The dependence of galaxy group star formation rates and metallicities on large-scale environment

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ABSTRACT

We construct a sample of 75 863 star-forming galaxies with robust metallicity and star formation rate (SFR) measurements from the Sloan Digital Sky Survey Data Release 7, from which we select a clean sample of compact group (CG) galaxies. The CGs are defined to be close configurations of at least four galaxies that are otherwise apparently isolated. Our selection results in a sample of 112 spectroscopically identified CG galaxies, which can be further divided into groups that are either embedded within a larger structure, such as a cluster or large group, or truly isolated systems. The CGs then serve as a probe into the influence of large-scale environment on a galaxy’s evolution, while keeping the local density fixed at high values. We find that the SFRs of star-forming galaxies in CGs are significantly different between isolated and embedded systems. Galaxies in isolated systems show significantly enhanced SFR, relative to a control sample matched in mass and redshift, a trend not seen in the embedded systems. Galaxies in isolated systems exhibit a median SFR enhancement at a fixed stellar mass of $+0.07 \pm 0.03$ dex. These dependences on large-scale environment are small in magnitude relative to the apparent influence of local-scale effects found in previous studies, but the significance of the difference in SFRs between our two samples constrains the effect of large-scale environment to be non-zero. We find no significant change in the gas-phase interstellar metallicity for either the isolated or embedded CG sample relative to their controls. However, simulated samples that include artificial offsets indicate that we are only sensitive to metallicity changes of log O/H $> 0.13$ dex (at 99 per cent confidence), which is considerably larger than the typical metallicity differences seen in previous environmental studies.

Key words: galaxies: abundances – galaxies: evolution – galaxies: groups: general – galaxies: interactions – galaxies: star formation.

1 INTRODUCTION

The evolution of a galaxy is fundamentally shaped by its environment. Qualitative evidence of the influence of environment has been known since the 1930s (e.g. Hubble & Humason 1931); the large surveys now available have added their statistical weight to its influence, allowing a quantification of environmental changes. Nearly every observable quantity of a galaxy has been shown to vary with environment, including star formation rates (SFRs), morphologies, colours, active galactic nucleus (AGN) fractions and mean stellar mass (e.g. Dressler 1980; Balogh et al. 2004; Kauffmann et al. 2004; Croton et al. 2005; Baldry et al. 2006; Park et al. 2007). The primary mechanisms that can operate in denser environments are strangulation, harassment and ram-pressure stripping (e.g. Gunn & Gott 1972; Larson, Tinsley & Caldwell 1980; Moore et al. 1996). However, disentangling which of these might be a fundamental variable and which are corollary effects is a non-trivial task (e.g. Whitmore & Gilmore 1991; Blanton et al. 2005; Blanton & Berlind 2007; Skibba et al. 2009). Moreover, relatively simple processes such as individual galaxy–galaxy interactions become complicated by the influence of a local, high-density environment. For example, at low densities, close galaxy pairs show enhanced SFRs (Lambas et al. 2003; Alonso et al. 2004; Ellison et al. 2010). However, once the galaxy pair is found within a high-density environment, the strength of the SFR enhancement diminishes or becomes undetectable (Alonso et al. 2004; Baldry et al. 2006; Ellison et al. 2010). Clearly, galaxies are sensitive to their environment beyond the scale of their nearest neighbour. The question remains, how far beyond the nearest neighbour does environment matter? Is it merely a local density effect, or does cluster membership, with scales far beyond the local, also impact a galaxy’s evolution? This work will attempt to address this question.

Several density trends are well documented in the literature for low-redshift galaxy samples. The morphology–density and colour–density relations describe the declining fractions of blue, late-type galaxies with increasing density (Dressler 1980; Postman & Geller 1984; Balogh et al. 1997, 1998; Martinez et al. 2002; Tanaka et al. 2008).
2004; Baldry et al. 2006). The overall distribution of SFRs also correlates with density, with the average galactic SFR declining as density increases (Hashimoto et al. 1998; Kauffmann et al. 2004; Cooper et al. 2008; Poggianti et al. 2008). Interpretations of the SFR–density relation are complicated by the increasing fraction of low (or non-)star-forming elliptical galaxies as density increases. The contribution of early-type galaxies will bias the average SFR to lower values at higher densities (e.g. Balogh et al. 2004).

The dependence of SFR on density becomes much less clear for only the star-forming subsample of galaxies, with many conflicting interpretations. Some studies find that among the star-forming fraction there is no residual dependence on density (Couch et al. 2001; Balogh et al. 2004; Tanaka et al. 2004; Patiri et al. 2006; Weinmann et al. 2006; Park et al. 2007; Peng et al. 2010; McGee et al. 2011; I deve et al. 2012). According to these works, the observed decrease in SFR with increasing density is entirely due to the changing fraction of star-forming galaxies with density, and once this dependence is eliminated, the distribution of SFRs is independent of density. Other studies counter these results, finding that the population change is not enough to account for the entire SFR–density relation, and that a density dependence remains (Balogh et al. 1998; Pimbblet et al. 2002; Gómez et al. 2003; Welikala et al. 2008). Moreover, the scale over which the SFR is influenced by its surroundings is widely debated. Many authors find that it is primarily on the local scale (generally considered to be of the order of 1 Mpc or less) that the residual SFR–density dependence is found (Hashimoto et al. 1998; Carter et al. 2001; Lewis et al. 2002; Kauffmann et al. 2004; Blanton et al. 2006; Blanton & Berlind 2007). By contrast, some studies indicate that the environment on scales of the order of several Mpc is of greater importance than that of sub-Mpc scales (Goto et al. 2003; Park & Hwang 2009).

A further probe into the scales involved in environmental effects comes from the gas-phase metallicity, which, like the SFR, can be modulated by the gas supply (Ellison et al. 2008a; Lara-López et al. 2010; Mannucci et al. 2010; Yates, Kauffmann & Guo 2012). In samples of interacting pairs, changes in the gas-phase metallicity and SFR are linked, and have been shown to respond to some of the same physical processes (Scudder et al. 2012). Theory offers the picture of an interaction triggering large-scale gas flow from the outer regions of a galaxy to the centre, and the enhanced densities of gas sparking star formation (Barnes & Hernquist 1996; Mihos & Hernquist 1996; Barnes 2004; Montuori et al. 2010; Rupke, Kewley & Barnes 2010; Torrey et al. 2012). In agreement with this theoretical picture, close galaxy pairs show enhanced SFRs (Larson & Tinsley 1978; Donzelli & Pastoriza 1997; Barton, Geller & Kenyon 2000; Lambas et al. 2003; Alonso et al. 2004, 2006; Woods & Geller 2007; Ellison et al. 2008b, 2010) and diluted metallicities (Kewley, Geller & Barton 2006; Ellison et al. 2008b; Michel-Dansac et al. 2008). This indicates that gas-phase metallicities ought to change, as the SFRs do, with density. In confirmation of this idea, studies of galaxies in clusters and other dense environments have shown metal enhancement relative to the field (Mouchine, Baldry & Barmford 2007; Cooper et al. 2008; Ellison et al. 2009).

In this paper, we employ a new tactic to investigate the effects of large-scale environmental dependences. We select two samples of galaxies with similarly high small-scale densities, but with different large-scale environments. To this end, we use the catalogue of 3491 compact group (CG) galaxies in 828 CGs presented in Mendel et al. (2011, henceforth M11) as a refinement on the sample of McConnachie et al. (2009, henceforth M09). Although the original CG selection criteria were designed to identify groups that are not part of a larger overdensity (Hickson 1982; M09), M11 find that the Sloan Digital Sky Survey (SDSS) CG sample can be divided into two distinct populations. One population appears to be truly isolated, whereas the other population appears embedded within a large-scale structure, but isolated from other galaxies within the group. M11 show that despite the strong differences in their large-scale environments, the galaxies in these ‘embedded’ and ‘isolated’ groups have similar morphological properties. In this paper, we investigate the spectroscopic properties of the embedded and isolated CG galaxies, focusing on their SFRs and metallicities. The photometric catalogue of CG galaxies is therefore cross-matched with a spectroscopic sample of emission line galaxies from the SDSS Data Release 7 (DR7; Abazajian et al. 2009). In Section 2, we describe the sample selection, including metallicity and AGN calibrations. In Section 3, we describe our methods for quantifying differences between the isolated and embedded CG galaxies and a sample of control galaxies. In Section 4, we discuss the implications of our results, along with a comparison to previous works and present our conclusions in Section 5.

We assume \( \Omega_M = 0.3, \Omega_{\Lambda} = 0.7 \) and \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \).

2 Sample Selection

Our spectroscopic sample is taken from the publicly available Max Planck Institute for Astrophysics/Johns Hopkins University (MPA/JHU) SDSS DR7 catalogue\(^1\) of 927 552 galaxies. This catalogue provides measurements of up to 12 emission lines per galaxy, corrected for stellar absorption lines and Galactic reddening. Of these lines, we will eventually require robust flux measurements to be present in H\(\alpha\), H\(\beta\), [O\(\text{II}\)]\(\lambda\lambda3727, 5007\) and [N\(\text{II}\)]\(\lambda6584\) for metallicity calibrations.\(^2\) As some of these galaxies are not unique objects within the catalogue, we use the MPA/JHU’s duplicate catalogue\(^3\) to remove duplicate galaxies from the sample. In this section, we describe the quality control measures taken in order to select a reliable sample of star-forming galaxies with measurable metallicities.

2.1 Quality Control

In order to ensure that the flux measurements will be robust for subsequent metallicity calculations, careful checks were made on the quality of the flux measurements. As an initial step, all galaxies with zero and negative flux values were excluded. Flux values of zero were determined to be either due to clipped lines or due to the line being redshifted out of the spectral range of the SDSS. Negative flux values, by contrast, seemed to be largely due to poorly subtracted Balmer absorption.

A redshift cut was imposed on the galaxies to ensure that the spectral lines needed for the metallicity calibrations will not have been shifted out of the spectral range or into a region of the spectrum dominated by sky line residuals. The bluest wavelength of the emission lines needed in our analysis, [O\(\text{II}\)]\(\lambda3727\), dictates the lower redshift limit. This line has to be redshifted at least to the

\(^1\) Available at http://www.mpa-garching.mpg.de/SDSS/DR7/raw_data.html

\(^2\) Recently, Groves, Brinchmann & Walcher (2012) have found that the H\(\beta\) equivalent widths from this catalogue are systematically underestimated by 0.35 Å. We do not expect this to affect our results, as all our comparisons are relative, and the underestimation found is constant across the entire sample.

\(^3\) Available at http://www.mpa-garching.mpg.de/SDSS/DR7/Data/all_matches_dr7.dat.
lower limit of the SDSS spectra at 3800 Å. At the other end of the spectrum, significant sky line residuals appear at ~8000 Å. We use Hα to set the upper redshift, by requiring that Hα cannot be shifted past 8000 Å. These wavelength constraints result in a redshift range of 0.02 ≤ z ≤ 0.25. Additionally, we require that the catalogue flag z-warning be set to 0; a non-zero value for this parameter indicates a bad redshift.

An inspection of the distribution of flux values for emission lines showed that both the flux values and their errors were bimodal with a prominent secondary peak at flux values >10^{-11} erg s^{-1} cm^{-2}. A number of galaxies with the highest flux values were visually inspected and the emission line fluxes were remeasured manually. The manually measured emission line fluxes were found to be within the bounds of the lower flux peak, indicating that the high flux values were spurious. The continuum fluxes and errors were also found to be bimodal. The secondary peak in the continuum error (>10^{-9} erg s^{-1} cm^{-2}) pushes the continuum fluxes, and thus the line flux, to extremely large values. Imposing a cut around the main distribution of continuum flux errors eliminated the majority of the secondary (high value) flux peak. The remainder of the high fluxes were found to be associated with high flux errors, and imposing a flux error threshold eliminated the last remnants of the secondary peak in the flux values.

It is standard practice to impose a signal-to-noise ratio (S/N) cut on emission line fluxes to ensure high-quality metallicity determinations (e.g. Kewley & Ellison 2008, henceforth KE08). We adopt a fairly standard S/N cut of 5 on all emission lines needed for our metallicity calibrations. We also impose a S/N > 5 cut on the Balmer ratio (the ratio of Hα to Hβ flux) to minimize the scatter away from the theoretical Case B recombination limit. Our placement of the S/N cut in the Balmer ratio is motivated by the data; less stringent S/N cuts yield a rapid increase in the scatter in the Balmer ratio. However, increasing the severity of this cut would not significantly decrease the scatter, and would serve only to limit our statistics. As we expect some random scatter below the theoretical lower limit of 2.85, we permit 3σ scatter below the theoretical limit on the Balmer ratio (see Fig. 1). This ensures that all Balmer ratios are reasonable, and does not exclude a large number of galaxies. A summary of the final quality control cuts is presented in Table 1.

With robust flux values in hand, we next correct for internal galactic reddening to obtain intrinsic fluxes, using the Small Magellanic Cloud (SMC) extinction curve presented in Pei (1992). E(B − V) values for the SMC and the Milky Way are very similar at these wavelengths, so our decision to use the SMC curve does not affect our results.

### 2.2 AGN removal

Before metallicities can be calculated, any galaxies containing an AGN must be identified and excluded. AGN are known to alter emission line strengths, which makes any metallicity calculated for a galaxy hosting an AGN unreliable. The canonical method of discriminating between star-forming and AGN galaxies is through the use of emission line ratios (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987). In particular, the most broadly used diagnostic plot is the so-called BPT diagram, after the Baldwin et al. (1981) work in which it was proposed, which plots [O ii]λλ 5007/Hβ against [N ii]λ6584/Hα. The [O ii] line is collisionally excited in both star-forming and AGN regions, so it cannot distinguish between the two ionization sources, but rather serves as a metric for the strength of the ionization field. [N ii], by contrast, originates in partially ionized regions, which are found preferentially around AGN sources due to the power-law radiation they produce. Photoionization from O- and B-type stars does not produce a large partially ionized region, so the [N ii] line strength is relatively small in galaxies dominated by young stellar light. The combination of these two line ratios in the BPT diagram thus allows for differentiation between galaxies dominated by star formation and those with fluxes dominated by an AGN. In order for a galaxy in our sample to pass this diagnostic, it must have reliable detections in all four of the required emission lines.

There are a number of possible lines drawn on the BPT diagram to distinguish between star forming and AGN. We select the diagnostic of Kauffmann et al. (2003b, henceforth K03). K03 is an empirical model, designed to follow the left-hand wing of the BPT diagram and is defined as follows:

\[
\log([\text{O ii}]\lambda 5007/H\beta) = \frac{0.61 \log([\text{N ii}]\lambda 6584/H\alpha) - 0.05}{1.30}.
\]

The K03 demarcation follows the star-forming wing closely, so the fraction of AGN galaxies included in the SF sample should be low; Stasinska et al. (2006) estimate only 3 per cent contamination from AGN galaxies. We classify the sample of galaxies as star
forming or AGN based upon this diagnostic, resulting in a final star-forming sample of 126,756 galaxies.

2.3 Metallicity calibrations

The metallicity calibration adopted here is the adaptation of the Kewley & Dopita (2002, henceforth KD02) recommended method presented in KE08, which we refer to as the KD02–KE08 method. This calibration does not require the detection of as many strong lines (and in particular does not require the [S ii] line), which helps to keep the final sample as large as possible. The KD02–KE08 calibration has low intrinsic scatter, and is easily converted into other metallicity calibrations without significant residuals.

The original KD02 calibration is based on photoionization models and stellar population synthesis for high metallicities, and an average of $R_{23}$ methods for low metallicities, where $R_{23}$ is defined as

$$R_{23} = \frac{[O\text{ III}]\lambda3727 + [O\text{ III}]\lambda4959 + [O\text{ III}]\lambda5007}{H\beta}. \quad (2)$$

The modification implemented by KE08 is in using a different set of $R_{23}$ methods for the low-metallicity galaxies. For high metallicities $\log([N\text{ II}]\lambda3963/[O\text{ II}]) > -1.2$, the KD02–KE08 calibration is the same as presented in KD02. This calibration requires only [N II] and [O II] detections; as long as the galaxy is in the upper branch regime, we do not require any stronger line detections for the metallicity calibration. For $\log([N\text{ II}]\lambda3963/[O\text{ II}]) < -1.2$, the lower branch has changed from the original average of the Zaritsky, Kennicutt & Huchra (1994) and McGaugh (1991) calibrations to an average of the Kobulnicky & Kewley (2004) and McGaugh (1991) lower branch calibrations, all of which are based on the $R_{23}$ and $O_{32}$ diagnostics, where $O_{32}$ is defined as

$$O_{32} = \frac{[O\text{ III}]\lambda4959 + [O\text{ III}]\lambda5007}{[O\text{ II}]\lambda3727}. \quad (3)$$

The Kobulnicky & Kewley (2004) calibration takes an iterative approach, solving both for the ionization parameter (defined as the number of ionizing photons per number of hydrogen atoms) and the metallicity simultaneously. As these lower branch calibrations require the [O III] lines, galaxies that fall in the lower branch have the additional criteria that they must have significant detections in [O III] lines.

2.3.1 Final metallicity sample

Our final metallicity sample is 75,863 galaxies and represents both the sample with which we cross-match the CG sample and the basis of the pool from which we construct a control sample. The metallicity sample is significantly smaller than our initial star-forming sample because the metallicity calculation requires additional emission line detections beyond those required to classify the galaxy as star forming. We take stellar mass values as calculated by the MPA/JHU group from fitting models to the five-band SDSS DR7 photometry. These masses are, in general, in good agreement with spectroscopically derived values calculated by Kauflmann et al. (2003a). SFRs within the SDSS fibre (3 arcsec) are taken from Brinchmann et al. (2004), who use a set of six emission line fits to determine the SFR. Aperture-corrected SFRs are also present in the catalogue.

These SFRs are corrected from fibre to total values by calculating the galaxy light not contained within the fibre; by fitting models to the photometry of the galaxy outside the fibre, the aperture correction can be effectively made (see Brinchmann et al. 2004 for a full discussion of their aperture correction methodology). Salim et al. (2007) compare the results of this methodology with the SFRs obtained from ultraviolet flux, and find that for star-forming galaxies the two methods agree very well, with no bias introduced by the aperture corrections. We use the aperture-corrected SFR values for the rest of this work.

2.4 Compact group sample

Our parent CG sample consists of 3491 CG galaxies in 828 CGs (M11). This sample is a refinement of the Catalogue A of M09. Typical intergalactic distances within the groups are a few tens of kpc, ranging up to 140 kpc. The M09 CG sample applies a modification of the original criteria laid out by Hickson (1982) to the SDSS DR6, with isolation, minimum number of galaxies and density requirements.

(i) $N(\Delta m = 3) \geq 4$.
(ii) $\theta_G \geq 36\theta_c$.
(iii) $\mu_e \leq 26.0$ mag arcsec$^{-2}$.

$N(\Delta m = 3)$ is the number of galaxies within 3 mag of the brightest galaxy within the group, $\mu_e$ is the surface brightness of the group, $\theta_G$ is the angular size of the group and $\theta_c$ is the size of the circle beyond which there are no galaxies within the 3 mag required for group membership. These criteria guarantee that there must be at least four galaxies in the group and the group itself must be separated by at least three times its own radius from any other equally bright galaxies. The surface brightness criterion guarantees the compactness of the group. Applying these criteria, M09 find 2297 CGs, containing 9713 galaxies, down to a limiting magnitude of $r = 18$. However, there is no redshift criterion in the identification process for these galaxies; galaxies identified as a CG are done so based only on their photometry, regardless of whether or not they have concordant redshifts. Approximately 50 per cent of the original 9713 galaxies have reliable spectroscopic redshifts in the DR7 (M11).

In order to address the issue of false (due to projections) CGs in the M09 sample, M11 apply a statistical likelihood restriction to the master CG sample. Briefly, by looking at the probability density functions for the combinations of spectroscopic and photometric redshifts available for CG galaxies found within a given group, a large fraction of interloping galaxies can be removed. If this process of interloper rejection results in the group failing the richness criterion used to define the sample, the entire group is rejected. M11 estimate that there could be 20–30 per cent contamination remaining in the cleaned sample. M11 identified a distinction in the distribution of distances between the CG and the next nearest cluster or rich group. Approximately 50 per cent of the cleaned CG sample can be classified as within $\leq 1$ Mpc $h^{-1}$ of a rich group, using the Tago et al. (2010) catalogue compiled from the DR7 (see fig. 5 in M11). The other half of the sample is distributed at distances $>1$ Mpc away from group structures. Placing a dividing line in the CGs at the minimum between the two distributions, M11 describe two populations: ‘embedded’ and ‘isolated’ CGs. We adopt this terminology for the galaxies residing within those groups. M11 show that the galaxies residing within the two density bins have systematically different photometric properties (i.e. an increase in the fraction of blue galaxies within isolated CGs).
We cross-match the galaxies belonging to either embedded or isolated CGs with our final metallicity and SFR sample to select only the galaxies residing in CGs that also have robust metallicities and SFRs. This cross-matching results in our final CG galaxy sample of 112 galaxies. Splitting the sample into embedded and isolated CGs results in 62 galaxies in isolated CGs, and 50 galaxies in CGs embedded within a large-scale structure. For a list of the embedded and isolated CG galaxies and their properties see Tables A1 and A2, respectively. SDSS thumbnails of four random embedded CGs and four isolated CGs are presented in Figs A1 and A2, respectively.

2.5 Matching to controls

In order to make an effective comparison between our CG sample of galaxies and a control sample of galaxies, we must eliminate any major sources of bias. The three major sources of bias are stellar mass, redshift and environment (Perez, Tissera & Blaizot 2009). As we are looking for an effect that varies with environment, we cannot match in that property, but we wish to match a control sample to the CG sample in stellar mass and redshift, such that the distribution of stellar mass and redshift in the control matches the distributions in the CG sample. Our control pool is defined as any galaxy in the final metallicity sample that is not flagged as belonging to a CG.

Galaxies in our CG sample are matched to galaxies in the control pool simultaneously in total stellar mass and redshift, in a similar way to Ellison et al. (2008b). Briefly, this algorithm finds the best simultaneous match in mass and redshift to each galaxy in the CG sample. Once every galaxy has been matched to a control, a Kolmogorov–Smirnov (KS) test is used on the total distributions of the CG sample and control. If the KS test finds that the distributions are consistent with being drawn from the same parent distribution at >30 per cent, then the matching continues without replacement until a maximum of 50 control galaxies have been matched to each CG galaxy in our sample, or the KS test results in a probability <30 per cent. Since the pool of possible control galaxies is large compared to the CG galaxy sample, the matching procedure reaches the full capacity of 50 matches per CG galaxy. Our final CG samples of 62 isolated CGs and 50 embedded CGs thus have control samples of 3100 and 2500 galaxies, respectively. The masses and redshifts of the control galaxies are typically matched to within 0.05 dex and 0.003, respectively, of the CG galaxy value. The E(B – V) values of the galaxies are found to be consistent among all four samples when a KS test is applied.

The resulting normalized distributions of mass and redshift are shown in Fig. 2. The control samples and the CG samples can be seen to match very well in both mass and redshift (the KS-test probabilities are >99 per cent between CG galaxies and their controls for both mass and redshift distributions). The embedded and isolated galaxies are also statistically similar to each other in both stellar mass and redshift, with KS-test values of 32.57 and 49.16 per cent, respectively.

![Figure 2. Normalized distributions of isolated (left panels) and embedded (right panels) CG galaxies and their controls for total stellar mass (upper panels) and redshift (lower panels). Galaxies are matched to controls in total stellar mass and redshift simultaneously until 50 control galaxies are matched to each group galaxy. KS-test probabilities that the samples are drawn from the same population are >99 per cent for the control and CG galaxy distributions in all panels.](https://academic.oup.com/mnras/article-abstract/423/3/2690/2460765)

3 OFFSETS IN THE SFR AND METALLICITY OF COMPACT GROUP GALAXIES

In this section, we present our methodology for finding and quantifying differences between the SFRs and metallicities of CG galaxies and their controls. We also present a set of bootstrap simulations to quantify the significance of a given measured offset.

\[ \Delta \log(O/H) = (\log(O/H)_{\text{12,observed}} - \mu_{1/2} \log(O/H)_{\text{12,controls}}), \]

\[ \Delta \log(SFR) = \log(SFR)_{\text{observed}} - \mu_{1/2} \log(SFR)_{\text{controls}}, \]

where \( \mu_{1/2} \) signifies the median. The calculated offsets are presented in Figs 3 and 4. The median metallicity offset for the isolated CG galaxies (solid vertical line in Fig. 3) is \(-0.02 \pm 0.04 \) dex (metal poor), whereas the embedded population has a median metallicity offset of \(0.00 \pm 0.02 \) dex (no offset; dashed vertical line). The uncertainty on the median is calculated using a jackknife technique. For each sample (embedded and isolated) the median offset is re-calculated by systematically removing one galaxy. For a sample of \( N \) galaxies, the jackknife error on the median is given by

\[ \sigma = \sqrt{\frac{N - 1}{N} \sum_{i=1}^{N} (\mu_{1/2}(N) - \mu_{1/2}(N-1))^2}, \]

where \( \mu_{1/2}(N) \) is the median value for the full sample of \( N \) galaxies, \( \mu_{1/2}(N-1) \) is the median value for \( N - 1 \) galaxies, and each of the \( N \) galaxies is removed from the sample once.

The SFR offset distribution is shown in Fig. 4; the embedded CG galaxies have SFRs that are lower than the control, with a median offset of \(-0.03 \pm 0.05 \) dex. Isolated CG galaxies, by contrast, have a median offset of \(+0.07 \pm 0.03 \). Again, uncertainties are determined from the jackknife statistic.

In order to determine whether the measured median offsets are strongly influenced by the errors on the SFRs, we use a Monte Carlo resampling simulation to test the sensitivity of our results. We define a distribution of possible SFR values as a Gaussian with mean of the original SFR, and with width defined as the 1σ errors on the offset.

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CG galaxies. While the median SFR of the embedded CG galaxies is consistent with the control, the median SFR of the isolated CG galaxies is significantly offset from its control at ~2σ. Further, the isolated and embedded medians are significantly different from each other at the 1σ level.

3.2 Significance simulations for the SFRs

The jackknife technique estimates the statistical error on our samples of ~60 galaxies. However, we also want to quantify how often a given median offset will occur by chance (due to the intrinsic scatter in the SFR–mass relation). A random sample of 60 galaxies is therefore bootstrapped from the control sample 10 000 times. Recall that each control is one of 50 that has been matched to a given CG galaxy. When one of them is selected at random, the 49 others in the set which are not selected as the ‘sample’ are left as the ‘control’. Offsets are then calculated between the randomly selected galaxy and each of the remaining controls. The median offset for the sample of 60 galaxies is determined, along with the jackknife error on that median. As the galaxies selected are part of the control pool, and no offset is artificially introduced, the majority of these offsets should be centred around zero. For each median, the significance σ is calculated by dividing the measured median offset by the jackknife error on the median. The fraction of the total number of runs with significant offsets (defined as σ > 1, 2, 3 or 4) can then be calculated.

We can now compute for any given offset the fraction of the total number of bootstraps which returned significant medians at or beyond the offset being investigated. The results are shown in the top panel of Fig. 5. The different lines indicate different values of σ. To compare to our results, the SFR enhancement seen in isolated CGs would be along the 2σ line. This simulation indicates that there is a 0.19 per cent chance of detecting an SFR enhancement of +0.07 ±0.03 dex at random. We therefore conclude that the SFR enhancement we have detected, at its given observed significance, has a very low probability of occurring by chance due to scatter.

Whilst the above procedure assesses the probability that a given offset is found between the CG and control samples, we can also quantify the significance of the difference between the embedded and isolated samples. This is achieved by repeating the bootstrapping procedure described above, but this time selecting two separate samples of 60, and the absolute value of the difference in their median offsets is found. We then find the percentage of iterations where the simulated differences in median is greater than a given offset. The results of the two sample bootstraps are shown in the lower panel of Fig. 5. The probability of a range of 0.10 dex between two samples drawn at random from the control SFR–mass relation is 0.67 per cent, which corresponds to >2σ significance.

3.3 Upper limit simulations for metallicities

Although we find a statistically significant difference between the SFRs of embedded and isolated CGs, the metallicity offsets are inconclusive (~0.02 ± 0.04 and 0.00 ± 0.02 for isolated and embedded CGs, respectively). Metallicity offsets in both embedded and isolated structures are statistically consistent with their control samples. To test the sensitivity of our null result given the sample size, we run a set of simulations similar to the bootstrap used in Section 3.2, but now introducing an artificial offset. In this simulation, 60 galaxies are randomly selected from the control sample and an artificial, single value offset (i) is added to all the metallicities of the selected galaxies. The resultant metallicities are then run through
the offset calculation algorithm. Offsets are calculated between each of the 60 randomly selected galaxies and the remaining 49 in its matched set. The median measured offset (m) of the 60 galaxies is recorded. This step allows us to quantify the difference between the input offset i and the recovered offset m through our algorithm. We expect i − m = 0 if the sample can accurately recover the input metallicity offset. This bootstrap process is repeated 5000 times. We calculate the jackknife error on each of the median values returned by the bootstrap. For each realization, we calculate a significance σ by dividing the measured offset m by the jackknife error. We can then find the fraction of the total number of bootstrapped samples which return significant offsets for a given i. This fraction is then recorded, and plotted in the top panel of Fig. 6. Red, green and blue points reflect the fractions for σ > 1, 2 and 3, respectively. Each inserted offset requires a separate, independent run of 5000 iterations of the bootstrap, and is plotted as a separate point in the figure.

In the bottom panel of Fig. 6, the median difference between the input and measured offsets (i − m) is shown for those runs which returned significant medians at the 3σ level, as a function of the inserted offset i. This panel indicates that we are able to accurately recover an offset, if it is systematically different from the control. For values of i smaller than ±0.05, (i − m) shows an asymmetric shift away from zero. At very small i, it becomes increasingly unlikely for an offset m to be measured as significant. Therefore, those simulations which are measured as significant at small i are likely to be those which have scattered to median values further from zero. Negative values of i therefore preferentially return more negative values of m, and positive values of i return more positive values of m.

With these simulations as a base, we may compare the fractions of significant measured offsets returned by any given iteration of the bootstrap with the magnitude of offset we might expect to see. We use what has been found in previous studies of metallicity changes in high-density environments as a guideline for reasonable magnitudes of offsets. The metallicity suppressions found in the pairs sample of Ellison et al. (2008b) and of Michel-Dansac et al. (2008) are of the order of 0.05 dex, and the enhancements in overdensities in Cooper et al. (2008) are ~0.03 dex. Similar magnitudes are found by Ellison et al. (2009), who find offsets of 0.04 dex in galaxies in high-density regions, relative to their control. Mouhcine et al. (2007) find slightly higher differences in metallicity of 0.06–0.08 dex between high- and low-density environments. For offsets in the range 0.03–0.05 dex, we find that we only have a 34.8–51.1 per cent chance of detecting a 3σ result. We do not reach 99 per cent confidence levels of detecting a 1σ offset with our sample size until we reach offsets of 0.13 dex, which is much larger than anything previously discussed in the literature. The lack of significant metallicity offset in our CG sample may therefore be a limitation of our sample size. The fact that our metallicity results are both consistent with the control, combined with the results of this simulation, indicate our sample is unlikely to result in a significant offset of the magnitude suggested by the literature.
In summary, the offsets in SFR in our CG samples appear to be statistically distinct from each other, and galaxies in isolated CGs have significantly enhanced SFRs, whereas embedded CGs show no enhancement. However, the measured metallicity offsets are not sufficiently sensitive to probe metallicity differences between embedded and isolated CG galaxies and their controls.

4 DISCUSSION

We have used the varying large-scale environments of a consistently selected sample of compact, high-density groups to probe the influence of the presence of a rich group or cluster. The CG selection criteria allow us to select a consistently dense local environment on scales of ~100 kpc (see fig. 6 of M11) which, ignoring all external influences, ought to be subject to the same internal evolutionary processes. Galaxies in CG systems typically have small projected separations from each other; for our sample, the median projected separation to the nearest neighbour is 46 kpc for both isolated and embedded samples. In galaxy pairs, separations ≤30 kpc result in significantly enhanced SFRs (e.g. Barton et al. 2000; Lambas et al. 2003; Alonso et al. 2004, 2006; Ellison et al. 2008b, 2010; Scudder et al. 2012). Our sample has a significant population of galaxies with separations of this order, making galaxy–galaxy interactions an appealing explanation for the SFR enhancement seen in the isolated CG sample. The level of offset seen in our sample of isolated CG galaxies (+0.07 dex) may appear modest, but is comparable to studies of merger-induced star formation, which generally find median SFR enhancements of around +0.1 dex (e.g. Ellison et al. 2008b; Scudder et al. 2012). If the isolation criterion of the CG selection is effective at limiting outside influences, and interactions are the only dominant mechanism for transformations, we might expect both samples of CG galaxies to show consistent SFR enhancements over the control.

We find that galaxies in CGs in close proximity to a cluster or rich group (<1 Mpc) do not show the same preferential enhancement as their counterparts in isolated CGs. The embedded CG galaxies instead show consistency with the average galaxy in the control. Galaxies in isolated CGs (>1 Mpc from large-scale structures), by contrast, show SFR enhancements over the control, consistent with the general trend presented by the SFR–density relation. This SFR disparity indicates that the local overdensities identified by the CG selection criteria cannot be considered in isolation. The presence of a nearby rich group exerts some influence on the star-forming galaxies found within CGs, either by introducing an additional quenching mechanism, or because the galaxies within rich groups are physically distinct from their isolated counterparts. The SFRs and metallicities of the galaxies within those groups therefore serve as diagnostics of the impact of the larger scale environment. However, given the small magnitude of the difference between the two CG samples, the large-scale environment does not appear to drive major changes in a galaxy’s evolution at fixed local density.

4.1 Density scale dependences

Having determined the sensitivity and significance of the metallicity and SFR offsets, we wish to compare these results to previous work. However, previous metrics of environment usually fall into one of the two categories: either an nth nearest neighbour approach, or calculating galaxy density within annuli of increasing radius around a given point. In this work, we have used a new method of determining the large-scale environment of a galaxy. Our division of galaxies into embedded and isolated systems is a binary assignment, based upon the presence (or lack) of rich group structure within a cylinder in redshift and projected separation space, centred upon the CG. This is an entirely different method of characterizing the nature of a galaxy’s environment than has been typically used in the past.

Comparisons to the results found using existing measures of environment will require attention to the methodology of those metrics to be sure that they can probe the same kinds of overdensities. Since the nth neighbour and annulus methods are calculated using entirely different algorithms, the meaning of the densities returned (as it applies to our CG sample) will vary, and comparisons to the results presented here must bear this in mind. In addition, most previous work has focused upon the relative importance of local- and large-scale dependences. This relative comparison is one that we cannot address in this work, as our classifications of embedded and isolated are not relative selections, and the local density – that of the CG itself – is relatively constant across our sample. Therefore, in comparing to previous work, we can only determine whether or not the previously obtained results are consistent with some level of SFR dependence on large-scale environment as measured by our own method, to the extent that the density metrics may be compared.

The nth nearest neighbour approach identifies high-density regions of space by returning a shorter distance to the nth neighbour in dense regions, and a longer distance in lower density regions (e.g. Hashimoto et al. 1998; Carter et al. 2001). Varying the value of n effectively changes the distance scales over which one wishes to probe the densities. With small values of n, the densities returned will be more reflective of local-scale densities. Larger values of n will necessarily wander further afield to reach more distant neighbours. These distant neighbours will return a much larger volume of space over which to average the galaxy density, relative to their locally dense counterparts. The larger distances for isolated systems means that the densities derived from the identified nth neighbour will be more reflective of a large-scale density than those in locally dense environments (which return smaller distances), even if those local overdensities are relatively isolated from other structures (Weinmann et al. 2006). Since the distance to nth nearest neighbour can vary smoothly from system to system, the distance scales being probed will also vary strongly as a function of local galaxy density. Furthermore, since the distance to nth nearest neighbour is converted into a density, information about the distribution of those galaxies on scales less than that distance is lost. For the purposes of comparison to our metric, the nth nearest neighbour algorithm simply needs to be able to distinguish between isolated and embedded CG systems. Both isolated and embedded CGs have similar densities in the cores, but exhibit different galaxy surface densities on scales of 0.1–1 Mpc (M11). As long as the distances returned by the nth nearest neighbour probe these scales, they should be able to distinguish between the isolated and embedded systems.

This relatively straightforward criterion for comparison with the nth nearest neighbour provides a sharp contrast with the other main metric of galaxy density. The annulus approach is more difficult to compare to our method. In this approach, the galaxy density within annuli of increasing radius is measured (e.g. Lewis et al. 2002; Kauffmann et al. 2004; Blanton et al. 2006). Many works place their dividing line between ‘local’ and ‘large’ scales at 1 Mpc. The densities within the annulus of radius 1–3 or 1–6 Mpc is therefore used as their measure of large-scale environment. 1 Mpc is also a natural dividing line in our sample, but only in the sense that this is the distance to the nearest group that distinguishes isolated and embedded CGs. The annulus approach is sensitive to the presence of broad overdensities beyond the distance of the defined ‘large scale’. 

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generally 1–6 Mpc away from the selected galaxy. Our method provides the ability to define a system as embedded even when the overdensity is entirely on scales <1 Mpc. In this case, the CG would still distinctly be embedded in a more massive halo than its own, but would not be distinguished as ‘large-scale’ structure by an annulus of radius >1 Mpc. If some fraction of the rich group extends beyond 1 Mpc distant from the CG galaxy, then it would be detected by the >1 Mpc annulus. However, M11 show that rich groups and CGs in any environment converge to similar galaxy densities at separations ~1 Mpc. With the median distance from CG centre to a rich group for embedded groups being of the order of ~0.3 Mpc, and the majority of rich groups’ strong galaxy surface density visible on scales <1 Mpc, we might expect that only a small fraction of the galaxies within a rich group to extend beyond the 1 Mpc threshold. Furthermore, the annulus method loses all information on scales smaller than the area of the annulus. If an annulus contains an overdensity, but also contains a very low density region, these two extremes will average to a value that is not representative of either region.

With these differences in mind, we can now attempt to compare our results of an SFR dependence on large-scale environment with previous studies. We emphasize that we are investigating only the dependence on those galaxies which are star forming relative to a star-forming control, not the overall trend of SFR with density. Those works which conclude that the large-scale environment affects the evolution of star-forming galaxies by way of the cluster-centric radius (Park & Hwang 2009) or dark matter halo mass (Goto et al. 2003; Weinmann et al. 2006) are compatible with our results. However, a large body of work in the literature (using a mixture of methodologies) has concluded that the local-scale effects dominate galaxy evolution (e.g. Hashimoto et al. 1998; Carter et al. 2001; Lewis et al. 2002; Kauffmann et al. 2004; Blanton et al. 2006; Blanton & Berlind 2007). These analyses consistently find a strong SFR dependence upon local galaxy density, with either very weak or absent dependence upon galaxy densities beyond the 1 Mpc scale. For example, Blanton et al. (2006) constrain the large-scale (1–6 Mpc) effects to be small, but do not exclude them as a minor contributor. Our results are not in disagreement with those studies which found that the local scales dominate galaxy evolution, consigning the large-scale effects to a minor role. The small difference in $\Delta \log(\text{SFR})$ between star-forming galaxies in isolated and embedded CGs surely confirms the minor nature of the large-scale environment. Our work indicates simply that there is a non-zero effect upon the galaxies within a larger structure beyond local density effects; it does not require that the effect must be the dominant one. Other works in the literature are less conservative, and interpret the lack of a strong dependence upon the galaxy densities at >1 Mpc radii as evidence that the large-scale environment does not have an effect upon a galaxy. Blanton & Berlind (2007) find that for the star-forming fraction, large-scale structure (defined as structure in an annulus >1 Mpc) has no discernable effect upon the galaxy, with a bias in their measurement of no more than 5 per cent and density error of the order of 15 per cent. Kauffmann et al. (2004) found that local densities dominate the SFR evolution; at low masses, the SFR of a galaxy was up to 10 times lower in high local densities than it was in low local densities. When testing the spatial scales between 1 and 3 Mpc, they found a very noisy relation in the 4000-Å break strength, their metric for SFR, with density: consistent with no dependence. In contrast, we have found that SFRs do depend, albeit at a low level, on their association with a large-scale structure.

Reconciling our results with those in the literature likely comes down to the nature of the ‘environment’ identified by the different density metrics that have been previously used. Our division in environment identifies galaxies which are within 1 Mpc of a larger group than the CG itself. By the time scales of >1 Mpc from the centre of a group are reached, the galaxy densities for isolated, embedded and rich groups have all converged (M11). This indicates that most of the galaxy overdensity due to the rich group has also dwindled by 1 Mpc from the centre. If the groups are then sufficiently far away from the CG, they might cross over into the >1 Mpc annulus, and be detected as an overdensity by that metric. However, the peak of the distribution of the distance to the nearest rich group is ~0.3 Mpc for embedded structures (M11). At 0.3 Mpc, the majority of the rich group will be found within 1 Mpc of the CG, and would not significantly increase the measured density for annuli >1 Mpc. Therefore, even though the embedded CGs are situated in a significantly different environment than the isolated CGs, the overall galaxy density no longer reflects this difference at scales >1 Mpc. Dividing environmental factors into large- and local-scale effects simply by using a cut in radius may blend extremely local drivers of evolution and some larger scale environmental factors. Our metric therefore cleanly separates those groups embedded in a more massive halo from those which are independent haloes, no matter what the projected scale of the more massive group may be.

4.2 Physical drivers

The interpretation of the difference between embedded and isolated galaxy SFRs depends on whether the galaxies are intrinsically and physically different when they are found within an overdensity, relative to in isolation, or whether the overdensity is imposing an additional processing mechanism on an initially similar set of galaxies. If the former, then galaxies found within large-scale structure are reacting to the same set of evolutionary processes as galaxies in isolation, but their intrinsic properties make SFR enhancement (for example) more difficult to achieve.

One mechanism by which a physical difference in the galaxy populations between embedded and isolated CGs might arise is assembly bias (e.g. Croton, Gao & White 2007; Cooper et al. 2010). Assembly bias states that galaxies in high-mass potentials tend to be older, as they collapsed and began to cluster at earlier times. In this scenario, one might expect clusters to contain a higher fraction of old, so-called ‘red and dead’ galaxies, galaxies which have undergone many mergers, or galaxies which have been affected by the cluster potential through quenching mechanisms for a longer period of time. Galaxies in rich groups tend to be preferentially gas poor (e.g. Chung et al. 2009) as a result. This framework offers one explanation for the SFR suppression in overdense regions. If galaxies within rich groups are simply older than their counterparts in the isolated groups, then they would be further along in their evolution, and may be further along the process of gas exhaustion and consumption. If the CG galaxies, due to their age, in addition to any environmental effects, are preferentially gas poor, then it will be significantly more difficult to trigger an SFR enhancement after an interaction (e.g. Alonso et al. 2006). Their isolated counterparts, having collapsed at later times, are younger, more gas rich, and at a much earlier stage in their evolution; these galaxies will show SFR enhancements much more easily, as their gas reservoir is less depleted. This explanation does not require a difference in the mechanisms that modulate SFRs in the two environments; the difference in intrinsic galaxy properties is enough to alter the galaxy’s response to the same large-scale environmental mechanisms. However, all the galaxies in our sample are emission line galaxies. While their SFRs may be lower than the average galaxy,
they still have significant amounts of gas. They cannot have been so affected by quenching and stripping mechanisms as to remove all their gas, if they can maintain strong emission lines. A large portion of the galaxies in our sample, regardless of their classification as embedded or isolated, retain relatively late-type morphologies (see Figs A1 and A2). The maintenance of the emission lines and their late-type morphologies limits the magnitude of the environmental and age-related evolution that the galaxies could have undergone. Turning to consider processes that could alter the SFRs of a given galaxy in a different environment, we can eliminate quenching mechanisms that function on very small scales such as those associated with interactions; these should be consistently affecting both isolated and embedded systems. Whatever mechanism is preventing SFR enhancement in embedded CG galaxies must be associated with the larger scale cluster potential, and not simply with the high densities of the CG system. One explanation could be the difference in evolutionary processes in central and satellite galaxies. Galaxy populations divided in this way show that galaxies which are not the dominant galaxy in the dark matter halo undergo stronger environmental processes than the central galaxy does (Haines et al. 2006; Kimm et al. 2009; Peng et al. 2011; Tinker, Wetzel & Conroy 2011). Embedded CGs would, by definition, be a satellite halo within the larger cluster halo. The enhanced processing seen in most satellites would therefore be systematically applied to all galaxies in the embedded systems. Blanton & Berlind (2007) find that high-density substructures (on scales of <300 kpc) within a cluster are more correlated than expected with hosting red galaxies, i.e. these galaxies are further along in the quenching process. By contrast, the probability of the dominant galaxy in the potential being in our sample is significantly higher for isolated systems, where the CG environment is more likely to be an isolated halo.

If the difference between galaxies in isolated and embedded CG systems is not due to a systematic physical difference in galaxy population, then the galaxies in both systems ought to have begun their evolution in the CG as a roughly uniform population of galaxies. In order to explain the absence of the SFR enhancement seen in the isolated CG galaxies, an additional evolutionary force must be at work in embedded CG galaxies due to the cluster potential that is not in effect in isolated haloes. This brings into suspicion the main drivers of galaxy evolution in clusters: ram-pressure stripping, galaxy–galaxy harassment and strangulation. The isolation criterion for CG selection means that external galaxy harassment is unlikely to be a significant influence. Galaxy harassment within the CG would contribute similar levels of evolutionary processing to both galaxy populations of CGs, and is therefore not a useful explanation for the difference in SFR response. Further, CGs have relatively low velocity differences, so harassment within the group itself is unlikely to dominate over lower velocity tidal interactions. This leaves ram-pressure stripping (removal of cold gas from the disc) and strangulation (removal of the external gas supply). Weinmann et al. (2006) argue that ram-pressure stripping should affect low-mass galaxies more quickly, as they have a smaller potential and are more easily stripped of their gas, within a halo of given mass. This ought to result in a higher fraction of low-mass early-type galaxies relative to the fraction of high-mass early types. Their sample, taken from the SDSS DR2, contradicts this prediction, finding no evidence for preferential changes to the lower mass galaxies. Wetzel, Tinker & Conroy (2011) find that galaxies introduced into a larger halo can retain their SFR at pre-accretion levels for 1–2 Gyr before rapid quenching takes place; if ram-pressure stripping were the dominant mechanism, the galaxies would have their cold gas removed on much quicker time-scales. Ram-pressure stripping is also excluded by a number of other authors (e.g. Tanaka et al. 2004; Blanton & Berlind 2007) due to the large radial extent of SFR suppressions, and SFR suppressions in low-mass haloes. Neither of these environments are expected to have the dense intracluster medium needed to support effective ram-pressure stripping (e.g. Rasmussen et al. 2008). This leaves strangulation as the prime suspect for SFR suppression in cluster environments, as it could still remove the hot halo of gas around a galaxy in lower density or lower mass environments (Balogh, Navarro & Morris 2000). Furthermore, it does not affect the morphologies or cold gas reservoirs of the galaxies involved (Weinmann et al. 2006). M11 find that the morphologies within embedded and isolated CGs are very similar, which also supports the idea of an environmental process being at work, rather than different evolutions due to age or gas exhaustion. Strangulation therefore appears to be an appealing mechanism for long-term suppression of SFR in emission line galaxies.

5 CONCLUSIONS

We present a sample of robustly calculated gas-phase metallicities and SFRs for a sample of 75 863 star-forming galaxies in the SDSS DR7. These metallicities use emission line fluxes which passed rigorous quality control, and are cleaned of any AGN contribution. From this sample, we define a CG sample of 112 galaxies that is uniformly selected on criteria for local richness and cleaned of likely interlopers. The CG sample is further split by large-scale environment into isolated and embedded subsamples, with 62 and 50 galaxies in each sample, respectively. These two samples of star-forming CG galaxies therefore have the same (very high) local density, but different large-scale environments. The samples of CG galaxies are simultaneously matched in mass and redshift with 50 non-CG galaxies each in order to form robust control samples. By comparing the control samples with the CG galaxy properties, we can measure the difference in the SFR and metallicity at fixed mass. The main conclusions of our work are as follows.

(i) Isolated and embedded CG galaxies are offset from each other, and isolated CG galaxies are significantly enhanced relative to the field SFR–mass relation. Embedded galaxies do not show a similar enhancement. The SFRs of the galaxies in isolated CG systems show a median enhancement of +0.07 ± 0.03 dex, whereas the galaxies in embedded systems show a median offset of −0.03 ± 0.05 dex. A series of bootstrap and Monte Carlo simulations indicate that this offset is robust. Our results indicate that, even though previous works have found a primary dependence on local density, the SFRs of star-forming galaxies in locally overdense regions are mildly sensitive to large-scale environment at fixed local density.

(ii) We find no evidence for a significant metallicity offset in either isolated or embedded samples relative to their control samples. However, this non-detection is likely to be a result of small number statistics, as our sample is not likely to detect offsets of the order of 0.03–0.05 dex, which is the typical metallicity offset expected due to interactions or density-driven effects. Our sample is therefore inconclusive with regards to the metallicity offsets. The simulations indicate that at 99 per cent confidence we could have detected an offset of 0.13 dex.

Criteria classically used to select CGs define a consistent set of high-density groups of galaxies. However, when these systems are divided according to the presence of a nearby cluster or rich group, the SFRs of the star-forming galaxies within these systems become divided. The environmental split in median SFR demonstrates that large-scale structure can exert an effect upon substructure found
within it, even if at a low level, and that substructure is relatively isolated from other galaxies. The two possible explanations are: galaxies found within overdense regions are intrinsically different from galaxies in low-density regions, which alters their response to the same local overdensities, or that the rich group structure imposes an additional evolutionary mechanism on to the galaxies in embedded CGs. This may give further support to the differences in satellite and central galaxy evolution, with strangulation, found only in cluster environments, as an effective process in slowly shutting down star formation.

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APPENDIX A: FIGURES AND TABLES

In the appendix, we include additional figures and tables for illustrative purposes. Figs A1 and A2 show Sloan images of sample CGs from the embedded and isolated samples, respectively. Tables A1 and A2 contain information on the embedded and isolated CG galaxies, respectively. Fig. A3 shows the results of the Monte Carlo simulation conducted in Section 3.

Figure A1. Four embedded CG galaxies, selected at random. The images are centred on the galaxy in the spectroscopic sample (identified by SDSS ObjID in the lower left-hand corner), and are approximately 200 arcsec to a side.
Figure A2. Four isolated CG galaxies, selected at random. The images are centred on the galaxy contained in the spectroscopic sample (identified by SDSS ObjID in the lower left-hand corner), and are approximately 200 arcsec to a side.

Table A1. Embedded CG galaxy properties. SDSS ObjID is the unique identifier for that galaxy within Sloan, CG ObjID is the Galaxy ID from the M09 catalogue where numbers before the decimal indicate the group ID, and the number after the decimal varies between galaxies within one group. Metallicity calculations are described in Section 2.3. SFR values come from the calculations of Brinchmann et al. (2004).

| SDSS ObjID | CG ObjID   | Redshift | Stellar mass $\log(M_\star)$ (M$_\odot$) | Metallicity $12+\log(O/H)$ | SFR $\log$(SFR) (M$_\odot$ yr$^{-1}$) |
|------------|------------|----------|----------------------------------------|-----------------------------|----------------------------------|
| 587735348567736612 | SDSSCGA00374.4 | 0.066 | 9.70 | 8.97 | -0.23 |
| 587732470923591912 | SDSSCGA02222.4 | 0.089 | 9.91 | 8.96 | 0.22 |
| 587742551749427305 | SDSSCGA01310.2 | 0.072 | 10.09 | 9.09 | 0.58 |
| 587739629557907538 | SDSSCGA00209.3 | 0.063 | 9.78 | 9.00 | 0.51 |
| 58773652909933590 | SDSSCGA00436.4 | 0.109 | 10.79 | 9.29 | 1.59 |
| 58774261458212294 | SDSSCGA00213.1 | 0.127 | 10.85 | 9.23 | 1.29 |
| 587731499184423092 | SDSSCGA01085.4 | 0.050 | 9.52 | 8.96 | -0.43 |
| 588017702397476999 | SDSSCGA01110.2 | 0.067 | 10.02 | 9.04 | 0.34 |
| 587741600963297361 | SDSSCGA00933.2 | 0.059 | 10.46 | 8.99 | 0.29 |
| 58772915790514663 | SDSSCGA01012.4 | 0.069 | 9.64 | 9.01 | -0.05 |
| 587736619327553911 | SDSSCGA01186.2 | 0.089 | 10.13 | 9.03 | 0.61 |
| 587744727687954659 | SDSSCGA01185.4 | 0.092 | 10.07 | 9.20 | 0.31 |
| 587729160048148639 | SDSSCGA01232.2 | 0.091 | 9.88 | 8.94 | 0.38 |
| 587742551749427435 | SDSSCGA01310.3 | 0.071 | 9.51 | 8.91 | 0.03 |
| 58774206215993500 | SDSSCGA00253.2 | 0.077 | 10.15 | 9.17 | 0.72 |
| 587739648868505610 | SDSSCGA00838.4 | 0.133 | 10.26 | 9.16 | 0.60 |
| 587741421632356738 | SDSSCGA00979.4 | 0.051 | 9.59 | 8.99 | -0.42 |
| 588017116128870540 | SDSSCGA01825.1 | 0.071 | 10.04 | 8.96 | 0.62 |
| 588848901523439828 | SDSSCGA01598.4 | 0.082 | 10.44 | 9.17 | 0.33 |
| 587729388223201436 | SDSSCGA01434.3 | 0.035 | 9.80 | 9.11 | -0.34 |
Table A1  — continued

| SDSS ObjID   | CG ObjID      | Redshift | Stellar mass (M$_\odot$) | Metallicity 12+ log(O/H) | SFR log(SFR) (M$_\odot$ yr$^{-1}$) |
|--------------|---------------|----------|--------------------------|--------------------------|----------------------------------|
| SDSSCGA01825.2 | SDSSCGA01825.2 | 0.071 | 10.22 | 9.24 | 0.42 |
| SDSSCGA02027.5 | SDSSCGA02027.5 | 0.065 | 9.73 | 9.04 | –0.06 |
| SDSSCGA04354.4 | SDSSCGA04354.4 | 0.048 | 9.61 | 9.05 | –0.46 |
| SDSSCGA01858.4 | SDSSCGA01858.4 | 0.095 | 10.00 | 9.05 | 0.45 |
| SDSSCGA01272.3 | SDSSCGA01272.3 | 0.042 | 9.17 | 8.71 | –0.83 |
| SDSSCGA01487.3 | SDSSCGA01487.3 | 0.096 | 9.98 | 9.00 | 0.47 |
| SDSSCGA01858.3 | SDSSCGA01858.3 | 0.095 | 10.00 | 9.03 | 0.52 |
| SDSSCGA01272.3 | SDSSCGA01272.3 | 0.042 | 9.17 | 8.71 | –0.83 |
| SDSSCGA01487.3 | SDSSCGA01487.3 | 0.096 | 9.98 | 9.00 | 0.47 |
| SDSSCGA01858.4 | SDSSCGA01858.4 | 0.095 | 10.00 | 9.05 | 0.45 |

Table A2. Same as Table A1, but for the isolated CG galaxies.

| SDSS ObjID   | CG ObjID      | Redshift | Stellar mass (M$_\odot$) | Metallicity 12+ log(O/H) | SFR log(SFR) (M$_\odot$ yr$^{-1}$) |
|--------------|---------------|----------|--------------------------|--------------------------|----------------------------------|
| SDSSCGA01177.2 | SDSSCGA01177.2 | 0.114 | 10.61 | 9.10 | 0.82 |
| SDSSCGA01088.4 | SDSSCGA01088.4 | 0.061 | 10.11 | 8.99 | –0.51 |
| SDSSCGA00878.2 | SDSSCGA00878.2 | 0.030 | 9.97 | 9.22 | 0.72 |
| SDSSCGA01128.1 | SDSSCGA01128.1 | 0.054 | 10.48 | 9.04 | 0.41 |
| SDSSCGA01311.1 | SDSSCGA01311.1 | 0.054 | 10.48 | 9.04 | 0.41 |
| SDSSCGA01461.4 | SDSSCGA01461.4 | 0.041 | 10.24 | 9.21 | 0.13 |
| SDSSCGA01533.2 | SDSSCGA01533.2 | 0.066 | 10.16 | 9.18 | 0.35 |
| SDSSCGA01070.4 | SDSSCGA01070.4 | 0.085 | 9.87 | 9.09 | 0.65 |
| SDSSCGA00882752.2 | SDSSCGA00882752.2 | 0.097 | 10.27 | 9.18 | 0.50 |
| SDSSCGA002231.4 | SDSSCGA002231.4 | 0.083 | 9.79 | 8.87 | –0.07 |
| SDSSCGA002231.4 | SDSSCGA002231.4 | 0.083 | 9.79 | 8.87 | –0.07 |
| SDSSCGA002231.4 | SDSSCGA002231.4 | 0.083 | 9.79 | 8.87 | –0.07 |

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**Table A2 – continued**

| SDSS ObjID | CG ObjID   | Redshift | Stellar mass log($M_\ast$) ($M_\odot$) | Metallicity 12+ log(O/H) | SFR log($\text{SFR}$) ($M_\odot$ yr$^{-1}$) |
|------------|------------|----------|----------------------------------------|--------------------------|---------------------------------------------|
| 587742013820305436 SDSSCGA01370.2 | 0.01 | 9.95 | 8.90 | 0.84 |
| 58774257521000950 SDSSCGA01809.3 | 0.003 | 10.33 | 9.19 | 0.48 |
| 58801762721721251 SDSSCGA01937.3 | 0.074 | 10.09 | 9.11 | 0.53 |
| 588007000648855395 SDSSCGA00936.1 | 0.074 | 10.19 | 9.07 | 0.80 |
| 587736958138368784 SDSSCGA00878.3 | 0.031 | 9.71 | 9.16 | -0.50 |
| 587738947198910752 SDSSCGA01710.2 | 0.043 | 9.71 | 8.94 | -0.19 |
| 587734893272129437 SDSSCGA00945.1 | 0.060 | 10.56 | 9.16 | 0.79 |
| 58774172067826052 SDSSCGA00562.2 | 0.067 | 9.50 | 8.90 | 0.39 |
| 587726101490827456 SDSSCGA00370.3 | 0.086 | 10.20 | 9.00 | 0.56 |
| 587725469057351815 SDSSCGA01097.1 | 0.132 | 11.09 | 8.89 | 0.87 |
| 587736782540964307 SDSSCGA01542.3 | 0.124 | 10.69 | 9.27 | 0.76 |
| 58773911527301957 SDSSCGA01970.3 | 0.099 | 9.74 | 8.88 | 0.21 |
| 58773961230554751 SDSSCGA00820.2 | 0.073 | 10.20 | 9.09 | 0.37 |
| 58801762721721162 SDSSCGA01937.4 | 0.074 | 10.40 | 9.03 | 1.03 |
| 588848900472111426 SDSSCGA01473.2 | 0.076 | 10.11 | 9.18 | 0.48 |
| 58773940570711699 SDSSCGA01128.2 | 0.054 | 10.46 | 9.08 | 0.67 |
| 5888489932340185 SDSSCGA00476.3 | 0.093 | 10.44 | 9.21 | 0.62 |
| 5877294075622376 SDSSCGA02056.3 | 0.029 | 9.82 | 9.02 | -0.46 |
| 58773911028992231 SDSSCGA01347.2 | 0.068 | 9.57 | 8.93 | 0.23 |
| 58772994444119019 SDSSCGA01703.2 | 0.120 | 10.36 | 9.13 | 0.74 |
| 58772984444119010 SDSSCGA01703.3 | 0.121 | 10.68 | 9.27 | 0.72 |
| 58773564565584070 SDSSCGA00337.4 | 0.069 | 9.79 | 9.01 | 0.49 |
| 58773811646697402 SDSSCGA01583.3 | 0.103 | 9.81 | 8.95 | 0.46 |
| 587742578054201471 SDSSCGA01218.3 | 0.099 | 10.53 | 9.20 | 0.52 |
| 58801697882571672 SDSSCGA02227.3 | 0.082 | 10.12 | 9.05 | 0.71 |
| 58773961023054752 SDSSCGA00820.3 | 0.072 | 9.91 | 8.92 | 0.35 |
| 58800936800381825 SDSSCGA02225.5 | 0.092 | 10.13 | 9.04 | 0.44 |
| 587738421048294053 SDSSCGA00614.3 | 0.079 | 10.00 | 8.93 | 0.33 |
| 587742013279713696 SDSSCGA01348.3 | 0.102 | 9.96 | 8.96 | 0.54 |
| 58774160305970870 SDSSCGA00610.3 | 0.081 | 10.08 | 8.99 | 0.19 |
| 58774277455508821 SDSSCGA01132.3 | 0.123 | 10.22 | 9.14 | 0.59 |

**Figure A3.** Results of a Monte Carlo simulation on the SFR values of CG galaxies. The distribution of median offsets for the isolated (blue solid) and embedded (red dashed) CG galaxies is shown after 10,000 resamplings of the error distribution. Both control and CG galaxies were redrawn, and their offsets recalculated. The median of the distribution of median offsets for isolated CGs is +0.07 ± 0.03 dex, where the uncertainty is a 1σ width of the distribution. Embedded CG galaxies show median SFRs of −0.06 ± 0.06 dex. These distributions indicate that the effect of errors on the SFRs is not likely to change the results of our analysis. KS tests indicate a 0 per cent chance that the two distributions were drawn from the same parent sample.

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