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Compact groups in theory and practice – II. Comparing the observed and predicted nature of galaxies in compact groups

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ABSTRACT

We examine the properties of galaxies in compact groups (CGs) identified in a mock galaxy catalogue based upon the Millennium Run simulation. The overall properties of groups identified in projection are in general agreement with the best available observational constraints. However, only ∼30 per cent of these simulated groups are found to be truly compact in three dimensions, suggesting that interlopers strongly affect our observed understanding of the properties of galaxies in CGs. These simulations predict that genuine CG galaxies are an extremely homogeneous population, confined nearly exclusively to the red sequence: they are best described as 'red and dead' ellipticals. When interlopers are included, the population becomes much more heterogeneous, due to bluer, star-forming, gas-rich, late-type galaxies incorrectly identified as CG members. These models suggest that selection of members by redshift, such that the line-of-sight velocity dispersion of the group is less than 1000 km s^{-1}, significantly reduces contamination to the 30 per cent level. Selection of members by galaxy colour, a technique used frequently for galaxy clusters, is also predicted to dramatically reduce contamination rates for CG studies.

Key words: galaxies: evolution – galaxies: general – galaxies: interactions – galaxies: statistics.

1 INTRODUCTION

Compact groups (CGs) of galaxies are spatially dense groupings of generally four or more galaxies. In contrast to galaxies found in cluster cores (Zabludoff, Huchra & Geller 1980), the projected velocity dispersions of CGs are generally small (∼200 km s^{-1}; Hickson et al. 1992). This combination of low velocity dispersions and high spatial densities makes CGs an optimal environment for dynamical interactions and mergers to occur. Galaxy interactions, whether in groups or pairs, have been shown to influence the observed properties of galaxies (Larson & Tinsley 1978; Kennicutt et al. 1987; Barton, Geller & Kenyon 2000; Schwarzkopf & Dettmar 2000; Lambas et al. 2003; Alonso et al. 2004; Nikolic, Cullen & Alexander 2004; Patton et al. 2005; Geller et al. 2006), and so CGs are an ideal environment in which to study the effects of encounters on galaxy morphology.

Observational studies of CGs reveal that galaxies in these environments tend to be systematically different from the field population. Perhaps most striking of all, the fraction of early-type galaxies in CGs in magnitude-limited surveys is significantly higher than in the field; Hickson, Kindl & Huchra (1988) found 51 per cent of their CG galaxies were early-type, compared to ∼20 per cent of the field (Nilson 1973; Gisler 1980). Similarly, Palumbo et al. (1995) found 55 per cent of galaxies in their CG sample were early-type. Early-type galaxies can be formed via the merging of late-type systems (e.g. Barnes 1989), and so these results can be explained by frequent interactions and mergers between the galaxies in the CG environment.

One result of mergers which might be expected is an enhanced star formation rate (SFR), triggered by the redistribution of gas as galaxies tidally interact. Close pairs of galaxies are observed to have enhanced SFRs, consistent with this picture (e.g. Carlberg, Pritchet & Infante 1994; Ellison et al. 2008, and references therein). Yet in clusters, SFRs are low when the local density is high (e.g. Lewis et al. 2002; Gómez et al. 2003), therefore it is not clear a priori which way the SFRs will go in CG galaxies. One possible scenario is that galaxy interactions led to an exhaustion of gas in these galaxies through previous starbursts and/or stripping (either tidal or ram pressure). Indeed, Williams & Rood (1987) found CG galaxies to

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be deficient in H I by a factor of 2 on average when compared to galaxies in loose groups, and Menon (1995) found a significant deficiency in total radio emission from CG spirals compared to field spirals, again implying a reduced gaseous content.

Differences have also been measured in the mean colours of CG and field galaxies. In very broad terms, redder galaxies in the field generally consist of an older and/or more metal rich stellar population than bluer galaxies, although other effects such as extinction can play a significant role. Lee et al. (2004) found the rest-frame colours of their CG sample which were on average redder than field galaxies at approximately the 2σ level. Deng et al. (2007) also found that the mean colours of galaxies in CGs were redder and had a smaller dispersion in colour than galaxies in their control sample.

Clearly, over the past several decades there has been considerable observational effort to determine the properties of galaxies in CGs. Cosmological simulations now have sufficient detail and statistics to examine the properties of galaxies in CGs and provide a meaningful comparison with observations. For example, do these models predict that CGs should have an excess of early-type galaxies and, if so, how large is the excess? How does this compare to observations? What about the colours and SFRs of the galaxies? Can any differences between the observed and predicted properties of CG galaxies be traced back to inadequacies in the modelling or observational effects?

In McConnachie, Ellison & Patton (2008) (hereafter Paper I), we identified CGs in a mock galaxy catalogue (Blaizot et al. 2005) based upon the Millennium Run simulation (Springel et al. 2005) and investigated their spatial properties. In this paper, the second in the series, we determine the main physical properties of the galaxies in these CGs and compare them to observational results to determine if our observational and theoretical understanding of these galaxies are in conflict and, if so, why.

In Section 2, we review how CGs are identified and quantified from the mock catalogue. We also review how the main physical parameters for the simulated galaxies, which we will compare to observations, are calculated, and discuss possible limitations. In Section 3, we determine the range of properties shown by the CGs in the mock catalogue and compare them to a control sample. We postpone the majority of the discussion of our results and comparison to observations until Section 4, and we summarize our results in Section 5.

2 SAMPLE SELECTION

In Paper I, CGs are identified in a mock galaxy catalogue based upon their projected characteristics using the original Hickson criteria (Hickson 1982). We refer to these galaxy associations identified in the simulation as Hickson Associations (HAs), in recognition of the fact that we find ~70 per cent of HAs in the simulation are not truly compact in three dimensions (for example, they are projections of looser groups or physically unassociated galaxies) and that they may contain interlopers. Compact Associations (CAs) are defined as being that subset of HAs which are truly compact in three dimensions. In Paper I, the degree of compactness of each group is quantified using the concept of three dimensional *linking length*, ℓ (e.g. Huchra & Geller 1982). We show that a good criterion for defining CAs in simulations, where three dimensional information is available, are those HAs which have $\ell < 200\,h^{-1}$ kpc. 'CGs' refers to observationally identified systems, and 'HCGs' (Hickson Compact Groups) refers explicitly to those systems identified in the original Hickson (1982) catalogue. Table 1 summarizes this terminology.

Table 1. Summary of terminology used in this paper.

System	Acronym	Definition
(Hickson) Compact Group	(H)CG	Observationally identified systems (using the original Hickson (1982) criteria).
Hickson Associations	HA	Identified in the mock catalogue using Hickson's criteria.
Compact Associations	CA	The subset of HAs which are truly compact in three dimensions.

2.1 The identification of CGs

The Millennium Run simulation by Springel et al. (2005) evolves 2160^3 dark matter particles in a cube with 500 h^{-1} Mpc sides, assuming a Λ cold dark matter (CDM) cosmology ($h = 0.73$, $\Omega_\Lambda = 0.75, \Omega_M = 0.25$), where the Hubble constant is parametrized as $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. De Lucia & Blaizot (2007) track the formation of galaxies from the dark matter distribution using semi-analytic techniques, and their resulting catalogue provides the three dimensional positions and velocities of the galaxies, and various properties such as bulge and stellar masses, colours and SFRs.

Mock galaxy catalogues were created from the output of the De Lucia & Blaizot (2007) catalogue using the Mock Map Facility (MoMaF) code of Blaizot et al. (2005). We use the 'Blaizot_Allsky_PT_1' catalogue which is publicly available on the Millennium website.[1] This mock catalogue contains ~5.7 million galaxies brighter than $m_r = 18$. Paper I applies the Hickson criteria to this mock galaxy catalogue and examines the spatial properties of the HAs identified.

In Paper I, 15 122 HAs were identified in the mock galaxy catalogue, consisting of a total of 64 525 galaxies. However, only 28 per cent of these HAs are CAs (i.e. physically compact with no interlopers). This strongly suggests that interlopers have had a significant effect on the implied observational properties of galaxies in CGs, where it is more difficult to determine the three dimensional reality of the systems being studied.

We emphasize that the term 'interloper' does not necessarily imply that the galaxy is at a significantly different redshift to the CG; rather, it means that the galaxy is unlikely to have evolved in the dense environment expected of a CG. We define CAs as that subset of HAs with $\ell < 200\,h^{-1}$ kpc. Any galaxy greater than $200\,h^{-1}$ kpc away from the main concentration of galaxies of a CG is therefore classed as an interloper, even though it may belong to the same larger-scale environment as the CG (e.g. a surrounding loose group) and may not have a discordant redshift. Nevertheless, its inclusion in a study of the properties of CG galaxies – which we are ultimately interested in because of their evolution in an environment where interactions should be common – could potentially bias any conclusions which are drawn. In addition, the grouping of galaxies which remains should not strictly be classed as a CG, since it probably would not satisfy the selection criteria for a CG (particularly regarding the number of members and the surface brightness criteria) were it not for the presence of the interloper(s).

[1] http://www.mpa-garching.mpg.de/millennium/

2.2 Summary of relevant semi-analytics within the simulation

In the semi-analytic models on which the mock galaxy catalogues are based, physically motivated recipes for the baryonic distribution are applied to the collisionless dark matter distribution to create realistic galaxy populations. In very broad terms, galaxy formation in these models is the process by which hot gas cools within dark matter haloes to form stars. A galaxy's merger history, its SFR and various feedback processes combine to determine its evolution. Galaxies are centred at the position of the most bound particle in the dark matter halo. Due to the high resolution of the Millennium Run, the positions and velocities of these galaxies can be accurately determined by following the orbits and merging histories of the (sub)haloes within the simulation.

Below is a brief overview of the physical treatment of various processes which govern the main observable properties of the galaxies which we will examine in detail in Section 3. We refer the reader to De Lucia & Blaizot (2007), and references therein, for a more complete description of the semi-analytic methods. The initial identification of the CGs from these semi-analytic catalogues was made in Paper I using the observational criteria of Hickson (1982). Recently, these mock catalogues have been used in a similar way for a similar purpose by Kitzbichler & White (2008) in their study of close galaxy pairs.

2.2.1 Cold gas

De Lucia & Blaizot (2007) assume that as each dark matter halo collapses, some baryonic matter collapses with it (determined as a fraction of the dark matter mass). This gas is shock heated to the virial temperature of the halo and, following Kauffmann et al. (1999) and Springel et al. (2001), a cooling time is computed for the gas using cooling curves dependent on the temperature and metallicity (Sutherland & Dopita 1993). A cooling radius, defined as the radius at which the cooling time of a galaxy is equal to the age of the Universe, is calculated, and all gas within the cooling radius is then treated as cold gas.[2] The cold gas is then accreted on to the disc of the central galaxy in the halo on the free-fall time-scale. There is assumed to be no cooling on to satellite galaxies.

While the detailed chemistry of the cold gas cannot be followed in the simulation, we assume that the cold gas fraction will trace the H I abundance. This allows comparison to observations and seems a reasonable assumption, considering the fraction of other atomic or molecular gases compared to H I in galaxies is usually small.

2.2.2 Star formation

Star formation occurs in two modes. In the first, as long as the mass of cold gas is greater than a critical value, $M_{\rm crit}$, star formation proceeds at a continual rate defined as

$$\dot{M}_* = \frac{\alpha(M_{\rm cold} - M_{\rm crit})}{t_{\rm dyn}}. \quad (1)$$

$M_{\rm cold}$ and $t_{\rm dyn}$ are the cold gas mass and the galactic dynamical time, respectively, and α is the efficiency by which gas is converted into stars. In the second mode, star formation occurs in starbursts triggered by mergers (Section 2.2.4).

[2] The cooling radius will continue to propagate outwards with time in a galaxy until either all of the hot gas in the halo has cooled or more material is injected into the halo via feedback processes or mergers with other galaxies.

2.2.3 Luminosity and colour

Photometric properties of the galaxies are determined using the stellar population synthesis models of Bruzual & Charlot (2003). An initial mass function is adopted and used to compute the number of stars formed in each mass interval. These stars then evolve along theoretical evolutionary tracks, primarily governed by their mass and metallicity. The spectral energy distribution (SED) of the galaxy is computed by convolving the evolution of the SED of each single-age stellar population with the star formation history of the galaxy. Convolving the SED with the filter responses gives the luminosities and colours of each galaxy.

2.2.4 Bulge mass fraction

Galaxy bulges form via mergers and disc instabilities. Discs are stable if

$$\frac{V_c}{\sqrt{G M_{\rm disc}/r_{\rm disc}}} \geq 1. \quad (2)$$

$M_{\rm disc}$, $r_{\rm disc}$ and V_c are the mass, radius and rotational velocity of the disc, respectively. The ratio on the left-hand side of equation (2) is computed for every galaxy at every time-step. If necessary, stellar mass is transferred from the disc to the bulge until the inequality is satisfied.

For mergers between galaxies, the 'collisional starburst' method of Somerville, Primack & Faber (2001) is applied. If two galaxies, G_1 and G_2, with baryonic masses $M_1 > M_2$, merge, the gas contained within both galaxies coalesce to form the disc of the post-merger galaxy, G_f. The bulge of G_f is composed of the bulge stars from G_1 and all the stars from G_2.

During a merger where $M_1 \gg M_2$, no star formation is triggered. In the case of a major merger ($M_2/M_1 > 0.3$), the discs are completely destroyed and all the stellar mass is transferred to the bulge component of G_f.[3] Additionally, a fraction of cold gas from the two merging galaxies is instantaneously consumed in a starburst. These new stars are added to the bulge component of G_f.

3 THE PROPERTIES OF GALAXIES IN CGs

In this section, we determine how the properties of galaxies in HAs (the equivalent of HCGs in the mock catalogue) compare to the field population. Further, we compare the properties of CAs to those of HAs, to gain insight into how observational studies of CGs may have been biased by the presence of a significant number of interlopers. We note that, since CAs are an interloper-free subset of HAs, they do not have an exact observational analogue with which to compare directly.

3.1 The control sample

Stellar mass and redshift both correlate with many physical properties of galaxies due to dynamical and evolutionary considerations. We therefore compare the properties of the galaxies in our sample to those in a field (control) sample selected to match the mass and redshift distribution of HAs. Differences between the field and HAs can then be connected to their different environments, not to a difference in the stellar mass or redshift. We match the control sample

[3] It is possible for G_f to form a disc at a later time by the accretion of cold gas.

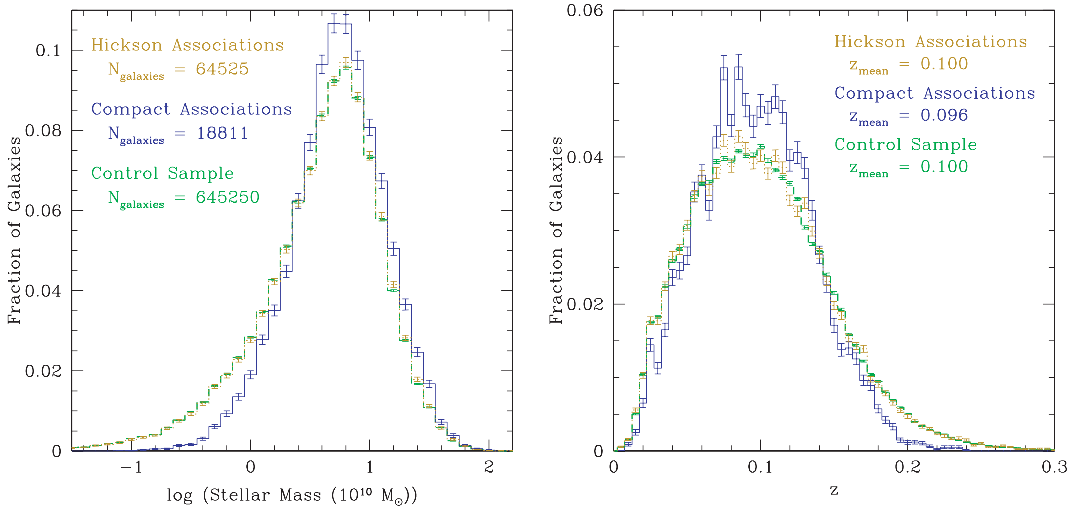

Figure 1. Left-hand panel: stellar mass distribution for galaxies in HAs is shown in dotted brown, the subset of these which are compact in three dimensions and contain no interlopers (i.e. CAs) is show in solid blue, and the control sample is shown in dashed green. The histograms have been normalized to have the same total number of galaxies in each sample. Right-hand panel: redshift distribution of our sample galaxies using same line styles as the left-hand panel. The control sample was constructed such as to be matched in both stellar mass and redshift to the HA galaxies. One dimensional Kolmogrov–Smirnov (KS) tests between the HA galaxies and the control sample galaxies show that for both the stellar mass and redshift distributions, the null hypothesis is accepted at the >90 per cent level.

to HAs because we will first compare HAs to the control in order to make a comparison analogous to observational comparisons of CGs and field galaxies. Later on, we compare HA to CA galaxies to understand the impact of contamination, therefore no control is required to match CA galaxies.

A control sample was constructed from the initial field sample which consisted of all galaxies in the Blaizot catalogue which are not members of an HA. For each HA galaxy, we found 10 unique field galaxies which have the same stellar mass and redshift as the HA galaxy to within a tolerance of 10 per cent. The control sample contains 645 250 galaxies and its stellar mass and redshift distributions are shown in Fig. 1. The left-hand panel of Fig. 1 shows the stellar mass distribution of all galaxies in HAs (dotted brown), CAs (solid blue) and our control sample (dashed green), where each has been normalized to have the same total number of galaxies. The distributions for HAs and the control sample effectively lie on top of one another. The right-hand panel shows the equivalent distributions for the redshift distribution of the galaxies in the groups. One dimensional Kolmogrov–Smirnov (KS) tests between the HA galaxies and the control sample galaxies show that for both mass and redshift, the null hypothesis that both distributions are drawn from the same underlying distribution is acceptable at the >90 per cent level. Galaxies in CAs have a slightly higher mean stellar mass than galaxies in HAs ($\bar{M}_* \simeq 7.9 \times 10^{10}\,\mathrm{M}_\odot$ compared to $\bar{M}_* \simeq 6.8 \times 10^{10}\,\mathrm{M}_\odot$) and a slightly lower mean redshift ($\bar{z}_{\mathrm{CA}} = 0.096$ compared to $\bar{z}_{\mathrm{control}} = 0.100$).

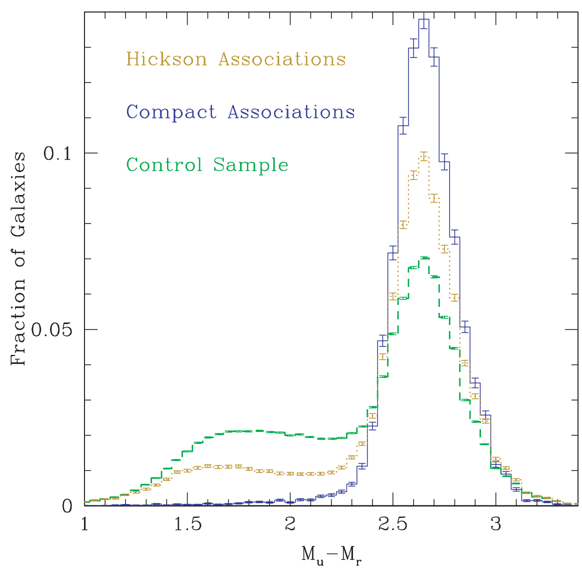

Figure 2. $(M_u - M_r)$ colour distributions for galaxies in HAs, CAs and our control sample, with the same line styles and scaling as used in Fig. 1. The distribution of the control sample is bimodal, representing galaxies in the red sequence and blue cloud. HAs are also bimodal, but there is a far greater proportion of redder galaxies in comparison to the control sample. In contrast, CAs are nearly all red, $(M_u - M_r) \gtrsim 2.25$, with only a very low level tail to bluer colours.

3.2 Colour

In observational studies, galaxies in CGs are found on average to be redder than the field population (Lee et al. 2004; Deng et al. 2007). Galaxy colour is a broad indication of the age and metallicity of the luminosity-weighted mean stellar populations of a galaxy, with older populations and more metal-rich populations generally appearing redder. To some extent, colour also correlates with galactic morphology, with late-type, spiral galaxies generally appearing bluer than early-type, elliptical galaxies.

For colour analysis in this paper, we use the rest frame Sloan filters (*ugriz*) available in the mock catalogue which take into account the effects of dust in each galaxy. Fig. 2 shows the $(M_u - M_r)$ colour distribution of galaxies in the HAs, CAs and the control sample, represented by the equivalent line styles and scaling to Fig. 1.

The control sample distribution is bimodal, with the largest and reddest peak centred near $(M_u - M_r) \simeq 2.7$ and a broader, secondary, bluer feature centred around $(M_u - M_r) \simeq 1.8$. The $(M_u - M_r)$ colour distribution of galaxies in HAs is qualitatively similar to the control sample, showing a similar bimodal structure. However, the red peak is much more dominant for the HAs than for the control, and the bluer feature is considerably weaker. In all, 79 per cent of galaxies in HAs are redder than $(M_u - M_r) = 2.25$, compared to 63 per cent for the control.

The distribution of CA galaxies in Fig. 2 stands out in comparison to the control and HA galaxies; in contrast to these two populations, virtually no galaxies in CAs are bluer than $(M_u - M_r) \sim 2.25$ and the distribution is clearly unimodal. Given that the contamination by the control sample consists of both blue and red galaxies, HAs appear to have a population of blue galaxies which are mistaken for true CG galaxies. However, in the environment of CAs (i.e. all galaxies are in very close proximity), there appears to be a dearth of blue and a dominance of red galaxies. Recent work by Baldry et al. (2006) has also found that semi-analytical models predict the fraction of red galaxies as a function of environment and mass that is qualitatively similar to observations.

3.3 Early- and late-type galaxies

Dressler (1980) was the first to show that the proportion of elliptical and lenticular galaxies increases at the expense of spiral galaxies in regions with higher projected galaxy density. Numerical simulations (Roos & Norman 1979; Farouki & Shapiro 1982; Barnes 1992) support this result by demonstrating that a merger between two spiral galaxies almost always ends in an elliptical galaxy. Therefore, environments rich in interactions and merger events (that is, high galaxy density and low velocity dispersions) are expected to be fertile regions for the formation of elliptical galaxies.

The above expectations appear to have been observationally confirmed for CGs. Studies have shown that CGs contain a significantly different morphological population of galaxies than does the field (Hickson 1982; Williams & Rood 1987; Sulentic 1987; Hickson, Kindl & Huchra 1988; Rood & Williams 1989; Prandoni, Iovino & MacGillivray 1994; Lee et al. 2004; Andernach & Coziol 2007). Hickson et al. (1988) have shown that CGs contain a higher fraction of early-type galaxies as compared to a field population and more recently, Andernach & Coziol (2007) show that CGs isolated from large-scale structures have a higher fraction of S0 galaxies as compared to the field.

We quantify the fraction of early- and late-type galaxies in our mock survey by using the ratio of bulge-to-total stellar mass (*B*/*T*) for each galaxy. Following Schade et al. (1996), we consider a galaxy to be bulge-dominated (early-type) if its bulge-to-total ratio is $B/T \gtrsim 0.6$ and disc-dominated (late-type) if $B/T \lesssim 0.4$. However, these cuts are indicative only, and we stress that the *B*/*T* ratio is not sufficient by itself to determine morphology from an observational perspective, although it is the most analogous quantity in the simulations and is still useful from a statistical perspective.

The left-hand panel of Fig. 3 shows the distribution of *B*/*T* for all the galaxies in the HAs, CAs and the control sample, where the line styles and normalization are the same as in Fig. 1. The shaded parts of Fig. 3 show the approximate regimes of late- and early-type galaxies. In the left-hand panel, there is a spike of galaxies in all three samples with $B/T \sim 1$, that is pure bulge galaxies. This is a result of the recipe for bulge formation described in Section 2.2.4, since a merger between two galaxies of approximately equal size leads to most stars being deposited in a bulge. However, in this study, we are concerned only with the total fraction of early and late-type galaxies. Regardless of whether these galaxies are really pure bulges or not, it seems clear that they will be earlier type. In addition, all three samples show the same feature, and so our relative results on how galaxy morphology varies between the control, CAs and HAs will not be affected.

The left-hand panel of Fig. 3 shows that galaxies in the HA sample possess a much higher fraction of bulge-dominated galaxies than the control sample, qualitatively consistent with the observational results. Using our definition for early-type galaxies, we find 55 per cent of galaxies in HAs are bulge dominated, compared to only 35 per cent for the control sample.

A cursory glance at the left-hand panel of Fig. 3 shows that the effect of interloping galaxies is significant when examining the relative proportions of early and late-type galaxies in CGs. In particular, the *B*/*T* distribution of HAs compared to CAs is significantly

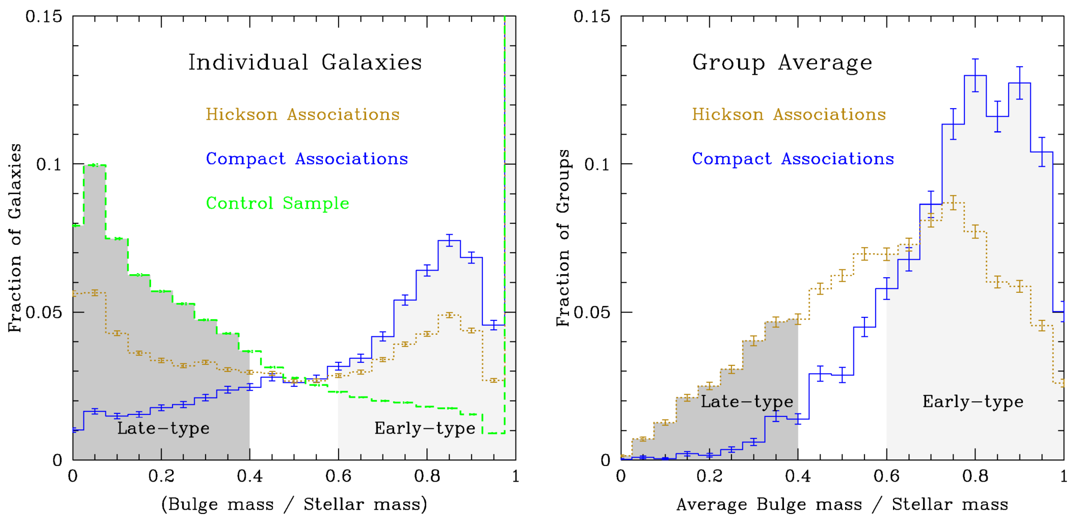

Figure 3. Left-hand panel: the distribution of bulge-to-total stellar mass (*B*/*T*) for all galaxies in HAs, CAs and our control sample, with the same line styles and scaling as Fig. 1. Right-hand panel: the average *B*/*T* for each HA and CA, scaled to have the same total number of systems. The *B*/*T* ratio can be used as a proxy for galaxy morphology, since late-type galaxies (spiral) have higher bulge fractions than early-type galaxies (elliptical). The shaded areas of the histograms show the approximate regimes of early ($B/T \gtrsim 0.6$) and late-type ($B/T \lesssim 0.4$) galaxies.

different. Whereas the distribution for HAs has roughly equal numbers of late- and early-type galaxies, the distribution of CAs peaks at $B/T \sim 0.85$ and has a tail to smaller values. Clearly, the preference for field galaxies to be late-type means that interlopers artificially increase the proportion of late-type galaxies which appear to be in CGs. In total, 74 per cent of CA galaxies (i.e. nearly three quarters of all galaxies in CAs) are bulge-dominated.

As well as examining individual galaxies, we can also determine the average morphology of the galaxies in each HA and CA to see if they are dominated by early or late-type galaxies. The right-hand panel of Fig. 3 shows the average B/T values for each HA and CA. Only 4 per cent of CAs are late-type dominated groups (with an average $B/T < 0.4$) whereas 84 per cent are dominated by early-type galaxies (with an average $B/T > 0.6$). This compares to 21 per cent of late-type dominated HAs and 54 per cent of early-type dominated HAs.

Therefore, we find a much higher fraction of early-type galaxies in CAs compared with HAs, which tentatively suggests that the fraction of early-type galaxies in observed CGs is likely to be underestimated by ∼40 per cent due to interlopers.

3.4 Cold gas fraction and SFRs

Williams & Rood (1987) obtained observations of neutral hydrogen (H I) in HCGs and estimated the mass of cool gas within each group. They found HCG galaxies to be deficient in H I by a factor of 2 on average when compared to galaxies with a similar morphology in loose groups. Haynes & Giovanelli (1986) found that, in regions of higher galaxy density, galaxies generally contain less H I compared to the field population. This result was echoed by Scodeggio & Gavazzi (1993) and later Maia et al. (1994), who found that the neutral hydrogen content of galaxies of the same morphology depended strongly on their environment. The low gaseous content of galaxies in high density environments can be attributed to the removal of gas through processes such as tidal and ram pressure stripping and/or enhanced star formation activity during interactions, processes which may play an important role in CG evolution.

The upper panel of Fig. 4 shows the distribution of the cold gas fraction of galaxies in HAs, CAs and the control sample, expressed as the ratio of cold gas mass to stellar mass. The line styles and scaling are the same as in Fig. 1. The control sample has a peak of relatively gas-rich galaxies with a significant tail of gas-poor systems. Galaxies in HAs are preferentially gas-poor relative to the control, although a significant gas-rich population is also present: 23 per cent of galaxies in HAs possess a cold gas fraction greater than 10 per cent, compared to 45 per cent of all control sample galaxies.

In contrast to both control and HA galaxies, CA galaxies are nearly exclusively gas deficient, with <4 per cent with a cold gas fraction greater than 10 per cent. Once again, interlopers appear to have the effect of increasing the apparent proportion of relatively gas-rich galaxies in CGs.

The bottom panel of Fig. 4 shows the distribution of specific SFR (SFR/stellar mass, hereafter SSFR) for all galaxies with SSFR > 10^{-14} yr^{-1}. The SSFR for HAs and the control sample are quantitatively different, with the former having a preference for lower values of the SSFR; 78 per cent of galaxies in HAs have SSFRs lower than 10^{-11} yr^{-1}, compared to 57 per cent for the control. However, there are qualitative similarities between the distributions, since both peak at 10^{-10} yr^{-1} and both have a significant number of galaxies with much lower rates.

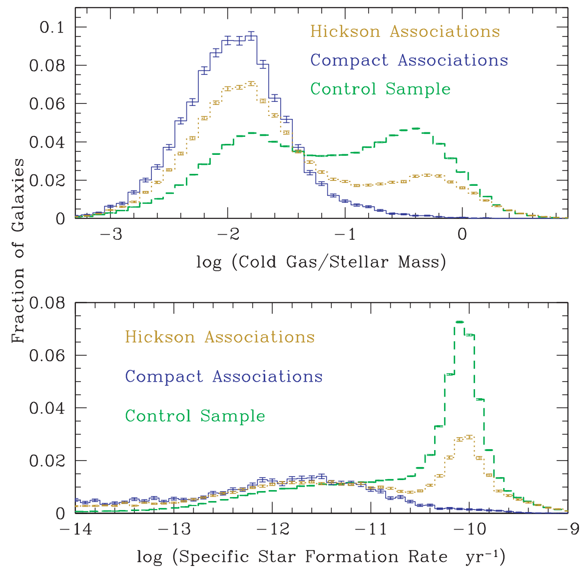

Figure 4. Top panel: distribution of cold gas fractions (cold gas mass/total stellar mass) for galaxies in HAs, CAs and the control sample, with the same line-styles and scaling the same as in Fig. 1. Bottom panel: SSFRs (SFR/stellar mass) above 10^{-14} yr^{-1} for galaxies in HAs, CAs and the control sample, with line-styles and scaling as in Fig. 1. The control sample has a peak of relatively gas-rich, star-forming galaxies (cold gas fraction $\gtrsim$10 per cent, SSFR $\gtrsim 10^{-10.5}$ yr^{-1}) and a large tail of gas poor galaxies with low specific star-forming rates. Galaxies in HAs follow a similar distribution, but with a larger proportion of gas poor, low star-forming galaxies. In contrast, CAs have effectively no gas-rich, star-forming galaxies.

CAs have very low SFRs on average, and a comparison of the distribution of SSFR for galaxies in CAs compared to that for the HAs is striking. Observations of HCGs suggest that they have SFRs which are similar to field galaxies (e.g. Iglesias-Páramo & Víchez 1999; Stevens et al. 2004). However, our results suggest that this is once again the result of interloping galaxies; CAs have effectively no galaxies with SSFRs in excess of $10^{-10.5}$ yr^{-1}.

3.5 Group velocity dispersion

One of the key observables for CGs, and one of the features which makes them potentially such interesting systems to study, is their line-of-sight velocity dispersion, $\sigma_{\rm LOS}$. This is generally measured to be relatively low ($\sigma_{\rm LOS} \sim 200\,{\rm km\,s^{-1}}$), but could be influenced by the inclusion of interloping galaxies. To see if this effect is significant, the top panel of Fig. 5 shows the distribution of line-of-sight velocity dispersions for the HAs (brown dotted line) and CAs (solid blue line), where the histograms have been scaled to have equal numbers of systems in each. This velocity dispersion has been calculated from the redshifts of each galaxy as listed in the mock catalogue, which includes both the Hubble velocity and the peculiar velocity components.

As the top panel of Fig. 5 makes clear, the HAs have a (very) significant tail to very high values of $\sigma_{\rm LOS}$ due to interloping galaxies at vastly different redshifts. Observationally, any candidate member of a CG which was measured to possess a very different redshift to the other members would be excluded from the calculation of the velocity dispersion since that is a clear indication that it is an interloper. For example, it is common practice to exclude any group which has an apparent velocity dispersion of $>1000\,{\rm km\,s^{-1}}$ (Hickson et al. 1992); in the simulation, there are virtually no

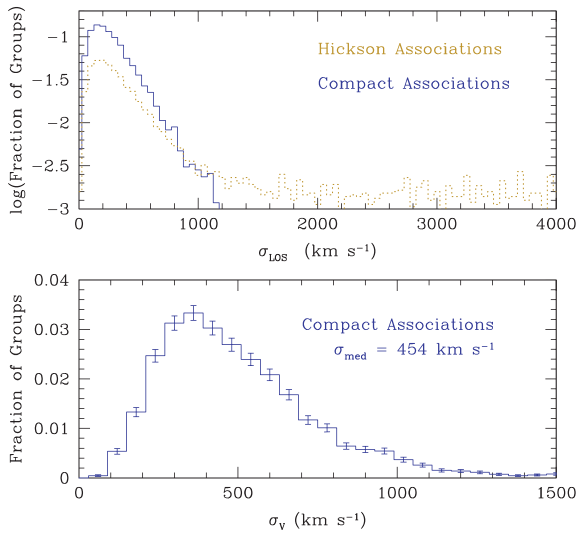

Figure 5. Top panel: the line-of-sight velocity dispersion ($\sigma_{\rm LOS}$) distribution of HAs and CAs (dotted brown and solid blue line, respectively), where the histograms have been normalized to have the same total number of groups. Bottom panel: the three dimensional velocity dispersion of CAs.

CAs with $\sigma_{\rm LOS} > 1000\,{\rm km\,s^{-1}}$, demonstrating the validity of this procedure.

The distribution of $\sigma_{\rm LOS}$ below $1000\,{\rm km\,s^{-1}}$ is very similar for both CAs and HAs, with a peak at $\sim$150–200 $\rm km\,s^{-1}$ and a mean value of $\sim 300\,{\rm km\,s^{-1}}$ for both samples. However, whereas there are $\sim$4200 CAs in total, and $\sim$6600 HAs with $\sigma_{\rm LOS} < 1000\,{\rm km\,s^{-1}}$. This implies that approximately one-third of all CGs with $\sigma_{\rm LOS} < 1000\,{\rm km\,s^{-1}}$ consist, at least in part, of interloping galaxies. These could act to contaminate any further study of CG galaxy properties.

Finally, the bottom panel of Fig. 5 shows the three dimensional velocity dispersions of all the CAs identified in the simulation. The peak de-projected velocity dispersion is at $\sigma_v \sim 350\,{\rm km\,s^{-1}}$, and the median velocity dispersion is $\sigma_{\rm med} \sim 450\,{\rm km\,s^{-1}}$. CAs therefore are generally low velocity dispersion systems, but it is interesting to note that there is a tail to very high values and that some CAs have intrinsic velocity dispersions in excess of $1000\,{\rm km\,s^{-1}}$.

4 OBSERVATIONAL COMPARISON AND DISCUSSION

In Section 3, we examined various (observable) properties of CGs found in a mock galaxy catalogue from De Lucia & Blaizot (2007) with the aim of comparing to observations of these systems. As with any such study, uncertainties in the input physics of the simulation on which the mock catalogue is based could affect our results. In this respect, our results are as robust as modern galaxy simulations allow. However, comparing a control sample to HA and CA galaxies provides a very powerful way to test the effect interlopers have on observed properties. Where possible, simulations are designed to reproduce the results of more detailed numerical simulations (for example in the case of galaxy mergers of specific mass ratios), and, importantly, recreate many of the important observational properties of low-redshift galaxy populations. In particular, it has been shown that the luminosity function, the global star formation history, the Tully–Fisher relation, the mass-metallicity relation and the colour–magnitude distribution are well matched to observations (e.g. Croton et al. 2006), and the statistics of the clustering properties of galaxies are also well reproduced (Springel et al. 2005; Li et al. 2007). Kitzbichler & White (2008) have recently used similar mock galaxy catalogues to those used here to investigate the nature and properties of close galaxy pairs and found good agreement with observations. Our results should therefore provide a useful comparison to observational samples of CG galaxies.

Fig. 6 summarizes some of our main results by displaying the $(M_u - M_r)$ versus M_r colour–magnitude distribution of galaxies in our samples. In both panels, the green density map (with square-root scaling) shows the distribution of galaxies in our field (control) sample. We re-emphasize that our control sample consists of

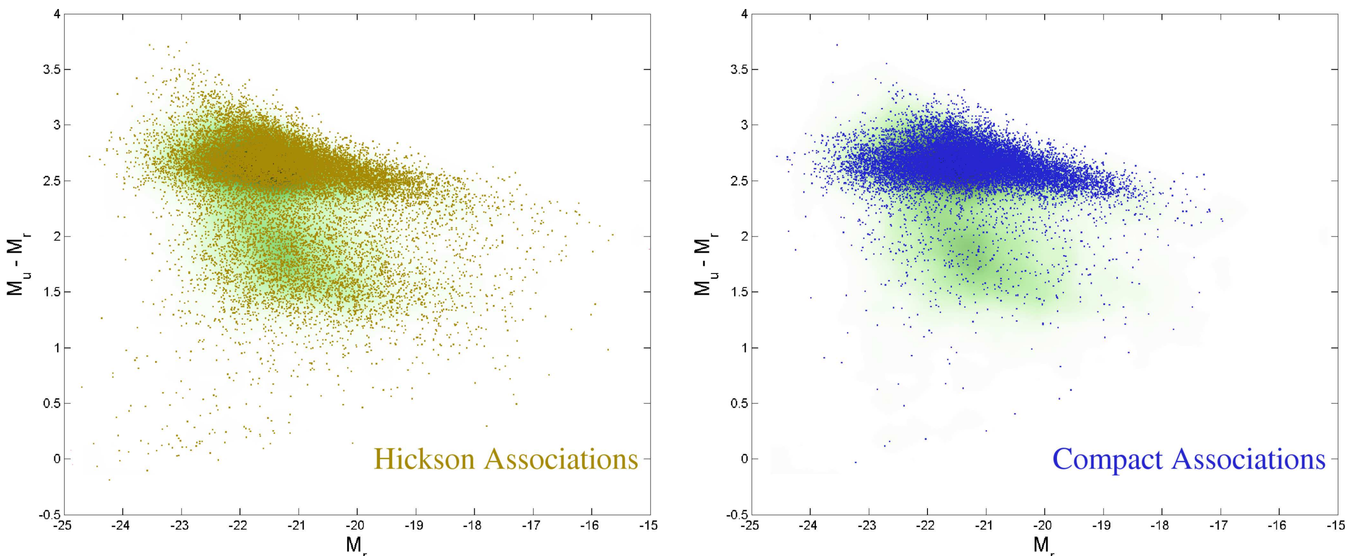

Figure 6. M_r versus $(M_u - M_r)$ colour–magnitude diagrams for the galaxies in our sample. The green density map in both panels (with square-root scaling) is the distribution of the mass-matched control sample. The brown points in the left-hand panel show the colour–magnitude distribution for a randomly selected 30 per cent of galaxies in HAs, and the blue points in the right-hand panel show the distribution for all the galaxies in CAs. The control sample shows the well-studied red sequence and blue cloud populations. HAs show a prominent red sequence and have a significant number of bluer galaxies occupying the cloud. Most striking of all, the CAs effectively lack a blue population and nearly all galaxies are found in a very strong red sequence.

galaxies matched in mass and redshift to HAs, and that these are drawn from the rest of the mock catalogue, which has been shown to reproduce many of the key properties of galaxies. In the left-hand panel, the brown points show the corresponding distribution of a random 30 per cent of galaxies identified as belonging to HAs, and in the right-hand panel the blue points show the distribution for all galaxies in CAs. We now discuss this figure in more detail in conjunction with the results presented in Section 3.

4.1 The effect of interlopers

4.1.1 The colour–magnitude diagram

It is well known observationally that galaxies have a bimodal colour magnitude distribution (Strateva et al. 2001; Baldry et al. 2004). In Fig. 6, the control population shows this distribution, with a relatively tight 'red sequence' [centred around $(M_u - M_r) \sim 2.7$] and a more diffuse 'blue cloud' [with $(M_u - M_r) \lesssim 2.3$] (Faber et al. 2007). The latter is populated predominantly by star-forming galaxies whereas the former consists of galaxies with low SFRs and older stellar populations in general (Strateva et al. 2001; Blanton et al. 2003; Bell et al 2004; Willmer et al. 2006).

The left-hand panel of Fig. 6 shows that the galaxies in HAs (that is, those simulated galaxies identified on application of the Hickson criteria) exhibit both a red sequence population and a blue cloud population. In contrast, galaxies in CAs (that is, those HAs which are physically dense and contain no interlopers) are confined nearly exclusively to the red sequence, with few galaxies occupying the blue cloud [97 per cent of CA galaxies are redder than $(M_u - M_r) = 2.25$]. The effect of interlopers in CGs therefore appears to introduce a population of blue, star-forming galaxies.

This conclusion is reinforced by our previous examination of colour (Section 3.3), cold gas fraction and SFR (Section 3.4) in these galaxies. We find galaxies in HAs are preferentially redder, have lower gas fractions and lower SSFRs than the control sample, but in all cases bluer, higher gas fraction, higher SSFR galaxies are present in significant numbers. Galaxies in CAs, however, are strikingly different in all three observables. For example, 21 per cent of galaxies in HAs are bluer than $(M_u - M_r) = 2.25$, 23 per cent of galaxies in HAs have cold gas fraction in excess of 10 and 22 per cent of galaxies in HAs have SSFRs higher than 10^{-11} yr^{-1}. In contrast, virtually no galaxies in CAs satisfy any of these three criteria. In addition, ~55 per cent of galaxies in HAs appear to be bulge dominated, whereas the fraction of bulge-dominated galaxies in CAs is significantly higher than this, at ~74 per cent.

Fig. 7 shows the distribution of the properties we have been discussing for all galaxies in HAs which are *not* CAs compared to the control sample. The galaxies in these $\ell > 200\,h^{-1}$ kpc HAs are clearly not randomly drawn from the field, since their distributions differ from the control sample in all panels of Fig. 7. As we show in Paper I, these HAs consist of some loose groups and sets of completely unassociated galaxies, as well as many galaxy pairs, triplets, and even some quadruplets, with unassociated background

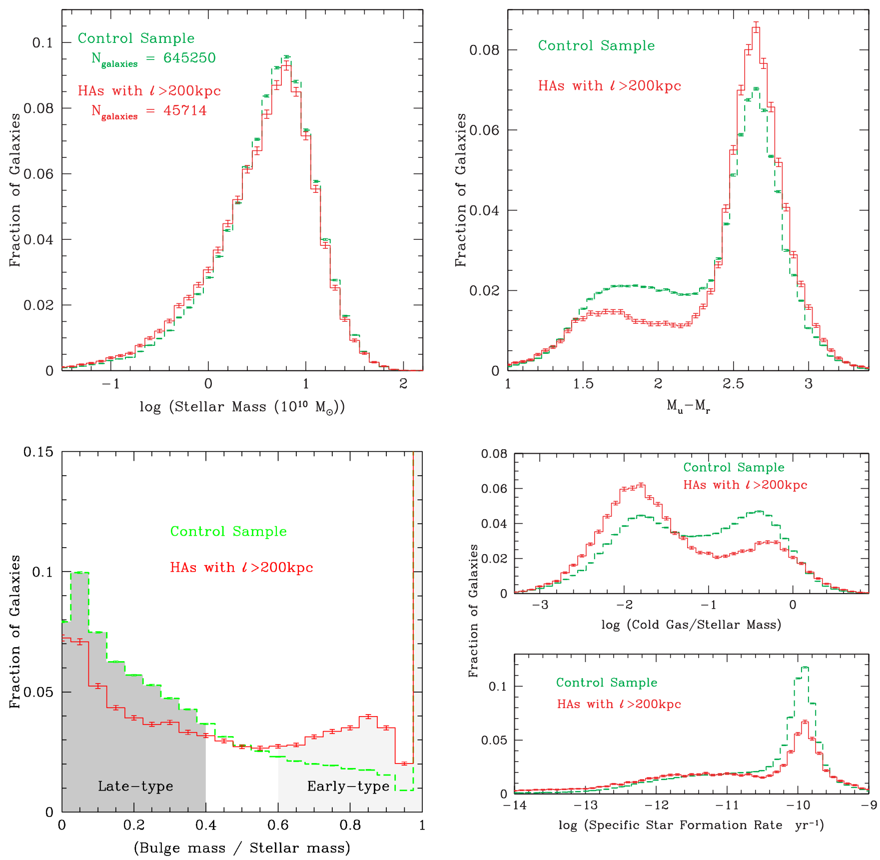

Figure 7. Distribution of various properties for the galaxies in the control sample (green dashed line) and for galaxies in the HAs which are *not* CAs (i.e. galaxies in HAs with $\ell > 200\,h^{-1}$ kpc and which have been classed as interlopers). The interlopers are clearly not randomly drawn from the field population but, like the control sample, there are a significant number of galaxies which are blue, star-forming, gas-rich, late-type systems which act to bias our understanding of CGs.

and/or foreground galaxies projected along the same line of sight. It is this population of interloping galaxies from the field which appears to bias our understanding of the evolution of galaxies in CGs.

4.1.2 Observational selection of CGs

We note that no cuts by velocity dispersion were applied when we identified HAs. In practice, a velocity dispersion cut can only be applied when a relatively small number of CGs are being studied, since getting redshift information for every galaxy in every group of a much larger sample is impractical. For example, in the SDSS, galaxies are quasi-randomly targeted for spectroscopy and the probability that all galaxies in a CG are selected for spectroscopy is very small, especially since fibre collisions will occur if trying to target all the members of a dense system. In the few situations where full redshift information is available, groups with very large velocity dispersions ($\sigma_{\rm LOS} \gtrsim 1000\,{\rm km\,s^{-1}}$) are usually discarded (e.g. Hickson et al. 1992) since it is likely they contain interlopers. Our analysis in Section 3.5 suggests that such an approach can greatly reduce contamination; however, over one-third of the systems identified are predicted to still contain interlopers and are therefore not genuine CGs. This population will still potentially act to bias any study of CG properties.

As discussed in Section 4.1.1, 97 per cent of galaxies in CAs are redder than $(M_u - M_r) = 2.25$. Our analysis of the mock catalogue therefore suggests that the purity of a CG sample can be significantly increased by only selecting those groups whose members are redder than $(M_u - M_r) \simeq 2.25$, since this will preferentially remove HAs which have $\ell > 200\,h^{-1}$ kpc. Of course, selecting CGs by colour may lead to a potential bias, since we select against any genuine CGs which happen to have bluer galaxies. However, for studies of CGs where the property of interest is not thought to depend strongly on colour, then this selection technique potentially offers the opportunity to greatly reduce contamination. Projects such as the Red Cluster Survey (Gladders & Yee 2005) adopt a similar methodology for the identification of galaxy clusters.

4.2 Observational comparisons

There is an extensive body of literature on the observational properties of galaxies in CGs and, in general, we find good correspondence between the properties of galaxies identified in HAs in the mock catalogue and those in reality. Observationally, CGs contain a greater proportion of early-type galaxies than the field; Hickson et al. (1988) and Palumbo et al. (1995) found that roughly half of all galaxies in CGs were early-type, compared to ~20 per cent for the field (Nilson 1973; Gisler 1980). We find that ~55 per cent of all galaxies in HAs in the mock catalogue (i.e. those galaxies identified as belonging to CGs through application of the Hickson criteria) have $B/T \geq 0.6$, and are probably best described as early-type. As discussed in the previous section, however, the true fraction of early-type galaxies in CGs is predicted to be nearer three quarters, since interlopers from the field (which are more likely to be late-type) can increase the apparent proportion of late-type galaxies in CGs.

Lee et al. (2004) and Deng et al. (2007) both find that galaxies in CGs are redder than the field population on average. Our results suggest the same; 79 per cent of galaxies in HAs are redder than $(M_u - M_r) = 2.25$, compared to only 63 per cent for the field. Lee et al. (2004) measure median colours for their CG galaxies of $(M_{r*} - M_{i*})_{\rm med} = 0.39$ and $(M_{u*} - M_{g*})_{\rm med} = 1.66$. Our values for

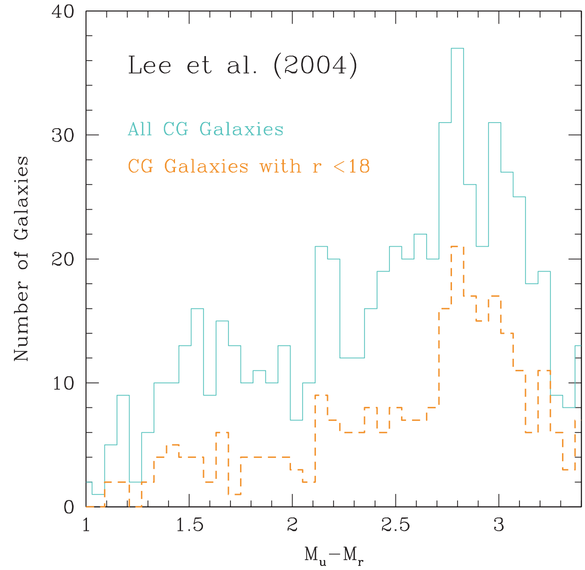

Figure 8. The observed $(M_u - M_r)$ colour distribution for CG galaxies identified by Lee et al. (2004) corrected for foreground extinction. CGs in the Lee et al. (2004) catalogue were identified using a galaxy catalogue with a magnitude limit of $r = 21$, three magnitudes deeper than our mock galaxy catalogue. The blue histogram shows all 744 galaxies in the observed CGs, whereas the orange histogram shows only those galaxies brighter than $r = 18$, the magnitude limit of our mock catalogue (although note that this subset of observed galaxies is different to those galaxies which would be identified had the original catalogue been magnitude limited at $r = 18$).

the galaxies in HAs compare very favourably to this, with $(M_r - M_i)_{\rm med} = 0.39$ and $(M_u - M_g)_{\rm med} = 1.66$. For the field samples, Lee et al. (2004) calculate $(M_{r*} - M_{i*})_{\rm med} = 0.38$ and $(M_{u*} - M_{g*})_{\rm med} = 1.58$, whereas we find $(M_{r*} - M_{i*})_{\rm med} = 0.38$ and $(M_{u*} - M_{g*})_{\rm med} = 1.61$.

Fig. 8 shows the observed (de-reddened) $(M_u - M_r)$ colour distribution for the Lee et al. (2004) CGs. The Lee et al. (2004) catalogue identifies CGs using a galaxy catalogue with a magnitude limit of $r = 21$, 3 mag deeper than our mock galaxy catalogue. The blue histogram therefore shows all 744 galaxies in the observed CGs, whereas the orange histogram shows only those galaxies brighter than $r = 18$, the magnitude limit of our mock catalogue (although note that this subset of observed galaxies is different form those galaxies which would be identified had the original catalogue had a magnitude limit of $r = 18$).

There are several qualitative and quantitative similarities between the observed colour distributions in Fig. 8 and the predicted ones in Fig. 2. In particular, there is a red peak with a blue tail in the data, with the peak at $(M_u - M_r) \sim 2.7$, similar to Fig. 2. 68 per cent of CG galaxies with $r \leq 21.0$ are redder than $(M_u - M_r) = 2.25$ (75 per cent of CG galaxies with $r \leq 18.0$). This compares favourably to the 79 per cent in the same colour range from the simulation, although it may suggest that the simulated galaxies are slightly too red compared to observations. However, the reddest galaxies are seen in the observations; whereas there are very few simulated CG galaxies with $(M_u - M_r) > 3$, 30 per cent of the galaxies in Fig. 8 are redder than this limit.

Williams & Rood (1987) found that galaxies in CGs appear deficient in H I by a factor of approximately 2 in comparison to the field. While it is not possible to calculate the fraction of H I in the galaxies in the simulation, it is possible to determine the fraction of 'cold gas' in galaxies in HAs and CAs relative to the field. We have made the assumption that the cold gas fraction traces the H I gas fraction and the fraction of other atomic or molecular gases should be negligible. Once again, we find that galaxies in HAs have, in general, a considerably lower cold gas fraction than the control sample (77 per cent of galaxies in HAs have a cold gas fraction less than 10 per cent, compared to 55 per cent for the control). The mean cold gas fraction of the control sample galaxies is ∼6–7 per cent, whereas the mean cold gas fraction for galaxies in HAs is approximately a factor of 2 smaller, at ∼3 per cent. This is in good relative agreement with observations, although we note that our control sample is not made up of galaxies exclusively in loose groups, as was the case for the observational study.

The main disagreement between our study and observational work is the comparison of SSFRs. Observational studies suggest that the SFRs of galaxies in CGs are broadly similar to the general field population (Iglesias-Páramo & Víchez 1999). Inspection of the lower panel of Fig. 4 shows that the SSFRs of field galaxies and HAs are quantitatively different, but they do share some similarities. In particular, they both have peaks at $\sim 10^{10}\,\mathrm{yr}^{-1}$ and tails to much lower values. It is possible that the observations do not yet have sufficient statistics to show the differences in the distributions, although it is equally possible that the differences do not exist. It is once again important to emphasize, however, that any similarities between the SFRs of HAs and the control sample disappear when one considers only those groups which are physically dense and which contain no interlopers.

These trends are also seen for galaxies in cluster environments: Giovanelli & Haynes (1983) found spiral galaxies in the Virgo cluster were deficient in H I relative to their counterparts in the field. Lower SFRs for galaxies in clusters compared with those in the field at the same redshift have also been found up to $z \sim 1$ (Kennicutt 1983; Balogh et al. 1997; Hashimoto et al. 1998; Poggianti et al. 1999; Postman, Lubin & Oke 2001; Gómez et al. 2003). Butcher & Oemler (1984) found that compact clusters at low redshift had cores which were essentially devoid of blue galaxies and a clear correlation between galaxy morphology with local density (Dressler 1980; Dressler et al. 1997) and cluster-centric radius (Whitmore, Gilmore & Jones 1993) has been observed.

It is reassuring to find that the observational properties of CGs are broadly reflected in the properties of the galaxies identified in the mock catalogue; these galaxies are generally more likely to be bulge-dominated systems than the field, are redder, have lower cold gas fractions, and exhibit relatively similar SFRs to the field population. In colour–magnitude space, galaxies identified as belonging to CGs (HAs) occupy a dominant red sequence but there are considerable numbers which occupy the blue cloud. On the removal of interlopers, nearly all galaxies in CGs occupy the red sequence (Fig. 6).

4.3 On the homogeneity of CAs

Our results agree well with the observations of CGs, but in addition strongly suggest that some of these results have been influenced by interloping galaxies which did not co-evolve with the other galaxies in the CG. When this is taken into account, the simulations suggest that the fraction of galaxies in CGs which are bulge-dominated, red, have low cold gas fractions and low SFR have been previously underestimated. The low SFRs that we imply are consistent with evolution in an environment where interactions were common, where either most of the gas was initially removed from these galaxies via stripping processes and/or the gas was used up in brief, intense periods of star formation shortly after the galaxy entered the CG environment.

What is very noticeable from our results, and is nicely summarized in the right-hand panel of Fig. 6, is the homogeneity of the galaxies in CAs; virtually all belong to the red sequence and are 'red and dead'. We first discuss if the origin of this result is due to a simplified treatment of gas removal in the semi-analytical modelling of satellites in these simulations (Section 4.3.1). On concluding that this is not the likely interpretation, we turn our attention to possible evolutionary scenarios for CGs (Section 4.3.2).

4.3.1 Central and satellite galaxy evolution

There are certain evolutionary processes which are believed to operate predominantly on satellite galaxies, and which do not affect central galaxies (that is, those at the centres of their own dark matter halo) to the same degree. In particular, when a smaller dark matter halo is accreted by, and becomes a satellite of, a larger dark matter halo, its hot, diffuse gas may be stripped. This gas can no longer feed the satellite galaxy, and so once the cold gas in the galaxy's disc is used up, its star-formation ends (termed 'strangulation'; Larson, Tinsley & Caldwell 1980; Balogh & Morris 2000). In circumstances where the external pressure is sufficiently high, ram pressure stripping may remove the cold gas directly, abruptly ending star formation (Gunn & Gott 1972).

In most semi-analytic models, the loss of a satellite's hot gas is modelled as an instantaneous process. However, it has been suggested that this is not a good approximation in all cases (e.g. Dekel & Birnboim 2006; McCarthy et al. 2008) and it has been shown that satellites simulated in this way are frequently too 'red and dead' in comparison to observational results (Baldry et al. 2006; Weinmann et al. 2006; Gilbank & Balogh 2008; Kang & van den Bosch 2008). In Paper I, we showed that just over half of CAs in our mock catalogue share a common dark matter halo, where one galaxy is considered to be the 'central' galaxy and the remaining ones are considered 'satellites' (although CAs consisting of four separate haloes, and thus four 'central' galaxies, do exist). Given the significant number of 'satellite' galaxies in our sample, it is important to determine if uncertainties in the treatment of strangulation for these objects have lead us to conclude, incorrectly, that CAs are predominantly red and dead.

Fig. 9 shows the colour (top left), cold gas fraction (top right), *B*/*T* (lower left) and SSFR (lower right) for all the galaxies which we identify as being a member of a CA in our mock catalogue, split according to whether they are a 'satellite' (orange solid lines) or a 'central' galaxy (blue dashed). Central galaxies of CAs are marginally bluer than satellites and have a slightly higher cold gas fraction. The central galaxy SSFR is significantly higher than for the satellites, reflecting the fact that strangulation has quenched star formation in satellites. The morphology of central galaxies in CAs, as represented by *B*/*T* (see Section 3.3), is a mix of early- and late-type but with a dominant peak around $B/T = 1$, which indicates that a major merger has occurred (recall Section 2.2.4). There is a similar peak for satellite galaxies, which show a preference towards having a higher bulge fraction than central galaxies.

From Fig. 9, we conclude that 'central' galaxies in CAs show some differences to 'satellite' galaxies in CAs, particularly regarding the SSFR. However, it is still the case that, for both central and satellite galaxies in CAs, they are much redder, have a considerably smaller cold gas fraction, are generally earlier type (as traced by

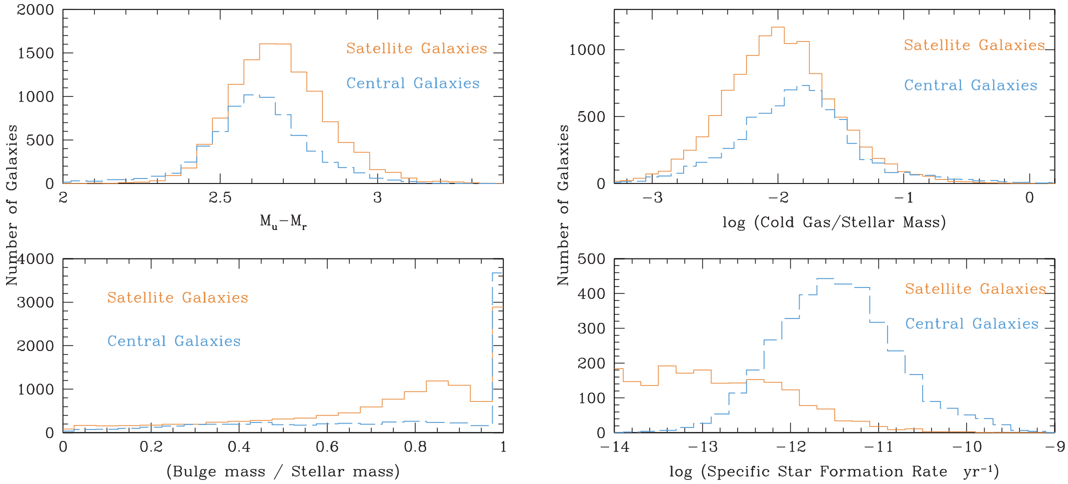

Figure 9. Shown above are the distributions for colour (upper left), cold gas fraction (upper right), *B*/*T* (lower left) and SSFR (lower right) for all galaxies in CAs divided into two subsets; 'satellite' galaxies (orange solid) and 'central' galaxies (dashed blue) (11634 and 7177 galaxies in each subset, respectively).

bulge fraction) and have significantly lower SSFR than the field galaxies in our sample (recall Figs 2, 3 and 4). Thus, our overall conclusion about CAs being 'red and dead' galaxies, significantly redder than the field population, stands even if we only consider 'central' galaxies. A simplified treatment of satellite strangulation cannot account for this result.

In the semi-analytic models, central galaxies are typically red if they are massive (where active galactic nucleus (AGN) feedback can offset a slowly cooling halo) whereas satellite galaxies tend to be red, independent of their stellar mass (Weinmann et al. 2006). To ensure that the high red fraction of CAs is not driven by a large (red) satellite population and massive (red) central galaxies, we examined the colour distribution of central CA galaxies as a function of stellar mass. At the low mass end, central galaxies in CAs still dominate the red sequence whereas galaxies in the control sample are still mostly in the blue cloud.

Finally, we note that central galaxies in the HAs, CAs and the control sample (matched in mass and redshift to the HAs) are all subject to the same uncertainties in the semi-analytic modelling (e.g. quenching, AGN feedback). Thus, the *relative* distribution of galaxy properties in each of these three subsets provide a more robust comparison than is possible using absolute values.

4.3.2 The evolution of CAs

Our current comparison between CGs identified in a mock catalogue to previous observations of CGs suggests that the former reproduce the latter well, given the current theoretical and observational limitations. However, the fact that the simulated CAs do not resemble typical field galaxies, and in fact show only a small spread in properties, leads us to consider possible evolutionary explanations which could produce this homogeneous population: (i) most CGs did not form out of the typical field galaxy population, and instead formed out of a population of 'red and dead', early-type galaxies; (ii) most CGs formed long ago, perhaps out of the typical field galaxy population, and the member galaxies evolved over cosmological time-scales to become a population of 'red and dead' ellipticals and (iii) CGs form continuously, perhaps out of the typical field galaxy population, and the evolutionary times of galaxies in CGs are very short so they quickly become a population of 'red and dead' ellipticals.

The origin for the different properties of CA galaxies compared to the field in these models must be rooted in their mass assembly and gas accretion histories. In a future contribution, we will explore the dynamical evolution of the simulated CGs in the semi-analytic simulations by tracing the progenitors of the galaxies and haloes identified as belonging to a CA in our $z = 0$ mock catalogue using the outputs of the simulation from previous time-steps. This enables us to reconstruct the formation history of the groups and compare their lifetimes to the evolutionary time-scales of galaxies, particularly those relating to movement on to the red sequence of the colour magnitude diagram.

5 SUMMARY

In this paper, we have compared the observed morphological properties of galaxies in CGs with those identified in a mock galaxy catalogue, to determine if and where our observational understanding of the evolution of these systems is in conflict with modern theoretical simulations of galaxy evolution. We find that the properties of galaxies identified as belonging to CGs in the simulation are in qualitative agreement with observations. Bluer galaxies, late-type galaxies, gas-rich galaxies and galaxies with higher SSFRs are all present in CGs. However, on average, CGs exhibit a higher proportion of early-type galaxies than the field, and are generally redder and gas deficient compared to the field. The SSFRs of CG galaxies are, on the other hand, relatively similar to the field.

Importantly, we find that the effect of interlopers on these results is significant. By using the full three dimensional positions of the galaxies in the mock catalogue, we can remove those groups which are not physically dense and/or which contain interlopers. The CGs which remain are found to consist nearly exclusively of red ($M_u - M_r$) $\gtrsim 2.5$, gas-deficient ($M_{\rm cold\,gas} < 0.1\ M_*$) galaxies with low SSFRs (SSFR $< 10^{-10.5}$ yr^{-1}).

We predict that approximately 84 per cent of CGs are dominated by early-type galaxies when interlopers are accounted for, compared to ∼54 per cent when they are not. Thus, modern cosmological simulations suggest that galaxies in CGs have homogeneous properties and are predominately 'red and dead'. In contrast, observations suggest that CGs exhibit a larger range in galaxy properties. Our results imply that the majority (but not all) of galaxies identified as being members of CGs which are late-type, blue, relatively gas rich and/or have relatively high SFRs are interlopers. Selection by colour is predicted to greatly reduce contamination levels of CGs, although this will introduce a potential bias into the population. Where redshift information is available for all prospective group members, observational contamination can be reduced; however, one-third of all CGs with low velocity dispersions ($\sigma_{\rm LOS} < 1000\,{\rm km\,s^{-1}}$) appear to contain interlopers.

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