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Central and satellite colours in galaxy groups: a comparison of the halo model and SDSS group catalogues

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ABSTRACT

Current analytic and semi-analytic dark matter halo models distinguish between the central galaxy in a halo and the satellite galaxies in halo substructures. It is expected that galaxy properties are correlated with host halo mass, and that central galaxies tend to be the most luminous, massive and reddest galaxies in haloes while the satellites around them are fainter and bluer. Using a recent halo-model description of the colour dependence of galaxy clustering (Skibba & Sheth), we investigate the colours of central and satellite galaxies predicted by the model and compare them to those of two galaxy group catalogues constructed from the Sloan Digital Sky Survey (SDSS; Yang et al.; Berlind et al.). In the model, the environmental dependence of galaxy colour is determined by that of halo mass, and the predicted colour mark correlations were shown to be consistent with SDSS measurements. The model assumes that satellites tend to follow a colour–magnitude sequence that approaches the red sequence at bright luminosities; the model's success suggests that bright satellites tend to be 'red and dead' while the star formation in fainter ones is in the process of being quenched. In both the model and the SDSS group catalogues, we find that at fixed luminosity or stellar mass, central galaxies tend to be bluer than satellites. In contrast, at fixed group richness or halo mass, central galaxies tend to be redder than satellites, and galaxy colours become redder with increasing mass. We also compare the central and satellite galaxy colour distributions, as a function of luminosity and as a function of richness, in the model and in the two group catalogues. Except for faint galaxies and small groups, the model and both group catalogues are in very good agreement.

Key words: methods: analytical – methods: statistical – galaxies: clusters: general – galaxies: formation – galaxies: haloes – large scale structure of the universe.

1 INTRODUCTION

In standard Λ cold dark matter (ΛCDM) cosmological models, CDM haloes form from the gravitational collapse of dark matter particles, and they assemble hierarchically, such that smaller haloes merge to form larger and more massive haloes. According to the current paradigm of galaxy formation, galaxies form within haloes, due to the cooling of hot gas. Haloes and galaxies evolve simultaneously, and the evolution of a galaxy is affected by its host halo. If the halo is accreted by a larger halo, the galaxy will be affected by it as well, and may interact or merge with the galaxies within the new host halo. Such 'satellite' galaxies in halo substructures no longer accrete hot gas, which instead is only accreted by the 'central' galaxy in the halo. The central galaxy consequently continues to grow, while other massive galaxies may merge into it, and therefore it is expected to be the most luminous and most massive galaxy in the halo.

For these reasons, current analytic and semi-analytic models distinguish between central and satellite galaxies, which at a given time are at different stages of evolution or may have evolved differently. As galaxies evolve, they transform from star-forming late-type galaxies into massive bulge-dominated galaxies with little or no ongoing star formation. It is thought that central galaxies undergo such a transformation by experiencing a major merger followed by active galactic nuclei (AGN) feedback preventing additional gas cooling and star formation. Satellite galaxies may have their star formation suppressed or 'quenched' by a number of other processes, such as ram-pressure stripping of the cold gas reservoir, 'harassment' by other satellites and 'strangulation' following the stripping of the hot gas reservoir, the latter of which appears to be the dominant process (e.g. Weinmann et al. 2006; van den Bosch et al. 2008a).

Galaxies in relatively dense environments tend to reside in groups and clusters hosted by massive haloes. Recent analyses with galaxy

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group catalogues have argued that many of these galaxies are very red with very low star formation rates, in contrast with galaxies in low-mass haloes in less dense environments, many of which are still quite blue with significant star formation (e.g. Berlind et al. 2006b; Weinmann et al. 2006). Measurements of the environmental dependence of galaxy colour have found trends that are qualitatively consistent with these claims (e.g. Blanton et al. 2005a; Zehavi et al. 2005; Tinker et al. 2007, Coil et al. 2008). In order to better understand galaxy and halo evolution, more models are needed that can explain the environmental dependence on colour, and more measurements of correlations between colour and environment are needed to better constrain such models. Skibba & Sheth (2008) (hereafter SS08) have taken a step in this direction: they developed and tested a halo model of the colour dependence of galaxy clustering in the Sloan Digital Sky Survey (SDSS). Their model successfully explains the correlation between colour and environment, quantified by the colour mark correlation function, while assuming that all environmental correlations are due to those of halo mass. They distinguish between central and satellite galaxies, whose properties are assumed to be determined by host halo mass. The purpose of this paper is to further investigate these central and satellite galaxy colours, and in particular to compare the predictions of the model with measurements from recent galaxy group catalogues (Berlind et al. 2006a; Yang et al. 2007, hereafter B06 and Y07, respectively).

This paper is organized as follows. In the next two sections, we briefly introduce the colour mark model and the galaxy group catalogues. In Section 4, we compare the satellite colour–magnitude sequence of the model to that of the Yang et al. catalogue, and we compare the central and satellite colours of the model and both group catalogues as a function of group richness, which is a useful proxy for halo mass. We summarize our results in Section 5.

2 HALO MODEL OF GALAXY COLOURS

Our halo model of the colour dependence of galaxy clustering is described in SS08, and we refer the reader to this paper for details.

Briefly, our model is based on the model of luminosity dependent clustering of Skibba et al. (2006), which explained the observed environmental dependence of luminosity by applying the luminosity-dependent halo occupation distribution (HOD) that was constrained by the observed luminosity-dependent correlation functions and galaxy number densities in the SDSS (Zehavi et al. 2005; Zheng, Coil & Zehavi 2007). The model of galaxy colours in SS08 added constraints from the bimodal distribution of $g - r$ colours of SDSS galaxies as a function of r-band luminosity. We made two assumptions: (i) that the bimodality of the colour distribution at fixed luminosity is independent of halo mass and (ii) that satellite galaxies tend to follow a particular sequence in the colour–magnitude diagram, one that approaches the red sequence with increasing luminosity:

$$\langle c|L\rangle_{\rm sat} = \langle g - r|M_r\rangle_{\rm sat} = 0.83 - 0.08\,(M_r + 20). \qquad (1)$$

These observational constraints and additional assumptions allowed SS08 to model the central and satellite galaxy colour 'marks' as a function of halo mass, $\langle c|M\rangle_{\rm cen}$ and $\langle c|M\rangle_{\rm sat}$. SS08 used the central and satellite galaxy marks to model colour mark correlation functions, in which all correlations between colour and environment are due to those between halo mass and environment. The modelled mark correlation functions were in very good agreement with their measurements with volume-limited SDSS catalogues, reproducing the observed correlations between galaxy colour and environment on scales of $100\,h^{-1}$ kpc $< r_{\rm p} < 30\,h^{-1}$ Mpc.

The two-point mark correlation function is simply the ratio $[1 + W(r)]/[1 + \xi(r)]$, where $\xi(r)$ is the traditional two-point correlation function and $W(r)$ is the same sum over galaxy pairs separated by r, but with each member of the pair weighted by the ratio of its mark to the mean mark (Beisbart & Kerscher 2000; Sheth 2005). In practice, we measure the *projected* clustering of galaxies, and so we use the following analogous statistic for both the measurements and the models, the marked projected correlation function:

$$M_{\rm p}(r_{\rm p}) = \frac{1 + W_{\rm p}(r_{\rm p})/r_{\rm p}}{1 + w_{\rm p}(r_{\rm p})/r_{\rm p}} \qquad (2)$$

where the projected two-point correlation function is

$$w_{\rm p}(r_{\rm p}) = 2\int_0^\infty {\rm d}\pi\,\xi(r_{\rm p},\pi) = 2\int_{r_{\rm p}}^\infty {\rm d}r\,\frac{r\,\xi(r)}{\sqrt{r^2 - r_{\rm p}{}^2}}. \qquad (3)$$

If mark correlations are consistent with unity, then the mark is not correlated with the environment at that scale; if the mark correlations are above unity, which is the case for galaxy luminosity and colour (Skibba et al. 2006; SS08), then higher values of the mark tend to be located in denser environments at that scale.

As an example, we show the $g - r$ colour mark correlation function for $M_r < -19.5$ in Fig. 1, reproduced from SS08 (their fig. 6). The solid curve shows the halo model's prediction, which is in agreement with the measurements of the colour mark correlations in the SDSS, using Petrosian colours. Had we instead used L_r/L_g as the mark, the resulting mark correlations would be quantitatively stronger, but with larger uncertainties – the SDSS measurements would have similar statistical significance and constraining power as the $g - r$ mark measurements (see Skibba et al. 2006).

A few assumptions were made in the model that are worth discussing. First, it was assumed that the central galaxies lie at the centre of their host dark matter haloes, as is commonly assumed in HOD and conditional luminosity function (CLF) studies. However, central galaxies are often offset from the centre of the potential well

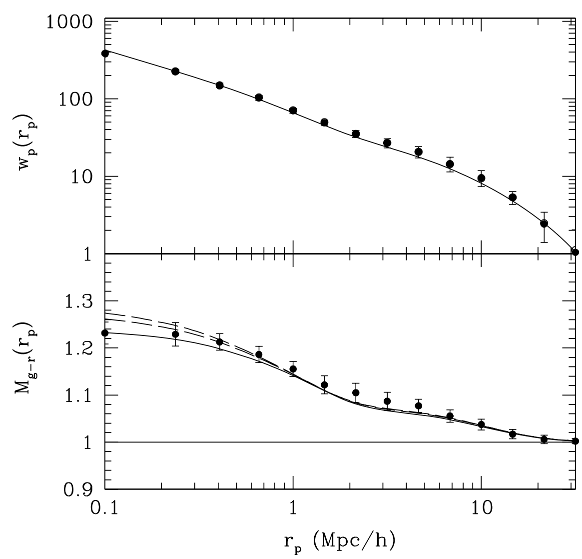

Figure 1. Projected two-point correlation function and $g - r$ colour mark correlation function for $M_r < -19.5$. Points show SDSS measurement for Petrosian colours, and solid curves show the fiducial model, both taken from SS08. Dashed curves show the range of colour mark correlations predicted by the model if colour gradients in groups and clusters are included (Hansen et al. 2007).

(van den Bosch et al. 2005), and this offset appears to weakly dependent on galaxy colour (Skibba et al., in preparation). Secondly, it was assumed that satellite galaxies follow the dark matter profile, while satellite galaxy number density profiles have been found to be less concentrated (e.g. Hansen et al. 2005; Yang et al. 2005b). These two effects are both too weak to significantly affect the marked galaxy clustering on scales of $r_p > 100\,\mathrm{kpc}\,h^{-1}$, however, and if the effects were stronger, then there would have been a discrepancy with the observed unmarked correlation function $w_p(r_p)$ as well, which was not the case.

Thirdly, we also assumed that there are not mark gradients within haloes, that is, that the colours of galaxies are independent of their distance from the halo centre. In contrast, Hansen et al. (2007) have shown that the $g - r$ colours of galaxies are ∼15–20 per cent redder in the inner regions of groups and clusters compared to the cluster outskirts (see their fig. 10). van den Bosch et al. (2008b) have shown a similar fractional increase in galaxy colours with decreasing halo-centric radius, down to halo masses of $10^{12}\,h^{-1}\,\mathrm{M}_\odot$. These colour gradients appear to be stronger than luminosity gradients in groups and clusters (Hansen et al. 2005; Martínez & Muriel 2006; Weinmann et al. 2006). Such a positional dependence on galaxy colours would only affect the colour mark correlations while leaving the unmarked correlation function unchanged. In order to model position-dependent colour marks in mark clustering statistics, the density profile of satellite galaxies must be replaced by a weighted profile (Navarro, Frenk & White 1997). The calculation is done in Fourier space (see Sheth 2005; and appendix B of SS08), and we replace $u_{\mathrm{gal}}(k|M)$, which is the Fourier transform of $\rho_{\mathrm{gal}}(r|M)$, by a weighted number density profile

$$w(k|M) = \frac{\int \mathrm{d}r'\, 4\pi r'^2\, c_{\mathrm{gal}}(r'|M)\, \rho_{\mathrm{gal}}(r'|M) \sin(kr')/kr'}{\int \mathrm{d}r'\, 4\pi r'^2\, c_{\mathrm{gal}}(r'|M)\, \rho_{\mathrm{gal}}(r'|M)}, \quad (4)$$

where $r' \equiv r/r_{\mathrm{vir}}(M)$ and $c_{\mathrm{gal}}(r'|M)$ quantify the dependence of galaxy colour on halo-centric radius, which we assume to be independent of mass because it is independent of cluster richness (Hansen et al. 2007; cf. van den Bosch et al. 2008b). The minimum and maximum amount of position dependence on galaxy colours result in slightly stronger colour mark correlations at small scales (lower and upper dashed curves in lower panel of Fig. 1) or in other words, colour gradients in haloes imply a slightly stronger environmental dependence on galaxy colour in halo environments ($r_p < 1\,\mathrm{Mpc}\,h^{-1}$). Note that colour gradients in clusters are much stronger at $z > 0.5$ (Loh et al. 2008) and would have a stronger effect on colour mark clustering at such redshifts.

Finally, the analytic halo-model description of the colour dependence on galaxy clustering uses the mean of the HOD and the mean colours of central and satellite galaxies. We are assuming that at fixed halo mass, the HOD and colour distributions are approximately independent of the environment – an assumption which is justified by some recent results (Blanton & Berlind 2007; van den Bosch et al. 2008b; SS08). To explore the central and satellite galaxy colour distributions predicted by the model, we construct mock galaxy catalogues. The mock catalogues are observationally constrained by the HOD as a function of luminosity, determined from galaxy clustering measurements in the SDSS (Zheng et al. 2007), and the bimodal colour distribution as a function of luminosity in the SDSS, fit as the sum of two Gaussian distributions, which we refer to as the 'red sequence' and the 'blue sequence'. In effect, since central and satellite galaxies have a range of colours at fixed luminosity, in the model satellite colours are drawn from the red sequence with some luminosity dependent probability and are otherwise drawn from the blue sequence; central galaxy colours are drawn with a similar procedure, but with a different luminosity-dependent probability. The details of the algorithm are described in Skibba et al. (2006) and SS08. SS08 showed that these mock catalogues, which include not only the means of the galaxy colours but their scatter as well, yield colour mark correlation functions that are consistent with the analytic model and with SDSS measurements.

The analysis in Section 4, in which we examine the colours of central and satellite galaxies, will constitute a test of this model, and in particular of the model's two assumptions described at the beginning of this section. We will compare the model's predictions of central and satellite galaxy colours to those of galaxy group catalogues, described in the following section.

3 DATA: SDSS GALAXY GROUP CATALOGUES

We will first compare our model to the Y07 group catalogue, which was constructed by applying the halo-based group finder of Yang et al. (2005a) to the New York University Value-Added Galaxy catalogue (NYU-VAGC; Blanton et al. 2005b), which is based on the SDSS (York et al. 2000) data release 4 (DR4) (Adelman-McCarthy et al. 2006).

The group finder uses halo properties as a function of the total luminosity or stellar mass of groups, and it also identifies 'groups' with only a single member. We used only those galaxies with spectroscopic redshifts from the SDSS or with redshifts taken from other surveys (their 'sample II') – that is, we excluded fibre-collided galaxies that were not assigned fibres. Including such galaxies does not affect the mean colours of central and satellite galaxies (shown in Section 4), although this is not the case for the mean central galaxy luminosities (see appendix of Skibba, Sheth & Martino 2007). Y07 have used mock catalogues to account for the effects of the survey edges when estimating group halo masses (see their paper for details). We only compare to volume-limited catalogues constructed from the sample II group catalogue in this work, and we have accounted for groups that overlap the redshift limits. In each group, we identify the 'central' galaxy as the most luminous in the r band, and the remaining galaxies brighter than the luminosity threshold are the 'satellites'. Labelling the most massive galaxy in a group, rather than the brightest, as the central one does not affect our results.

We will also compare to the central and satellite galaxy colours of a volume-limited group catalogue of B06, which is drawn from the SDSS large-scale structure sample *sample14* from the NYU-VAGC; the sample is a subsample of SDSS DR4 (Adelman-McCarthy et al. 2006). Fibre-collided galaxies are included, and each collided galaxy was given the redshift of its nearest neighbour, which was shown to be an adequate correction at least for groups with 10 or more members. To account for the survey edges, B06 excluded all groups whose centres lie less than 500 kpc from an edge in the tangential direction or less than $500\,\mathrm{km\,s^{-1}}$ from an edge in the radial direction. Groups were identified using a halo-based friends-of-friends algorithm, which used HOD models and the group multiplicity function. The group-finding algorithm only used the galaxy positions in redshift space, as opposed to the algorithm used by Y07.

In the following analysis, the magnitudes and colours of galaxies in the two group catalogues are Petrosian, and have been k-corrected and evolution corrected to $z = 0.1$.

4 COMPARISON OF THE MODEL AND GROUP CATALOGUES

The main purpose of this paper is to analyse the colours of central and satellite galaxies in groups and clusters. We compare

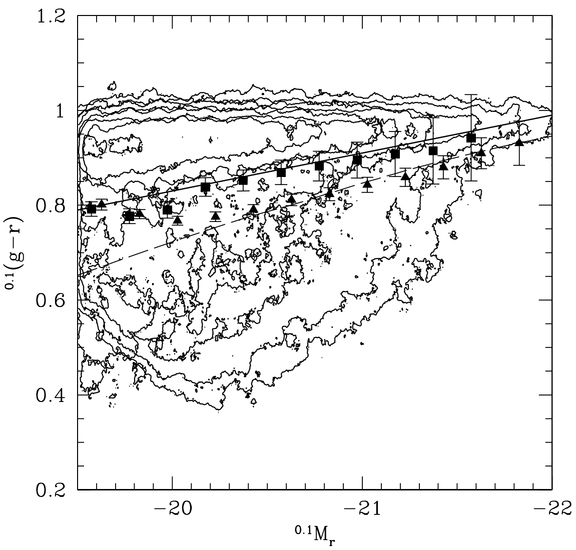

Figure 2. Colour–magnitude diagram of $M_r < -19.5$ volume-limited SDSS catalogue constructed from the Y07 group catalogue. Contours for central galaxies (with brightest r-band luminosity) and satellite galaxies are red and blue, respectively. The satellite galaxy colour–magnitude sequence $\langle c|L\rangle_{\rm sat}$ of the SS08 model (1) is shown as the thick solid line; the mean satellite galaxy colours at fixed luminosity of the group catalogue are shown as the square points, with Poisson errors. The colour–magnitude sequence of central galaxies in the model (5) and the group catalogue are also shown, by the dashed line and triangle points, respectively. The measured central and satellite colours (squares and triangles) are slightly offset, for clarity.

predictions of the colour mark model of SS08 to measurements from the Y07 and Berlind et al. (2006a) galaxy group catalogues. This analysis also constitutes a test of the model, which, as described in Section 2, made two assumptions in addition to those necessary to model the luminosity dependence of galaxy clustering: (i) that the bimodal colour distribution at fixed luminosity is independent of halo mass and (ii) satellite galaxies tend to follow a particular colour–magnitude sequence $\langle c|L\rangle_{\rm sat}$ that approaches the red sequence with increasing luminosity (equation 1).

4.1 Central and satellite colours as a function of luminosity

We test the latter assumption first. In Fig. 2, we show a colour–magnitude diagram with the model's satellite galaxy colour–magnitude sequence. It is similar to fig. 2 in SS08, but the contours are for a volume-limited catalogue constructed from the Y07 group catalogue, with limits $-23.5 < {}^{0.1}M_r < -19.5$, $0.017 < z < 0.082$, consisting of 59 085 galaxies. The figure shows the colour–magnitude contours of central and satellite galaxies in the catalogue (red and blue contours, respectively). Central and satellite galaxies appear to have somewhat similar bimodal colour distributions at faint luminosities. The majority of bright blue galaxies and luminous red galaxies are centrals, however, and as we will show later, they tend to reside in less massive and more massive haloes, respectively.

We compare the satellite galaxy colour–magnitude sequence $\langle c|L\rangle_{\rm sat}$ (1) of the model to the mean satellite colours in the Y07 group catalogue in Fig. 2. They are in excellent agreement: the model's satellite colour sequence is approximately only 0.01 mag redder than that of the group catalogue and within the Poisson errors across most of the luminosity range. The agreement between the model and the group catalogue is encouraging, and, in particular, it supports the use of (1) as the satellite galaxy colour sequence, which could be used as a constraint for galaxy formation models that include physical processes that quench the star formation of satellites.

We also show the colour–magnitude sequence of central galaxies in Fig. 2. In the model, this sequence is implied by the satellite sequence (1), the luminosity-dependent HOD and the observed colour–magnitude constraints:

$$\langle c|L\rangle_{\rm cen} = \langle c|L\rangle_{\rm all} + \frac{n_{\rm sat}(L)}{n_{\rm cen}(L)}\,[\langle c|L\rangle_{\rm all} - \langle c|L\rangle_{\rm sat}] \qquad (5)$$

(see SS08 for details). This sequence is consistent with the measurement from the Y07 catalogue, at least for $M_r < -20$. In both the model and the Y07 catalogue, at fixed luminosity, central galaxies tend to be *bluer* than satellite galaxies. van den Bosch et al. (2008a) found the same result, at fixed stellar mass. However, in a given halo, the central galaxy tends to be significantly brighter and more massive than its satellites, and it also tends to be redder, as we will show in Section 4.2.

Fig. 2 showed the mean central and satellite colours as a function of luminosity, $\langle c|L\rangle_{\rm cen}$ and $\langle c|L\rangle_{\rm sat}$. We now compare the central and satellite colour distributions, $p_{\rm cen}(c|L)$ and $p_{\rm sat}(c|L)$, in Figs 3 and 4. The model predictions are determined from a mock galaxy catalogue (described in Section 2), and they are compared to measurements from the Y07 group catalogue.

Overall, the agreement between the model and the group catalogue is quite good, especially for $M_r < -20.5$ (or $L > L_*$). For central galaxies, the bimodality of the colour distribution is stronger in the model than in the data at faint luminosities. This is partly due to the fact that the double-Gaussian fit to the colour distribution at fixed luminosity is not perfect, and slightly underpopulates the 'green valley' between the red and blue sequences at faint luminosities. This does not explain the discrepancy in the faintest bin, however. Faint central galaxies tend to reside in low mass haloes or small groups (e.g. Skibba et al. 2007), so the discrepancy could be due to inaccuracies in the model or its constraints at low mass or to inaccuracies in the group catalogue in poor groups.

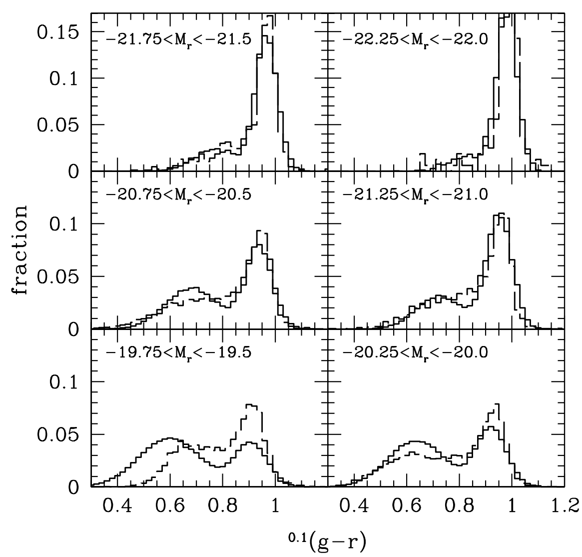

Figure 3. Distributions of $g - r$ colour of central galaxies as a function of luminosity. Solid black histograms show the predictions of the model (SS08), dashed blue histograms show the measurements from the Y07 group catalogue.

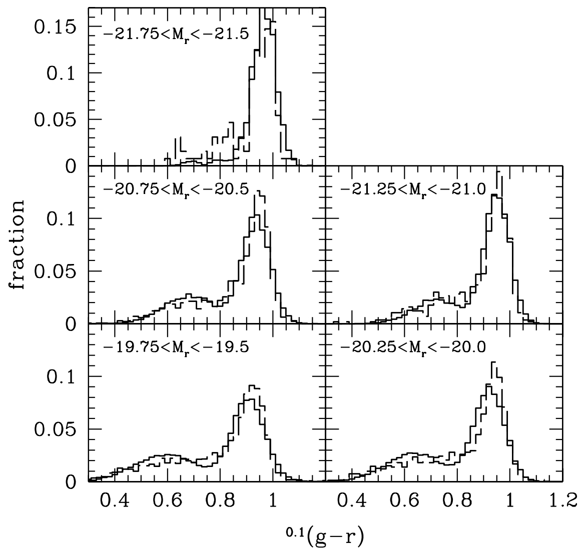

Figure 4. Same as Fig. 3, but for satellite galaxies. The brightest luminosity bin is excluded because of poor number statistics.

An interesting result is that both the model and the group catalogue agree that the red and blue sequence are peaked at approximately the same colours at fixed luminosities for central and satellite galaxies, and that the widths of the red and blue sequences narrow similarly with increasing luminosity for centrals and satellites. The difference between the central and satellite colour distributions is simply that the blue fraction at a given luminosity is lower for satellites: the red sequence of satellites becomes significantly populated at fainter luminosity than does the red sequence of centrals.

4.2 Central and satellite colours as a function of group richness

We now investigate the colours of central and satellite galaxies as a function of group richness, which is strongly correlated with halo mass. We constructed a volume-limited catalogue from the Y07 group catalogue similar to the one above, but with the following limits: $-23.5 < M_r < -19.9$ and $0.015 < z < 0.100$. We begin by examining the mean colours of centrals and satellites. The mean colour of central galaxies in the groups containing $N_{\rm gal}$ galaxies was defined as the mean value $\langle g - r\rangle$ of all central galaxies of such groups (rather than $-2.5\ \log_{10}\ \langle L_g/L_r\rangle$ or $-2.5\ \log_{10}\ \langle L_g\rangle/\langle L_r\rangle$). The mean satellite colour in groups of $N_{\rm gal}$ galaxies was computed similarly (i.e. the mean of satellite $g - r$).

We have also measured the mean colours of central and satellite galaxies in the similar volume-limited catalogue of B06. This $M_r < -19.9$ catalogue consists of 21 301 galaxies in 4119 groups having three or more members. In comparison, the corresponding Y07 catalogue contains 15 234 galaxies in 2163 groups (when fibre-collided galaxies are included), which are significantly smaller numbers considering that their catalogue was drawn from a later SDSS DR. The Berlind et al. catalogue has an overabundance of low-$N_{\rm gal}$ groups (see their appendix and that of Skibba et al. 2007), which does not appear to be the case for Yang et al. However, Berlind et al. only claim to be complete for $N_{\rm gal} \geq 10$, and for such richnesses the two group catalogues are in better agreement.

We will compare the mean central and satellite colours from both group catalogues to those predicted by the halo occupation model of SS08. The model colours are computed the same way as the central and satellite luminosities were computed in Skibba et al. (2007):

$$\langle c_{\rm cen}|N\rangle = \int_{M_{\rm min}(L_{\rm min})}^{\infty} {\rm d}M\ \frac{{\rm d}n(M)}{{\rm d}M}\ \frac{p(N|M)\,\langle c_{\rm cen}|M\rangle}{n_{\rm grp}(N)}, \quad (6)$$

and

$$\langle c_{\rm sat}|N, L_{\rm min}\rangle = \int_{M_{\rm min}(L_{\rm min})}^{\infty} {\rm d}M\ \frac{{\rm d}n(M)}{{\rm d}M}\ \frac{p(N|M)\,\langle c_{\rm sat}|M, L_{\rm min}\rangle}{n_{\rm grp}(N)}, \quad (7)$$

where ${\rm d}n/{\rm d}M$ is the halo mass function, $p(N|M)$ is the HOD, and $n_{\rm grp}(N)$ is the group multiplicity function.

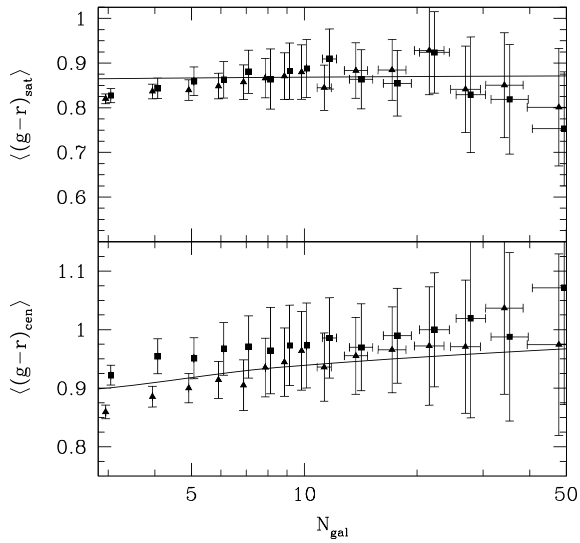

Figure 5. Mean central and satellite $g - r$ colours as a function of group richness, for $M_r < -19.9$. Solid curves show the model predictions (using equations 6 and 7), and red triangles and blue squares show the measurements from the B06 and Y07 galaxy group catalogues, respectively. Vertical error bars are the average of the Poisson errors (estimated from the number of groups in each bin) and bootstrap errors (estimated from the variance of 10 times as many pseudo-samples as the number of groups). Horizontal error bars show the $N_{\rm gal}$ bin widths.

Fig. 5 shows the results. In general, at fixed group richness, satellite galaxies tend to be bluer than central galaxies, by up to 0.1 mag. These trends are similar at fixed halo mass in the model (not shown), consistent with the results of Yang, Mo & van den Bosch (2008). Because of the dependence of the mean satellite colours on the luminosity threshold ($L_{\rm min}$ in equation 7), the difference between the colours of centrals and satellites would be even larger if fainter galaxies were included.

The model's central and satellite galaxy colours are in very good agreement with both group catalogues, from poor groups to rich clusters. The error bars on the measurements are fairly large, but the halo-model predictions are also uncertain due to uncertainties in the luminosity-dependent HOD and in the colour–magnitude constraints. The central galaxy colours are systematically redder in the Y07 catalogue than in the B06 catalogue. It could be due to the different cosmology assumed by Yang et al. ($\Omega_{\rm m} = 0.238$, $\sigma_8 = 0.75$) or it may be related to the different colour-dependent clustering at fixed group mass measured from the catalogues (Berlind et al. 2006b; Wang et al. 2008). It is of only weak statistical significance, however.

For the model, we have assumed that the bimodal colour distribution at fixed luminosity is independent of halo mass. Therefore, the satellite colours are only weakly dependent on group richness or

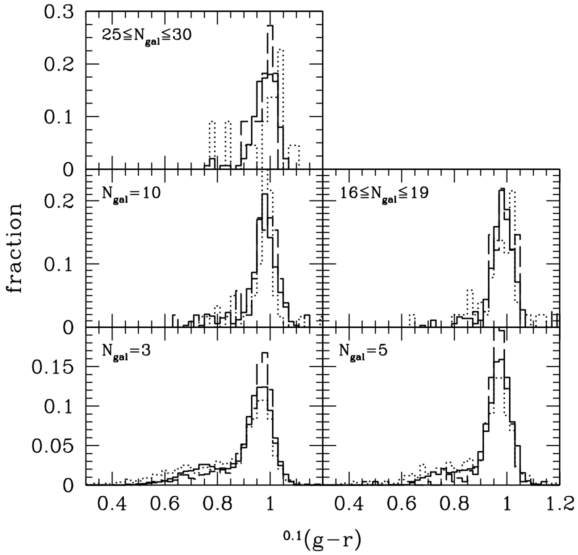

Figure 6. Distributions of $g-r$ colour of central galaxies as a function of group richness, for $M_r < -19.9$. Solid black histograms show the predictions of the model (SS08); dashed blue histograms show the measurements from the Y07 group catalogue; dotted red histograms show the measurements from the Berlind et al. (2006a) catalogue. A very large $N_{\rm gal}$ bin is not included, because of poor number statistics.

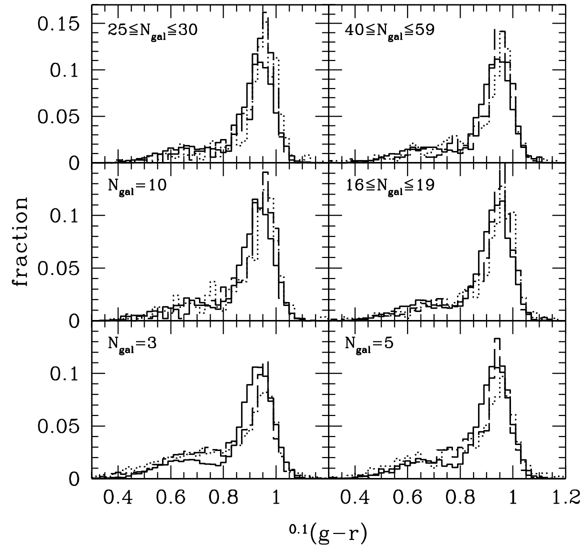

Figure 7. Same as Fig. 6, but for satellite galaxies. The three large $N_{\rm gal}$ bins are chosen to be the same as the fifth richest, third richest and richest bins in Fig. 5.

halo mass because the satellite luminosities are weakly dependent on them. Skibba et al. (2007) found that satellite galaxy luminosity is almost independent of group richness in their halo occupation model and in the group catalogues of Yang et al. (2005a) and B06. The result in the upper panel of Fig. 5 shows that this is also the case for satellite galaxy colours, and lends justification to the model's assumption that the colour distribution at given luminosity is independent of mass. This result has an interesting consequence: the fact that both the luminosity and colour of satellites is nearly independent of halo mass implies that the evolution of satellite galaxies is nearly independent of the environment. We discuss this further in Section 5.

Finally, we compare the central and satellite colour distributions as a function of group richness, $p_{\rm cen}(c|N_{\rm gal})$ and $p_{\rm sat}(c|N_{\rm gal})$, for $M_r < -19.9$, in Figs 6 and 7. The model predictions are determined from a mock galaxy catalogue (described in Section 2), and they are compared to measurements from the Y07 and B06 group catalogues.

Overall, there is impressive agreement between the model and group catalogues, even for groups with few members. For central galaxies in poor groups, the B06 catalogue has a slightly weaker red peak and a slightly more populated blue bump than in the Y07 catalogue, with the model between them. For satellite galaxies in poor groups, the red sequence is peaked at a slightly redder colour in the group catalogues than in the model, and the blue bump is slightly more populated in the catalogues. These differences are very small, however.

A comparison of the figures makes the following two conclusions evident. First, for central galaxies, while a significant fraction of them populates the blue cloud in small groups or low-mass haloes, the vast majority of them in large groups or massive haloes ($M > 10^{14}\,{\rm M}_\odot\,h^{-1}$) have moved on to the red sequence. Secondly, for satellite galaxies, the colour distribution has a significant blue bump even in massive groups and clusters. While there are large numbers of red satellites in such systems, of course, there is also a significant number of blue satellites as well, presumably tending to be located in the cluster outskirts, implied by the colour gradients discussed in Section 2. Moreover, the satellite colour distribution is almost independent of group richness or halo mass. This occurs in the model by construction: we have assumed that the colour distribution at fixed luminosity is independent of mass, and satellite luminosity only weakly depends on richness. The agreement with the group catalogues constitutes evidence in support of this assumption.

5 DISCUSSION

To summarize, we have compared the halo model of galaxy colours of SS08 to the colours of galaxies in the Y07 and B06 group catalogues. The model assumes that satellite galaxies tend to follow a particular sequence along the colour–magnitude diagram (1), such that it approaches the red sequence at bright luminosities, and we have found that this satellite colour sequence is in excellent agreement with measurements from the Yang et al. group catalogue. This constitutes support for the Skibba & Sheth model, and for the satellite colour sequence itself, which could be used as a constraint for galaxy formation models on the physical processes that quench the star formation of satellite galaxies. The satellite colour sequence as a function of luminosity can easily be converted into a sequence as a function of halo mass as well (see section 2.2 of Skibba & Sheth). The agreement between the model and the group catalogue suggests that a significant fraction of faint satellites (with $L < L_*$), which reside in low-mass haloes as well as cluster-sized haloes (Skibba et al. 2007), are still forming stars out of a dwindling gas supply and are in the process of being quenched and transformed into 'red and dead' galaxies.

van den Bosch et al. (2008a) recently used the Y07 group catalogue to explore the impact of various transformation mechanisms that are believed to operate on satellite galaxies. Based on the colours and concentrations of galaxies at fixed stellar mass, they found that the main mechanism that causes the transition of satellite galaxies from the blue to the red sequence is strangulation, in which the hot diffuse gas around newly accreted satellites is stripped, removing its fuel for future star formation. They ruled out other mechanisms, such as ram-pressure stripping, which is efficient only in massive haloes, and harassment, which alters galaxies' morphologies. Kang & van den Bosch (2008) used these results with their semi-analytic model to show that strangulation is inefficient and takes a few Gyr to operate. A similar conclusion was recently obtained by Font et al. (2008), who used a more sophisticated stripping model. Cattaneo et al. (2008) have recently used another semi-analytic model to show that the observed 'archaeological downsizing', in which stars in more massive galaxies tend to form earlier and over a shorter period, can be reproduced if strangulation shuts down star formation only above a critical halo mass $M_{\rm crit} \sim 10^{12}\,{\rm M}_{\odot}$. Gilbank & Balogh (2008) came to the same conclusion when attempting to reproduce the red sequence dwarf-to-giant ratio in clusters and the field. This critical mass is slightly larger than the minimum halo mass for $M_r < -19.5$, and at this mass scale the satellite colour sequence of the SS08 model is indeed approaching the red sequence.

We also analysed the colours of central and satellite galaxies as a function of group richness, quantified by the number of galaxies in a group more luminous than a given threshold. We showed that at fixed richness or halo mass, central galaxies tend to be redder than satellites, and the colour difference increases with richness. In contrast, at fixed luminosity or stellar mass, centrals tend to be bluer than satellites. This is simply explained by the fact that in a given halo, the central galaxy is usually the brightest and most massive galaxy. These results suggest that as central and satellite galaxies evolve, they may follow different paths along the colour–magnitude diagram. For example, central galaxies become more luminous as they evolve, whether secularly or with mergers, and may continue to form stars and remain blue even after forming a significant bulge component, and then move towards the red sequence after AGN feedback has operated. On the other hand, satellites may experience star formation quenching due to strangulation and approach the red sequence while they are still faint and disc-dominated. These issues are investigated further in Skibba et al. (2008), using morphology mark correlation functions with the SDSS Galaxy Zoo catalogue of visually classified morphologies.

For the colours of both central and satellite galaxies as a function of group richness, the model of SS08 and the two group catalogues of Y07 and B06 are in very good agreement. Central galaxies tend to be the reddest galaxy in a halo and are much redder than the typical satellite in large groups. Satellite galaxy colour, unlike that of centrals, is almost independent of group richness. The distributions of central and satellite colours as a function of richness in the model and group catalogues are also in good agreement. Central galaxies have a bimodal colour distribution in small groups, but the vast majority of them in larger groups have moved on to the red sequence. In contrast, the satellite colour distribution is almost independent of group richness. This occurs in the model by construction: we assumed that the colour distribution at fixed luminosity is independent of halo mass, and satellite luminosity only weakly depends on richness. The agreement with the group catalogues supports this assumption.

It is worth emphasizing that, while some authors focus on mean galaxy properties (e.g. Martínez & Muriel 2006; Conroy & Wechsler 2008) or on red or blue fractions (e.g. Weinmann et al. 2006; van den Bosch et al. 2008a), our model has predicted the mean and *distributions* of central and satellite galaxy colours, as a function of luminosity and richness, in agreement with the SDSS data for $M_r < -20$. This is quite a feat, considering that our model is fairly simple, based on luminosity-dependent clustering and colour–magnitude constraints, with very few assumptions.

It is interesting that satellite galaxy colour appears to be almost independent of host halo mass, and that this is also the case for satellite galaxy luminosity (Skibba et al. 2007). Since galaxy colour is tightly correlated with stellar mass-to-light ratio (Bell et al. 2003), this implies that satellite galaxies of a given stellar mass can also be found in haloes of a wide range of masses. This suggests that what most determines a satellite galaxy's properties, and its evolution in general, is its stellar mass, not its host halo mass. In addition, galaxy colour and luminosity are the primary properties that are most predictive of a galaxy's environment (Blanton et al. 2005a), so the flat relations of satellite galaxy colour and luminosity with halo mass suggest a dearth of environmental dependence for the transformation of satellite galaxies. This point was recently made by van den Bosch et al. (2008b), who used the Y07 group catalogue to show that the colour and concentration of satellite galaxies are almost completely determined by their stellar mass, with only a very weak dependence on halo mass and halo-centric radius. One consequence of this is that 'pre-processing' in groups cannot be the dominant process that differentiates the cluster galaxy population from that of the field.

Finally, Brown et al. (2008) recently completed a study of the evolution of the luminosity and stellar mass of red central and satellite galaxies, using halo occupation models. We can do a few simple comparisons between our results and theirs. They find that the stellar masses of luminous red central galaxies scale with halo mass to the power of $\approx$0.35. Using our model's relationship between central galaxy colour and halo mass (lower panel of Fig. 5) with the relation between colours and stellar mass-to-light ratios (Bell et al. 2003), we can estimate the relation between central galaxy stellar mass and halo mass for the model. We find that the slope of this relation approaches $\approx$0.37, similar to their result. Brown et al. also show that approximately 50 per cent of $10^{11.9}\,h^{-1}\,{\rm M}_{\odot}$ mass haloes host central galaxies that are red, and this fraction increases with halo mass. Our model predicts a fraction of $\approx$45 per cent at this mass, although our separation of 'red' and 'blue' galaxies is in terms of $g - r$ colour, while theirs is in terms of $U - V$. Finally, Brown et al. also conclude that the fraction of stellar mass within the satellite population increases with host halo mass, which is consistent with our results and Skibba et al. (2007).

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REFERENCES

Adelman-McCarthy J. K. et al., 2006, ApJS, 162, 38
Beisbart C., Kerscher M., 2000, ApJ, 545, 6
Bell E. F., McIntosh D. H., Katz N., Weinberg M. D., 2003, ApJS, 149, 289
Berlind A. A. et al., 2006a, ApJS, 167, 1 (B06)
Berlind A. A., Kazin E., Blanton M. R., Pueblas S., Scoccimarro R., Hogg D. W., 2006b, ApJ submitted (astro-ph/0610524)
Blanton M. R., Berlind A. A., 2007, ApJ, 664, 791
Blanton M. R., Eisenstein D., Hogg D. W., Schlegel D. J., Brinkmann J., 2005a, ApJ, 629, 143
Blanton M. R. et al., 2005b, AJ, 129, 2562
Brown M. J. I. et al., 2008, ApJ, 682, 937
Cattaneo A., Dekel A., Faber S. M., Guiderdoni B., 2008, MNRAS, 387, 567
Coil A. et al., 2008, ApJ, 672, 153
Conroy C., Wechsler R. H., 2008, preprint (astro-ph/0805.3346)
Font A. S. et al., 2008, MNRAS, 389, 1619
Gilbank D. G., Balogh M. L., 2008, MNRAS, 385, L116
Gunn J. E. et al., 1998, AJ, 116, 3040
Gunn J. E. et al., 2006, AJ, 131, 2332
Hansen S. M., McKay T. A., Wechsler R. H., Annis J., Sheldon E. S., Kimball A., 2005, ApJ, 633, 122
Hansen S. M., Sheldon E. S., Wechsler R. H., Koester B. P., 2007, preprint (astro-ph/0710.3780)
Kang X., van den Bosch F. C., 2008, ApJ, 676, L101
Loh Y.-S., Ellingson E., Yee H. K. C., Gilbank D. G., Gladders M. D., Barrientos L. F., 2008, ApJ, 680, 214
Martínez H. J., Muriel H., 2006, MNRAS, 370, 1003
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Sheth R. K., 2005, MNRAS, 364, 796
Skibba R. A., Sheth R. K., 2008, MNRAS, in press (astro-ph/0805.0310) (SS08)
Skibba R. A. et al., 2008, MNRAS, submitted (astro-ph/0811.3970)
Skibba R. A., Sheth R. K., Connolly A. J., Scranton R., 2006, MNRAS, 369, 68
Skibba R. A., Sheth R. K., Martino M. C., 2007, MNRAS, 382, 1940
Tinker J. L., Conroy C., Norberg P., Patiri S. G., Weinberg D. H., Warren M. S., 2008, ApJ, 686, 53
van den Bosch F. C., Weinmann S. M., Yang X., Mo H. J., Li C., Jing Y. P., 2005, MNRAS, 361, 1203
van den Bosch F. C., Aquino D., Yang X., Mo H. J., Pasquali A., McIntosh D. H., Weinmann S. M., Kang X., 2008a, MNRAS, 387, 79
van den Bosch F. C., Pasquali A., Yang X., Mo H. J., Weinmann S., McIntosh D. H., Aquino D., 2008b, preprint (astro-ph/0805.0002)
Wang Y., Yang X., Mo H. J., van den Bosch F. C., Weinmann S. M., Chu Y., 2008, ApJ, 687, 919
Weinmann S. M., van den Bosch F. C., Yang X., Mo H. J., 2006, MNRAS, 366, 2
Yang X., Mo H. J., van den Bosch F. C., Jing Y. P., 2005a, MNRAS, 356, 1293
Yang X., Mo H. J., van den Bosch F. C., Weinmann S. M., Li C., Jing Y. P., 2005b, MNRAS, 362, 711
Yang X., Mo H. J., van den Bosch F. C., Pasquali A., Li C., Barden M., 2007, ApJ, 671, 153 (Y07)
Yang X., Mo H. J., van den Bosch F. C., 2008, ApJ, 676, 248
York D. G. et al., 2000, AJ, 120, 1579
Zehavi I. et al., 2005, ApJ, 630, 1
Zheng Z., Coil A. L., Zehavi I., 2007, ApJ, 667, 760

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