisite massive super GMCs. These authors mention in passing that such discs may correspond to the turbulent and gas-rich galaxies observed at high redshift.

In this letter, we expand this idea and propose that the observed features of $z = 0$ GC populations can be explained by assuming that they formed in super-SF clumps in zSFGs. To test this hypothesis, we investigate whether zSFGs can account for the three main characteristics of local GC systems:

(i) the stellar populations of GCs,
(ii) the spatial distributions and kinematics of GC systems and
(iii) the numbers and mass spectra of GCs within galaxies.

GCs are a bimodal population in metallicity; metal-poor GCs increase in number with galaxy mass, and metal-rich GCs with bulge mass. Detailed observations of the Milky Way GC population additionally show that metal-poor GCs are associated spatially and kinematically with the galaxy halo and metal-rich GCs with the bulge and thick disc. Comparing these properties to those of the super-SF clumps in zSFGs (Section 2), we find that zSFGs are plausible formation sites for metal-rich GCs. This connection between an observed galaxy population and a GC population provides further insight into the formation of both metal-rich and metal-poor GCs (Section 3).

Throughout this letter, we assume a $\Lambda$-dominated cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2 COMPARISON OF GLOBULAR CLUSTERS AND $z \sim 2$ STAR-FORMING GALAXIES

2.1 Stellar populations

Stellar population ages, chemical abundances and metallicities provide important constrains on the formation epoch, duration and sites of GCs. The ages of GCs are measured via the location of their stars in colour–magnitude diagrams (for Milky Way GCs) and by comparing stellar absorption line indices in their spectra to single stellar population models (for GCs in other galaxies). However, both methods are limited by current observational and theoretical understanding of evolved stellar populations and can thus only constrain absolute ages to within a few Gyr for the oldest populations (age $\geq 10$ Gyr). Current estimates of the ages of GCs are 9–12 Gyr in the Milky Way (e.g. De Angeli et al. 2005; Mendel, Proctor & Forbes 2007) and 10 ± 2 Gyr in other galaxies (e.g. Puza, Kissler-Patig & Goudrooj 2006). Such ages are comparable to the look-back time at $z \sim 2$ of 10.2 Gyr but are consistent with formation redshifts $z \sim 1.5$–4.

The formation time-scale for GCs is known, via their high observed $\alpha$-enhancement ([α/Fe] $\sim 0.3$), to be rapid enough that Type Ia supernovae have not yet exploded and enriched the interstellar medium with Fe-peak elements (0.7–1 Gyr; Scannapieco & Bildsten 2005). GC formation must therefore occur during a relatively brief epoch of high SFR and significant mass growth; this is indeed the case for the gas-rich clump-driven phase in zSFGs, which has a duty cycle of 0.5–1 Gyr (Genzel et al. 2006, 2008; Daddi et al. 2007). The duration of this phase is limited by dynamical friction on the clumps, which causes them to lose angular momentum and migrate from the disc to the galaxy centre (Noguchi 1999; Immeli et al. 2004; Bournaud et al. 2007; Genzel et al. 2008), as well as by stellar feedback, which may disrupt the molecular component of individual clumps even earlier (Murray, Quataert & Thompson 2009). The $\alpha$-element enhancement from this short and powerful star formation event has been directly observed in zSFGs and higher redshift analogues to be 0.25–0.7 dex (Pettini et al. 2002; Halliday et al. 2008; Quider et al. 2009), comparable to those of GCs.

Finally, the most stringent constraint on GC formation comes from the metallicities of these systems, which have a clearly bimodal distribution. In most galaxies, the peaks of this distribution are near [Fe/H] $= -1.5$ and $-0.5$, with a slight dependence on the mass of the host galaxy (e.g. Brodie & Strader 2006; Peng et al. 2006b). In Fig. 1, we compare this relationship to an average measurement of [Fe/H] in zSFGs (Halliday et al. 2008). For additional reference, the approximate locations of the mass–metallicity relationships at several redshifts are indicated. The metal-poor GCs have metallicities far below those observed in zSFGs and...
therefore almost certainly did not form during the gas-rich clump-driven phase observed in z2SFGs. In contrast, the metal-rich GCs of z2SFGs overlap impressively with the galaxy masses and metallicities of z2SFGs.

This agreement of the look-back time, star formation duty cycle and metallicity of z2SFGs with the ages, elemental abundances and metallicities of metal-rich GCs suggests that this subpopulation of GCs could have been formed in z2SFGs.

2.2 Spatial distribution and kinematics

The formation scenario for GCs is also strongly constrained by their phase space distribution, which has been well measured only in the Milky Way. GC systems similar to that of the Galaxy have been observed in other local spiral galaxies (M31: Huchra, Brodie & Kent 1991; Barmby et al. 2000 and M81: Schroder et al. 2002), but have not yet been confirmed with large samples of GCs in lenticular and low-mass elliptical galaxies (Brodie & Strader 2006, but see e.g. Bridges et al. 1997; Kuntschner et al. 2002). In this section, we therefore must assume that the spatial distributions and dynamics of GC populations in the Milky Way are representative of those in bulge-dominated spiral, lenticular and low-mass elliptical galaxies; this allows us to examine whether the metal-rich GCs in such local galaxies could have been produced in z2SFGs.

The Milky Way’s metal-rich GC population is associated with both the bulge and the thick disc (Table 1). These GCs are centrally concentrated, with the majority of the population distributed spherically in the Galaxy centre (i.e. de Vaucouleurs profile) and having bulge-like kinematics (Côté 1999). A subset (∼1/3) of the metal-rich GCs are found at larger radii (r>4 kpc) and are rotationally supported (v/vσ ≳ 1; Côté 1999). Based on the similar kinematics and stellar populations of these ‘disc’ GCs and old thick disc stars, Zinn (1985) proposed that these GCs were formed during a ‘transient, thick-disc phase’. This prescient hypothesis virtually predicted modern observations of the gas-rich clump-driven phase in z2SFGs (h_r ∼ 1 kpc; v/vσ ∼ 2–6).

The current understanding of this phase further elucidates the connection between the metal-rich GCs potentially formed in super-SF clumps, thick discs and bulges. As the clumps (initially at r ∼ 5–10 kpc) migrate towards the centre of their host z2SFG to form a proto-bulge (r ≤ 3 kpc; Genzel et al. 2008), they presumably transport most of their newly formed GCs with them, with a smaller fraction of the GCs being stripped off during this process and remaining in the galaxy disc. This behaviour has been seen in simulations by Elmegreen, Bournaud & Elmegreen 2008b, who populate each clump with a point mass of ∼10^5–10^6 M⊙ (used in their model to represent intermediate mass black holes) and find that most, but not all, of these point masses migrate to the galaxy centre with their host clumps on short time-scales (t ≲ 1 Gyr). The final GC distribution and kinematics in fact mimic those of the stars, the majority of which are carried into the central few kpc, leaving behind a fraction of the mass in the (thick) disc (Bournaud et al. 2009). Those GCs that migrate all the way to the galaxy centre will interact with other GCs, other clumps and the assembling bulge; this scattering will cause them to lose some of their rotational support, creating the low v/vσ ‘bulge’ GC population (Table 1). Some of these bulge GCs may be tidally disrupted and destroyed during this process, and some may sink to the galaxy centre due to dynamical friction (see also Section 2.3). In contrast, the GCs that remained in the thick disc would not interact with other GCs or clumps and would therefore maintain the rotational support of the original clumpy thick disc (v/vσ ∼ 2–3 in thick-disc GCs; v/vσ ∼ 2–6 in z2SFGs).

The GC system that would result from a z2SFG would therefore be expected to have a primary component associated with the bulge and a less populous component associated with the thick disc, in excellent agreement with the observed properties of the metal-rich GC population. This scenario additionally explains why this GC population is associated with both the bulge and the thick disc.

2.3 Number and mass function

To evaluate whether super-SF clumps in z2SFGs can produce the number and mass distribution of the relevant (i.e. metal-rich) GC population, we employ a simple analytic model. We begin by estimating the number of metal-rich GCs expected in the z = 0 descendants of z2SFGs. In the local Universe, the parameter T = N/(M/10^8 M⊙) is used to express the number of GCs per 10^8 M⊙ of galaxy stellar mass (Zepf & Ashman 1993; Rhode, Zapf & Santos 2005). Peng et al. (2008) have measured this quantity for a large range of galaxy masses in Virgo early-type galaxies; they find a nearly constant value of T = 5 for galaxies with M_* = 0.02–2 × 10^11 M⊙. At z = 2, the z2SFGs have stellar masses of ∼10^10–10^11 M⊙ (e.g. Förster Schreiber et al. 2009). Assuming the factor 3 increase in halo mass expected between z = 2 and 0 (Conroy et al. 2008; Genel et al. 2008) includes a constant baryon fraction in the accreted material, this implies stellar masses at z = 0 of 3 × 10^10 to 3 × 10^11 M⊙ and thus T = 5 (or ∼150–1500 GCs) is appropriate for this population. (Similar predictions of GC numbers are also obtained using the universal cluster formation efficiency of McLaughlin 1999.) In this galaxy mass range, 20–40 per cent of GCs are observed to be metal-rich (Peng et al. 2006a, 2008), implying that z2SFGs should produce roughly 30–600 metal-rich GCs that persist to z = 0.

We now evaluate whether the super-SF clumps in z2SFGs can produce the requisite number of metal-rich GCs during the gas-rich clump-driven phase. Star formation within super-SF clumps has been explored analytically (Harris & Pudritz 1994; McLaughlin & Pudritz 1996) and has been observed for the GC-analogues, young massive clusters (YMCs), which form locally in gas-rich (e.g. LMC, M82) and high SF (e.g. the Antennae) environments (Elson & Fall 1985; Elmegreen & Efremov 1997; de Grijs, Bastian & Lamers...
2003: English & Freeman 2003; Wilson et al. 2003). These studies have concluded that star formation in super-SF regions plausibly proceeds in much the same fashion as in their less massive cousins, local GMCs; super-SF regions form gravitationally unstable structures with an efficiency of a few per cent and with a power-law mass spectrum of index $-2 < \alpha < -1.5$, the latter being a result of the turbulent cascade. The mass spectrum is limited at the high end, as in local GMCs, at $\sim 10^{-3}$ times the mass of the cloud, so super-SF clumps ($\sim 10^4 M_\odot$) form structures with masses up to $10^5 M_\odot$ (i.e. YMCs, potential GCs), while local GMCs form structures with masses up to $10^3 M_\odot$ (i.e. open clusters). At the low end of the mass spectrum, less is known about the limiting mass; here, we assume a similar scaling with cloud mass, such that the lower mass limit in local GMCs of $10^{-6}$ times the cloud mass ($\sim 1 M_\odot$) applies also to super-SF clumps.

Combining this information with observations of super-SF clumps in z2SFGs, we predict the number and mass function of (metal-rich) GCs that can be produced. Letting each super-SF clump form stellar clusters according to the mass range and spectrum described above results in $\sim 700$ objects per clump with mass $10^3$–$10^6 M_\odot$, distributed with a power law of assumed slope $\alpha = 2$ (Fig. 2). Fall & Zhang (2001) and Jordán et al. (2007) have shown that local GC mass spectra are not power laws but can instead be well represented by ‘evolved’ Schechter functions that flatten below a characteristic turn-over mass ($\sim 2 \times 10^3 M_\odot$), which they suggest results from the evaporation of lower mass GCs through two-body relaxation (see also McLaughlin & Fall 2008). At the high mass end (above a cut-off mass $M_c$), the distribution drops more steeply than a power law; this may be the result of higher mass GCs preferentially sinking to the galaxy centre with their host super-SF clumps through dynamical friction (Section 2.2) or being destroyed by gravitational shock heating in the potential of the host galaxy (Fall & Zhang 2001; McLaughlin & Fall 2008). Jordán et al. (2007) show that the evolved and initial mass functions can be straightforwardly linked (their equations 4–7), with the exact shape of the final mass function dependent on only two parameters, a cut-off mass ($M_c$) and a cumulative mass loss per GC ($\Delta$). Here, we adopt their values for $M_c$ and $\Delta$ appropriate for galaxies with masses characteristic of z2SFG descendants. Integrating the resulting evolved GC mass function suggests that, of the initial $\sim 700$ GCs per clump, $\sim 12$ will survive from $z \sim 2$ to 0 (Fig. 2). With $5$–$10$ clumps per galaxy, we therefore expect $3500$–$7000$ GCs to be created during a galaxy’s gas-rich clump-driven phase, of which $\sim 60$–$120$ survive to $z = 0$.

This order-of-magnitude calculation shows that z2SFGs may plausibly produce metal-rich GCs whose numbers and mass spectra compare well with GCs observed in local bulge-dominated galaxies. Variations in our simple assumptions of super-SF clump masses and numbers would increase the scatter in the predicted number of metal-rich GCs (60–120) to more closely match the full range observed locally in likely z2SFG descendants (30–600).

3 DISCUSSION AND CONCLUSIONS

In the literature, two broad models of GC formation are discussed: (i) Each galaxy halo creates a single GC population of roughly uniform metallicity, with the second GC population being a product of hierarchical merging (metal-poor GCs accreted from dwarf galaxies: Côté, Marzke & West 1998; metal-rich GCs created during gas-rich mergers: Ashman & Zepf 1992). (ii) Each galaxy halo has two distinct episodes of GC formation, with metal-poor GCs forming first during the collapse of the protogalactic cloud and metal-rich GCs in a subsequent phase of star formation (‘in situ’: Forbes, Brodie & Grillmair 1997). On the basis of the relation between galaxy luminosity (mass) and GC metallicity for both GC populations (Fig. 1), Strader, Brodie & Forbes (2004) have argued that the ‘in situ’ model is strongly preferred, since the accretion or creation of GCs during mergers would blur correlations between the properties of galaxies and their GCs.

Our hypothesis augments this model by providing a natural mechanism for the coincident formation of metal-rich GCs, bulges and thick discs. In Section 2, we have shown that the stellar populations, spatial distribution, kinematics, numbers and mass spectra of metal-rich GCs are all consistent with formation in super-SF clumps during the gas-rich clump-driven phase of a galaxy’s evolution. The rapid ($< 1$ Gyr) migration of these clumps to the centres of their host galaxies provides an effective means of transporting the majority of GCs to the vicinity of the proto-bulge formed from the coalescing clumps; this same mechanism also accounts for the thick-disc GCs, which, like the newly formed thick-disc stars, are stripped from their host clumps and left behind at large radii. This process has a built-in truncation mechanism: once a bulge has formed, it stabilizes the remaining disc against further fragmentation into large clumps (Bournaud et al. 2007). Since the clumps are responsible for simultaneous GC, bulge and thick disc formation, these must occur as a single, short ($< 1$ Gyr) and very significant event in the lifetime of a galaxy.

This scenario provides new insight into the process of galaxy assembly at high redshift. The formation of metal-rich GCs in the gas-rich clump-driven phase implies that the number of these GCs in a galaxy will be closely tied to the importance of this phase in the galaxy’s history. Galaxies with a more dramatic gas-rich clump-driven phase will produce more metal-rich GCs, and the coalescing clumps will create larger bulges, resulting in the observed

Figure 2. Predicted mass spectrum for structures formed in a z2SFG super-SF clump. The slope of the initial mass spectrum ($z \sim 2$; black) is observed to be common among all structures in the ISM (clouds, cores, open clusters, YMCs). The upper and lower limits are set by assuming that a molecular cloud forms structures with $10^{-6}$–$10^{-3}$ of its mass, as observed in local GMCs, and the normalization is set such that $\sim 5$ per cent of the original cloud mass will form stars, as observed locally (e.g. Wilson et al. 2003). The evolutionary model of Jordán et al. (2007) is applied to the initial mass spectrum and results in a preferential decrease of low-mass structures in the evolved mass spectrum ($z = 0$; red). Vertical dashed lines indicate the mass range in which bound structures are observed as GCs, and the shading and labels indicate the number of GCs produced per clump in this model.
correlation between bulge mass and the number of metal-rich GCs (Peng et al. 2006a). The potential association of galaxies at the massive end of this correlation (e.g. M87) with quiescent spheroids at z ~ 2 (e.g. Trujillo et al. 2006; Tacconi et al. 2008) suggests that the populous metal-rich GC populations in these local giant ellipticals may result from a gas-rich clump-driven phase that was very dramatic and occurred prior to z ~ 2 during the galaxies’ primary SF epochs or during a merger of two galaxies in the gas-rich clump-driven phase (see also e.g. Rhode & Zepf 2004). Conversely, the absence of significant metal-rich GC populations (and bulges) in late-type galaxies suggests that massive, migrating super-SF clumps did not play an important role in late-type galaxy formation.

Finally, the scenario proposed here also constrains metal-poor GC formation through the current understanding of the formation history of zSFGs. Significant observational and theoretical evidence indicates that zSFGs are assembled via the rapid and smooth transition of zSFGs. Significant observational and theoretical evidence indicates that zSFGs are assembled via the rapid and smooth transition of million solar mass clumps into the centres of haloes (e.g. Genzel et al. 2006; Daddi et al. 2007; Erb 2008; Dekel et al. 2009). This inflow is almost certainly also present at the earlier epochs in which metal-poor GCs form. These GCs may thus be formed within small concentrations inside filaments or at the intersection of filaments inside the collapsing dark matter halo. This insight is essentially an update of the dissipational collapse model of Searle & Zinn (1978) and Harris & Pudritz (1994) with the detailed information now available at high redshift, and it provides a simple mechanism through which the formation of metal-poor GCs is linked to that of the halo.

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