A re-examination of galactic conformity and a comparison with semi-analytic models of galaxy formation

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ABSTRACT

The observed correlation between star formation in central galaxies and in their neighbours (a phenomenon dubbed ‘galactic conformity’) is in need of a convincing physical explanation. To gain further insight, we use a volume-limited sample of galaxies with redshifts less than 0.03 drawn from the Sloan Digital Sky Survey Data Release 7 to investigate the scale dependence of the effect and how it changes as a function of the mass of the central galaxy. Conformity extends over a central galaxy stellar mass range spanning two orders of magnitude. The scale dependence and the precise nature of the effect depend on the mass of the central. In central galaxies with masses less than $10^{10}$ $M_\odot$, conformity extends out to scales in excess of 4 Mpc, well beyond the virial radii of their dark matter haloes. For low-mass central galaxies, conformity with neighbours on very large scales is only seen when they have low star formation rate or gas content. In contrast, at high stellar masses, conformity with neighbours applies in the gas-rich regime and is clearly confined to scales comparable to the virial radius of the dark matter halo of the central galaxy. Our analysis of a mock catalogue from the Guo et al. semi-analytic models shows that conformity-like effects arise because gas-poor satellite galaxies are sometimes misclassified as centrals. However, the effects in the models are much weaker than observed. Misclassification only influences the low-end tail of the SFR/$M_*$ distribution of neighbouring galaxies at large distances from the primary. The median and the upper percentiles of the SFR/$M_*$ distribution remain almost unchanged, which is in contradiction with the data. We speculate that the conformity between low-mass, gas-poor central galaxies and their distant neighbours may be a signature of ‘pre-heating’ of the intergalactic gas at an earlier epoch. The smaller scale conformity between high-mass, gas-rich central galaxies and their close neighbours may be a signature of ongoing gas accretion on to central galaxies in a minority of massive dark matter haloes.

Key words: galaxies: evolution – galaxies: haloes – galaxies: statistics.

1 INTRODUCTION

In a system of orbiting galaxies, the largest and most massive galaxy is often referred to as the ‘primary’, and the others are called satellites. The relationship between satellite galaxies and their primaries is one of the key tests of hierarchical galaxy formation models. In such models, galaxies form as gas cools and condenses at the centres of dark matter haloes. As time progresses, dark matter haloes merge and this leads to the formation of systems of galaxies orbiting within a common potential well. With the advent of large, wide-field imaging and spectroscopic surveys, there have been numerous studies of the properties satellite galaxies (e.g. McKay et al. 2002; Prada et al. 2003; Sales & Lambas 2004; Berlind et al. 2005; Yang et al. 2005; Weinmann et al. 2006; Norberg, Frenk & Cole 2008; Yang, Mo & van den Bosch 2008; More et al. 2009). The behaviour of the average line-of-sight velocity dispersion of satellites as a function of distance from the primary galaxy, as well as the number density distribution of satellites as a function of projected radius, probes the density distribution of the dark matter in galactic haloes. In general, the velocity dispersion distributions and density profiles of satellites galaxies are in reasonably good agreement with the predictions of the $\Lambda$ cold dark model ($\Lambda$CDM) model (Prada et al. 2003; Guo et al. 2011). In recent work, Wang

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& White (2012) and Sales et al. (2013) have shown that the luminosity and stellar mass functions of satellite galaxies predicted by semi-analytic models of galaxy formation embedded within high-resolution cosmological N-body simulations agree well with results derived from the Sloan Digital Sky Survey (SDSS). Our understanding of the observed colours, star formation rates and gas content of satellites is still not complete. These properties are extremely sensitive to the physical processes that regulate how gas is supplied to these systems. In addition, both hydrodynamical and gravitational forces act to remove gas from satellites. Galaxy formation models developed in the 1990s (e.g. Kauffmann, White & Guiderdoni 1993; Cole et al. 1994) generally assumed that the diffuse gas haloes surrounding galaxies were stripped instantaneously as soon as they became satellites. There is then no further supply of new gas to satellites, and they redden with respect to the primary galaxy as their internal reservoir of cold gas is consumed. Subsequent work found that these models predicted satellites that were too red to be consistent with observations (Baldry et al. 2006; Weinmann et al. 2006). Current models attempt to model tidal and ram-pressure stripping of the diffuse gas in a more realistic way (Font et al. 2008; Weinmann et al. 2010; Guo et al. 2011) and they produce satellite colour distributions in better agreement with the data.

We note that gas removal processes such as tidal interactions and ram-pressure stripping operate predominantly on smaller satellite galaxies, leaving the interstellar medium of the primary galaxy unperturbed. Only in the case of a very close encounter, would star formation in the primary galaxy respond to the presence of a satellite. The discovery that the properties of satellite galaxies are strongly correlated with those of their central galaxy, a phenomenon that has been called ‘galactic conformity’ (Weinmann et al. 2006), thus remains something of an enigma.

Yang, Mo & van den Bosch (2006) suggest that a halo that assembled a significant fraction of its mass at an early epoch, may have accreted all its satellites at higher redshifts than a similar halo that assembled late. They proposed that galactic conformity may thus be a straightforward manifestation of hierarchical structure formation and thus ought to be detectable in galaxy catalogues generated from N-body simulations + semi-analytic models. Wang & White (2012) analysed mock galaxy catalogues generated from the semi-analytic models of Guo et al. (2011). These authors find a conformity effect in the models and show that it arises because red central galaxies inhabit more massive dark matter haloes than blue galaxies of the same stellar mass.

Other authors have argued that more exotic hydrodynamical effects may be at play. Ann, Park & Choi (2008) argue that feedback processes that operated as the central galaxy formed affected the ability of surrounding galaxies to form stars. Kauffmann, Li & Heckman (2010) suggest that conformity is related to gas accretion. They propose that gas-rich satellites trace an underlying reservoir of ionized gas that is extended over large spatial scales, and that this reservoir fuels star formation in both the satellites and in the primary.

In an attempt to determine which viewpoint is correct, we have undertaken a re-analysis of galactic conformity using both SDSS data and the publicly available galaxy catalogues of Guo et al. (2011). We have made the following changes to the analysis procedures that were employed in previous papers.

(i) We restrict the analysis to a volume-limited sample of galaxies from the spectroscopic catalogue with log $M_*$ > 9.25 and with redshifts in the range $0.017 < z < 0.03$. Previous analyses of satellites have made use of much fainter galaxies identified in the SDSS imaging data without spectroscopic redshifts. It has thus been necessary to account for contamination from galaxies physically unrelated to the primary by means of statistical background subtraction. Our restriction to a sample of very nearby galaxies with spectroscopic redshifts decreases the number of primary galaxies we are able to analyse by large factor, but it produces a much purer set of satellites. The quantitative comparison with semi-analytic models is also greatly simplified.

(ii) Because we are not limited by background subtraction errors, we are able to analyse conformity effects out to projected radii of 4–5 Mpc. The analysis of Kauffmann et al. (2010) showed that correlations between satellite and central properties were still clearly present at projected separations of ~1 Mpc. The analysis of Wang & White (2012) was restricted to satellites within a projected distance of 300 kpc from the primary galaxy, so did not address the question of whether conformity persists out to large physical scales. In addition, we are now able to analyse the full distribution function of specific star formation rates in the population of neighbouring galaxies. It is very difficult to do this accurately using photometric data.

(iii) We define ‘central’ galaxies using an isolation criterion, rather than by selecting the most massive galaxy in groups and clusters, such as was done in the analysis of Weinmann et al. (2006). These authors used the group catalogue of Yang et al. (2007) to select their sample of central objects. We note that the Yang et al. methodology for identifying groups was optimized using simulations to select dark matter haloes with virial masses greater than $3 \times 10^{12} M_\odot$. We have specifically selected galaxies at low redshifts ($0.01 < z < 0.03$) to study conformity effects around low-mass galaxies that occupy dark matter haloes with masses lower than this value.

We note that the definition of a central galaxy using near neighbour positions, velocities and masses is a not a rigorous one. A fully correct identification of a central galaxy can only be made if the underlying dark matter potential can be mapped via gravitational lensing or X-ray emission from hot gas. In our study, we interpret our results quantitatively by implementing the same definition of central galaxy on mock catalogues from simulations.

(iv) Previous work has focused only on average colours, star formation rates and inferred gas fractions of satellite galaxies. In this analysis, we look at how relations between star formation rate, stellar mass and structural parameters change for galaxies located in the vicinity of red and blue primaries.

In agreement with previous results, we find conformity between the properties of central galaxies and their neighbours over a central galaxy stellar mass range spanning two orders of magnitude. However, our new analysis shows that the scale dependence of the effect depends on the mass of the central. Conformity effects extend to scales in excess of 4 Mpc around low-mass central galaxies and the strongest effects are seen at large separations (~1 Mpc) from the primary. In contrast, for high-mass central galaxies, conformity is clearly confined to scales less than 1–2 Mpc (i.e. within the scale of the dark matter halo). Conformity is only seen for low-mass central galaxies when they have lower-than-average star formation rate or gas content. Conformity applies when high-mass central galaxies are gas rich and strongly star forming. The observational results are not well reproduced by the current Guo et al. (2011) semi-analytic models.

Our paper is organized as follows. In Section 2, we describe the data used in this analysis. In Section 3, we present results from the
SDSS Data Release 7 (DR7) spectroscopic sample. These results are compared with the Guo et al. models in Section 4. In Sections 5 and 6, we summarize and discuss possible implications of our findings. Throughout this paper, we assume a spatially flat concordance cosmology with \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7 \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2 ANALYSIS TOOLS

2.1 Data

We begin with the parent galaxy sample constructed from the New York University Value Added Catalogue (NYU-VAGC) sample dr72 (Blanton et al. 2005), which consists of about half a million galaxies with \( r < 17.6, -24 < M_r < -16 \) and redshifts in the range \( 0.01 < z < 0.5 \). Here, \( r \) is the \( r \)-band Petrosian apparent magnitude, corrected for Galactic extinction, and \( M_r \) is the \( r \)-band Petrosian absolute magnitude, corrected for evolution and K-corrected to its value at \( z = 0.1 \).

From the parent sample, we select a volume-limited sample of galaxies with \( \log M_*= 9.25 \) and redshifts in the range \( 0.017 < z < 0.03 \). The lower limit in redshift ensures that we do not consider galaxies where the peculiar velocity would affect the conversion from redshift into distance by a significant factor. The upper limit in redshift ensures that we are able to detect all galaxies down to a limiting stellar mass of \( 2 \times 10^9 \text{ M}_\odot \), irrespective of the intrinsic colour of the system. These cuts result in a sample of 11 673 galaxies.

We define a galaxy with mass \( M_* \) to be a central galaxy if there is no other galaxy with stellar mass greater than \( M_* / 2 \) within a projected radius of 500 kpc and with velocity difference less than 500 km s\(^{-1}\). There are 7712 galaxies in our catalogue with stellar masses greater than \( 5 \times 10^9 \text{ M}_\odot \) to which we can apply this criterion; 4636 (i.e. 60 per cent) are classified as central galaxies. As we will show, this is in reasonably good agreement with the predictions of the semi-analytic models of Guo et al. (2011).

In this paper, we will make use of two different measures of gas content/star formation activity.

(i) The pseudo-H\(^\text{i}\) gas mass fraction estimates of Li et al. (2012) utilize a combination of four galaxy parameters:

\[
\log(M_{\text{H1}}/M_*) = -0.325 \log M_* - 0.237(NUV-r) - 0.354 \log M_* - 0.513 \Delta_{g-i} + 6.504,
\]

where \( M_* \) is the stellar mass, \( \mu_\text{g} \) is the surface stellar mass density given by \( \log \mu_\text{g} = \log M_* - \log (2\pi R_\text{eff}^2) \) (\( R_\text{eff} \) is the radius enclosing half the total z-band Petrosian flux and is in units of kpc). \( NUV-r \) is the global near-ultraviolet (NUV) to \( r \)-band colour. The NUV magnitude is provided by the Galaxy Evolution Explorer (GALEX) pipeline and the \( NUV-r \) colour is corrected for Galactic extinction following Wyder et al. (2007) with \( A_{\text{NUV}-r} = 1.9807A_r \), where \( A_r \) is the extinction in the \( r \) band derived from the dust maps of Schlegel, Finkbeiner & Davis (1998). \( \Delta_{g-i} \) is the colour gradient defined as the difference in \( g-i \) colour between the outer and inner regions of the galaxy. The inner region is defined to be the region within \( R_{\text{G}} \) and the outer region is the region between \( R_{\text{G}} \) and \( R_{\text{O}} \). As discussed in Li et al. (2012), the estimator has been calibrated using samples of nearby galaxies (0.025 < \( z \) < 0.05) with H\(^\text{i}\) line detections from the GALEX Arcibo SDSS Survey (Catiniella et al. 2010).

(ii) The specific star formation rate (SFR/\( M_* \)) evaluated within the SDSS fibre aperture is estimated using the methodology described in Brinchmann et al. (2004). These estimates are publicly available for all galaxies in the DR7 galaxy sample at http://www.mpa-garching.mpg.de/SDSS/DR7/.

We note that the main difference between the two measures is that the first is mainly sensitive to the age of stars in the outer regions of the galaxy, while the second is sensitive to the amount of ongoing star formation in the core of the galaxy. (At the median redshift of the galaxies in our sample, the 3 arcsec diameter SDSS fibre subtends a physical scale of only 1.37 kpc.)

2.2 Models

In this paper we compare our observational results to predictions from the galaxy formation models of Guo et al. (2011, hereafter G11). This model was created by implementing prescriptions for baryonic astrophysics on merger trees that follow the evolution of the halo/subhalo population in the Millennium II (Boylan-Kolchin et al. 2009) Simulation, a cubic region 137 Mpc on a side containing 2160\(^3 \) particles with mass \( 9.45 \times 10^9 \text{ M}_\odot \). The G11 model is the most recent semi-analytic model from the Munich group, in which the treatments of many of the physical processes have been significantly updated. G11 demonstrated that their model provided good fits not only to the luminosity and stellar mass functions of galaxies derived from SDSS data, but also to recent determinations of the abundance of satellite galaxies around the Milky Way and the clustering properties of galaxies as a function of stellar mass.

In this paper, we work with 13 830 galaxies with stellar masses greater than \( 2 \times 10^9 \text{ M}_\odot \) from the \( z = 0 \) output of the simulation. We identify central galaxies in the simulation box in the same way as in the observations, but in the simulation we know which galaxies are true central and satellite systems, so this allows us to evaluate the efficacy of our procedure. In Fig. 1, the thick dashed line shows the fraction of satellite galaxies \( F(\text{sat}) \) as a function of stellar mass for the simulated galaxies; it decreases from 0.55 at \( M_* = 3 \times 10^9 \text{ M}_\odot \) to around 0.25 at \( M_* = 3 \times 10^{11} \text{ M}_\odot \). The thin lines show \( F(\text{sat}) \) once the isolation cuts have been applied. Red, black, green, blue and cyan lines are for galaxies with increasing cold gas fractions. In the low-mass end, the isolation cuts decrease \( F(\text{sat}) \) by a factor of between 2 and 5, depending on gas fraction. At the high-mass end, the cuts have much smaller effect. This is because the

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The thick dashed line shows the fraction of satellite galaxies as a function of stellar mass for all galaxies in the \( z = 0 \) Millennium II simulation output. The coloured lines show the fraction of satellites once we apply the same isolation criterion used to construct our SDSS central galaxy sample (see text for details). Red, black, green, blue and cyan curves are for simulated galaxies with cold gas mass fractions in the 0–25th, 25–50th, 50–75th, >75th and >90th percentile ranges of the full distribution.
relation between central galaxy and dark matter halo mass is rather
flat for high-mass haloes and as a result, the true central galaxy is
not always the most massive galaxy in its immediate environment.
Nevertheless, we see that the predicted contamination from satellites
is always below 30 per cent for galaxies of all stellar masses and
gas fractions.

3 RESULTS FROM SDSS

3.1 Dependence of conformity on the stellar mass of the
primary, separation of the neighbour and star formation
activity tracer

In this section, we carry out a systematic exploration of how con-
formity between central galaxies and the surrounding population of
neighbours depends on (a) the stellar mass of the central, (b) the
physical separation between the neighbour and the central, (c) the
indicators used to trace star formation and cold gas content in both
the centrals and in their neighbours.

Figs 1–4 in this section focus on how the specific star formation
rates and gas content of the neighbouring galaxy population vary
as a function of projected radius from the central. Figs 5 and 6 then
explore how the relations between specific star formation rate/gas
content and galaxy mass/structural parameters for neighbouring
galaxies change according to the properties of the central object.

Figure 2. The specific star formation rate (measured within the SDSS fibre
aperture) of neighbouring galaxies is plotted as a function of projected dis-
tance from the central galaxies. Results are shown for central galaxies in the
stellar mass range $10 < \log M^* < 10.5 M_\odot$. In each of the four panels, the
central galaxies have been ordered by a different quantity: (a) pseudo-HI
mass fraction (top left), (b) H I deficiency parameter (top right), (c) fibre
specific star formation rate (bottom left) and (d) total specific star formation
rate (bottom right). Red, black, green, blue and cyan curves indicate re-
sults for central galaxies that fall into the 0–25th, 25–50th, 50–75th,
>75th and >90th percentile ranges of distribution of these four quantities.
Solid curves indicate the median of the SFR/$M^*$ distribution for neighbouring
galaxies at given radius, while upper and lower dotted curves indicate the
25th and 75th percentile ranges of distribution of these four quantities.
Error bars on the
median have been computed via boot-strap resampling.

Figure 3. As in Fig. 2, except for central galaxies in the stellar mass range
$11 < \log M^* < 11.5 M_\odot$.

Figure 4. As in Fig. 2, except results are shown for central galaxies in four
different stellar mass ranges. For simplicity, we only show the case where
central galaxies are ordered by H I deficiency.

We begin with the subset of central galaxies with stellar masses
in the range $10.0 < \log M^* < 10.5$. We divide these galaxies into
quartiles using four different measures.

(i) The pseudo- HI mass fraction estimate given in equation (1). Hereafter, we will denote this quantity as GS($M^*$).

(ii) The ‘HI deficiency parameter’ defined in Li et al. (2012),
which is the deviation in $\log(M_{HI}/M^*)$ from the value predicted
from the mean relation between $\log(M_{HI}/M^*)$ and the combination...
mass fraction. In subsequent work, Zhang et al. (2013) found that depletion of gas in galaxies in groups and clusters depended more strongly on the stellar surface density of the galaxy than on the mass of the galaxy. It is thus instructive to fix both stellar mass and galaxy size when we investigate how galaxies are affected by their environment.

(iii) The specific star formation rate SFR/M of central galaxies is shown as red, black, green and blue curves, respectively. The green curves show results for galaxies in the upper 90th percentiles of these quantities, i.e. cyan curves are for very unusually gas-rich or strongly star-forming central galaxies. The solid curves show the median fibre-based specific star formation rate of neighboring galaxies as a function of projected distance (in Mpc) from the central object. The lower and upper set of dotted lines show the 25th and 75th percentiles this quantity.

For all central galaxy bins, the specific star formation rates of neighbours as a function of projected radius first exhibit a drop, and then flatten out at radii larger than 500 kpc. This scale is artificially imposed by our definition that a central galaxy has to be a factor of 2 more massive than any neighbour within a projected radius of 500 kpc. Low-mass galaxies have higher specific star formation rates than high-mass galaxies, so by eliminating any galaxies with massive companions within R = 500 kpc, the specific star formation rates are forced to change in a discontinuous way at this radius.

It is apparent that for central galaxies with stellar masses \(\sim 10^{10} M_\odot\), conformity between central galaxies and neighbours is strong if the centrals have gas mass fractions/specific star formation rates less than the median value. It is absent for central galaxies with gas fractions and SFR/M values higher than the median. It is thus instructive to fix both stellar mass and galaxy size when we investigate how galaxies are affected by their environment.

(iv) The total specific star formation rate. We note that our estimate of SFR(total) is dominated by the aperture correction to SFR(fibre). In Brinchmann et al. (2004), which was based on SDSS Data Release 4 (DR4) data, the aperture corrections were done in an empirical manner. The procedure was later found to overestimate the SFR of red galaxies (Salim et al. 2007). In the DR7 release, the aperture corrections are computed by fitting the SDSS five-band photometry of the outer galaxy to a library of spectral energy distributions generated using population synthesis models using methodology similar to that outlined in the Salim et al. paper.
galaxies in the upper quartile of H I gas mass fraction, H I deficiency and total specific star formation rate. Secondly, unlike Fig. 2, no conformity is seen if the central galaxies are ordered by central specific star formation rate. Thirdly, conformity is largest at small separations and disappear at projected radii beyond ~2–3 Mpc.

In Fig. 4, we investigate trends with stellar mass in more detail by showing results in four different central galaxy stellar mass bins spanning the range $M_\star = 5 \times 10^9 – 3 \times 10^{11} M_\odot$. For simplicity, we only show the case where the central galaxies are ordered by H I deficiency. At low stellar masses, conformity is strongest on large scales and applies only in the gas-poor regime. At high stellar masses, conformity is strongest on small scales and applies only in the gas-rich regime. The cross-over between the two regimes occurs for central galaxies with stellar masses $\sim 3 \times 10^{10} M_\odot$. In the $10.5 < \log M_\star < 11 M_\odot$ bin, conformity is seen both on small scales for gas-rich central galaxies, and on large scales for gas-poor central galaxies.

So far, we have only investigated the sensitivity of conformity to the indicator used to partition central galaxies into gas-rich/strongly star-forming and gas-poor/weakly star-forming systems. We concluded that conformity is strongest when the central galaxies are sorted according to global quantities (total gas content and total specific star formation rate). What about the neighbours? Fig. 5 is the same as Fig. 4, except that we plot the pseudo-gas fractions of the neighbours instead of their central specific star formation rates. The amplitude of conformity effect is now much smaller. In the $10 < \log M_\star < 10.5 M_\odot$ bin, the difference in the median SFR/$M_\star$ (fibre) for neighbours around the most gas-rich centrals compared to the most gas-poor centrals is nearly a factor of 10. In contrast, the difference in the gas fraction is less than a factor of 2. This decrease in the amplitude holds in all four stellar mass bins.

What we conclude, therefore, is that an excess or deficiency in the gas content of central galaxies is most intrinsically correlated with the time-scale over which their neighbours have been building their central stellar populations.

### 3.2 Correlations between different galaxy properties in neighbouring galaxies

In the previous section, we examined how the median specific star formation rates and gas fractions of neighbouring galaxies at a given projected radius correlated with the properties of the central object. In this section, we study changes in the relations between different satellite properties such as stellar mass, stellar surface density, concentration index, specific star formation rate and gas mass fraction.

As discussed in the previous subsection, conformity is strongest on large scales for low-mass centrals, and on small scales for high-mass centrals. Here we analyse central galaxies in two different stellar mass ranges: $9.7 < \log M_\star < 10.3 M_\odot$ and $10.7 < \log M_\star < 11.5 M_\odot$. For the lower mass bin, we pick all neighbours with projected radii between 1 and 3 Mpc and $\Delta cz < 500$ km s$^{-1}$ and we plot relations between different properties. For central galaxies in the higher mass bin, we pick satellites with projected radii less than 0.6 Mpc and plot the corresponding relations in Fig. 7. In both plots, red, black, green and blue curves denote median relations for neighbours around central galaxies divided into four quartiles in H I deficiency parameter.

Echoing results presented in the previous section, we see that conformity effects only apply in the low-gas fraction regime for low-mass central galaxies (i.e. the blue and green curves are almost indistinguishable in Fig. 6). For high-mass central galaxies, conformity effects extend into the high gas mass fraction regime. In both Figs 6 and 7, we see that the largest changes occur in the relations between specific star formation rate measured in the fibre and galaxy mass and stellar surface density. Relations between structural parameters such as concentration and stellar surface density and stellar mass change more weakly. The largest changes in specific star formation rate occur for neighbours with stellar masses below a few $\times 10^{10} M_\odot$ and with stellar surface mass densities of a few $\times 10^5 M_\odot$ kpc$^{-2}$. In this regime, the median value of SFR/$M_\star$ changes from values around 1/15 Gyr$^{-1}$ for neighbours around gas-rich central galaxies, to values around 1/100 Gyr$^{-1}$ for neighbours around gas-poor central galaxies. In other words, if such a neighbour is found around a gas-rich central, it is building up its central stellar mass over time-scales comparable to the Hubble time. If it is found around a gas-poor central, the growth time of the central region of the galaxy is an order-of-magnitude longer. It is also interesting that the galaxy parameter regime where conformity effects are strongest is the same as the parameter regime of host galaxies of actively accreting present-day black holes (Heckman et al. 2004).

Finally, Fig. 8 is a simple summary of what we believe to be the main result of this section. We compare the systematic changes in the relations between fibre specific star formation rate and stellar surface mass density for distant neighbours around low-mass centrals (left) with those for near neighbours around high-mass centrals (right). Note that we have added central galaxies in the upper 90th percentile in H I content as a cyan curve in each panel. The difference in behaviour in the two panels as a function of the gas content.
of the central galaxies is quite striking. We will discuss possible interpretations in the final section.

4 RESULTS FROM SEMI-ANALYTIC MODELS

In this section, we present results from the semi-analytic model galaxy catalogues. As discussed in the Introduction, Wang & White (2012) have analysed conformity in these models and claim that the observed trends are explained because red galaxies inhabit more massive haloes than blue galaxies of the same mass. We do not disagree with the statement that the halo masses of red and blue galaxies of the same $M_*$ are different. As seen in Fig. 1, the fraction of central galaxies that are misclassified even after our isolation criterion is applied is significantly higher for gas-poor galaxies – all of these misclassified centrals are satellite systems in massive haloes. However, as we will show in this section, this effect cannot explain the trends seen in the observations.

The G11 model does not include detailed modelling of the density profiles of the stars and gas, so we only work with global specific star formation rates and gas fractions in this section. Fig. 9 is analogous to Fig. 2: we plot the specific star formation rates of neighbours as a function of projected distance from central galaxies with stellar masses in the range $9.7 < \log M_*/M_\odot < 10.3$ (left) and for close neighbours of central galaxies with stellar masses in the range $10.7 < \log M_*/M_\odot < 11.3$ (right). Red, black, green, blue and cyan curves are for central galaxies with H\textsuperscript{i} deficiency parameters in the 0–25th, 25–50th, 50–75th, >75th and >90th percentile ranges of H\textsuperscript{i} deficiency parameter.

The relations between fibre specific star formation rate and stellar mass for neighbours around central galaxies are different. As seen in Fig. 1, the fraction of central galaxies that are misclassified even after our isolation criterion is applied is significantly higher for gas-poor galaxies – all of these misclassified centrals are satellite systems in massive haloes. However, as we will show in this section, this effect cannot explain the trends seen in the observations.

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Similar to what is found in the observations, conformity mainly applies in the low gas fraction/specific star formation rate regime. However, in the data, the median specific star formation rate of the neighbours shifts by a factor of 5–10 between gas-poor and gas-rich central galaxies and the upper 75th percentiles of the distribution also show a pronounced effect. In the models, the median shifts by less than 50 per cent and the upper 75th percentile shows no effect whatsoever; the main shift is in the low SFR/M\textsubscript{\odot} tail of the distribution. This is because conformity effects in the models are caused by the increasing fraction of true satellite galaxies among objects classified as centrals using our isolation criterion. However,
shift in the median relation for neighbours around gas-rich and gas-poor central galaxies – only the lower percentiles of the distribution show a significant trend. These results disagree with those presented in Figs 6–8.

So far we have established that there is very significant disagreement between the data and the models. Can we now use the simulations to gain insight into what has to be changed to obtain a better match to the observations? One question we might ask is whether we need to modify the physical processes regulating gas accretion and star formation in galaxies that reside at the centres of their dark matter haloes, or whether it is the treatment of processes such as ram-pressure and tidal stripping in infalling satellites that needs changing, or both.

The middle panels of Fig. 11 show the fraction of neighbouring galaxies that are true satellites in the simulation, i.e. the fraction that do not reside at the centres of their host dark matter haloes. In the middle right-hand panel, F(sat) is very close to unity, because we have only included galaxies in the close vicinity (R < 600 kpc) of massive centrals. The conformity between gas-rich massive galaxies and near neighbours seen in the right-hand panel of Fig. 8 could thus plausibly be recovered by suitable changes to the recipes for gas stripping in the simulation.

In the left-hand panel of Fig. 11, we are considering neighbours out to much larger projected radii and F(sat) is around 0.5 on average. The fraction of true satellites among neighbours does depend on the gas fraction of the central object, but the effect is quite weak – F(sat) shifts by less than 50 per cent between the most gas-rich and gas-poor central galaxies. Let us assume for argument’s sake that all satellites are passive and have log SFR/M∗ ~ 10−12, and that all centrals are active with log SFR/M∗ ~ 10−10; a change in satellite fraction from 40 to 70 per cent would only change the average in log SFR/M∗ by 0.2 dex, which is far less than what is seen in Fig. 6.

The bottom left-hand panel shows the relation between halo mass and stellar mass for neighbouring galaxies around low-mass centrals that are themselves central objects in their dark matter haloes. In the models, this relation is quite insensitive to whether the low-mass central is gas rich or gas poor. We therefore conclude that the conformity between gas-poor central galaxies with low stellar masses and distant neighbours requires quenching processes to be coordinated in galaxies occupying disjoint and widely separated dark matter haloes.

5 SUMMARY

In this paper, we use a volume-limited sample of galaxies drawn from the SDSS DR7 with stellar masses greater than 2 × 10^9 M⊙ and redshifts less than 0.03 to perform a detailed analysis of the ‘conformity’ between the star formation rates of central galaxies and those of neighbouring galaxies pointed out by Weinmann et al. (2006). We investigate the scale dependence of the effect and how it changes as a function of the mass of the central. We also explore conformity a variety of different galaxy properties clarify which ones result in the strongest correlations between central galaxies and their neighbours. Finally, we test whether current semi-analytic models are able to match the data.

Our main results are as follows.

(i) Conformity between the properties of central galaxies and their neighbours extends over the full central galaxy stellar mass range that we were able to explore (5 × 10^9–3 × 10^11 M⊙).

(ii) The scale dependence of the effect depends on the mass of the central. Conformity extends to scales in excess of 4 Mpc around low-mass central galaxies and the strongest effects are seen at large separations (>1 Mpc) from the primary, well beyond the virial radius of its dark matter halo. In contrast, for high-mass galaxies, conformity is clearly confined to scales less than 1–2 Mpc.

(iii) For low-mass galaxies, conformity is only seen when the central galaxies have lower-than-average star formation rate or gas content. For high-mass galaxies, conformity applies in the high gas fraction especific star formation rate regime.

(iv) The strongest conformity effects arise when gas in central galaxies is correlated with central specific star formation rates in neighbouring galaxies with stellar masses less than a few ×10^10 M⊙ and stellar surface densities in the range 10^9–10^10 M⊙ kpc^{-2}.

(v) Conformity effects in the G11 models are much weaker than the ones that we observe. The effects in the models occur because a higher fraction of gas-poor galaxies are misclassified as centrals, even after our isolation cut is applied. Matching the data for low-mass central galaxies requires quenching processes to be coordinated in galaxies occupying disjoint and widely separated dark matter haloes.
of matching the observed conformity effects, because the ejected component is always returned to the same halo. If the ejected components of neighbouring galaxies were allowed to mix, it may be possible to obtain effects similar to those seen in the data.

6.2 High-mass galaxies and accretion

Conformity between high-mass central galaxies and their neighbours extends over spatial scales comparable to that of an individual massive dark matter halo. Conformity is strongest for a minority of the most gas-rich massive galaxies (see right-hand panel of Fig. 8), suggesting that accretion processes may be the underlying cause.

In Kauffmann et al. (2010), it was argued that blue, star-forming satellites trace an underlying reservoir of ionized gas that provides fuel for ongoing star formation in central galaxies. Accretion of both dark matter and gas from the surrounding environment is modelled in detail in the semi-analytic models, so the question arises as to why similar conformity effects are not seen in the high stellar mass bins in Fig. 10.

In the simulations, central galaxies with stellar masses of $\sim 10^{11} M_\odot$ reside in dark matter haloes with masses of few $\times 10^{12} M_\odot$ (see bottom left-hand panel of Fig. 11). In the models, gas cooling in haloes of this mass occurs from a corona of hot gas that is assumed to be in hydrostatic equilibrium with the surrounding dark matter halo. Cooling rates are regulated by 'radio-mode feedback', with efficiency that scales with the black hole mass of the central galaxy multiplied by $V_{\mathrm{vir}}^2$, where $V_{\mathrm{vir}}$ is the circular velocity of the dark matter halo (Croton et al. 2006). Cooling rates are thus mainly determined by the mass of the halo in which the galaxy resides. Because the cooling equations assume that the gas is always in equilibrium with the dark matter, cooling rates are not sensitive to the dynamical state of the halo or to its satellite population.

One possibility is that massive galaxies surrounded by blue satellites reside in massive dark matter haloes that have assembled relatively recently. Gas has not yet shocked and reached very high temperatures and is thus able to cool more efficiently on to the central object. The fact that the blue satellite population is most pronounced in the extreme tail of objects with the highest gas mass fractions, supports the notion that gas fuelling associated with blue satellites is a transient phase in the lives of these galaxies. Cooling and star formation may later be shut down by radio jets (see Chen et al. 2013).

One might ask why we do not observe any link between gas-rich central galaxies of low stellar masses and blue/star-forming neighbours. This might be expected in a scenario in which star formation in low-mass galaxies is fuelled by accretion of cold gas from surrounding filaments. However, as we have discussed, the dominant source of gas infall at low redshifts may be in the form of material previously ejected by supernovae-driven winds (see also Oppenheimer et al. 2010). The extent to which this gas would correlate with the present-day population of galaxies is currently not understood.

6.3 Implications for large-scale structure studies

We note that a large fraction of current work in cosmology is based on the premise that the statistical properties of a galaxy population can be predicted if one knows just two things: (a) the mass distribution of the dark matter haloes that host the galaxies and (b) the location of the galaxies in their haloes – in particular whether they are central galaxies or satellites. This forms the basis of the so-called halo occupation distribution (HOD) modelling technique.
The median stellar masses of neighbouring galaxies (solid lines), as well as the 25th and 75th percentiles of the stellar mass distributions of these objects (dotted lines), are plotted as a function of projected distance from central galaxies in the model. Results are shown for central galaxies in two stellar mass ranges. The central galaxies have been ordered by cold gas mass fraction and colour coded as in previous figures. Results from the SDSS DR7 are shown in the top two panels, while results from the G11 models are shown in the bottom panels.

The HOD framework also lies at the root of the idea that galaxies trace the underlying distribution in a simple enough way that they can be used as cosmological probes with high precision.

Most analyses that have tested the halo model have used luminosity or stellar-mass-selected samples as their basis. However, future baryon acoustic oscillation experiments such as Hobby–Eberly Telescope Dark Energy Experiment (HETDEX) and Big Baryon Oscillation Spectroscopic Survey (BigBOSS) aim to work with very well.

Finally, we would like to note that it would be useful to search for direct evidence of pre-heating of the gas around red, low-mass galaxies using quasar absorption lines as probes of the temperature of the surrounding IGM. It will also be important to understand the physical processes responsible for the heating. The strong correlation between gas content in low-mass central galaxies and the time-scale over which the neighbouring galaxies are building their central stellar populations offers a tantalizing hint that feedback processes associated with galaxy bulge and black hole formation may play a role. This will be the subject of future work.

**Figure 12.** The median stellar masses of neighbouring galaxies (solid lines), as well as the 25th and 75th percentiles of the stellar mass distributions of these objects (dotted lines), are plotted as a function of projected distance from central galaxies in the model. Results are shown for central galaxies in two stellar mass ranges. The central galaxies have been ordered by cold gas mass fraction and colour coded as in previous figures. Results from the SDSS DR7 are shown in the top two panels, while results from the G11 models are shown in the bottom panels.

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