Satellite Ecology: The Dearth of Environment Dependence

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ABSTRACT
Using the Sloan Digital Sky Survey (SDSS) galaxy group catalogue of Yang et al. (2007), we study the average colour (representing star formation history) and average concentration (representing mass assembly history) of satellite galaxies as function of (i) their stellar mass, (ii) their group mass, and (iii) their group-centric radius. We find that the colours and concentrations of satellite galaxies are (almost) completely determined by their stellar mass. In particular, at fixed stellar mass, the average colours and concentrations of satellite galaxies are independent of either halo mass or halo-centric radius. We find clear evidence for mass segregation of satellite galaxies in haloes of all masses, and argue that this explains why satellites at smaller halo-centric radii are somewhat redder and somewhat more concentrated. In addition, the weak colour and concentration dependence of satellite galaxies on halo mass is simply a reflection of the fact that more massive haloes host, on average, more massive satellites. Combining these results with the fact that satellite galaxies are, on average, redder and somewhat more concentrated than central galaxies of the same stellar mass, the following picture emerges: galaxies become redder and somewhat more concentrated once they fall into a bigger halo (i.e., once they become a satellite galaxy). This is a clear manifestation of environment dependence. However, there is no indication that the magnitude of the transformation (or its timescale) depends on environment; a galaxy undergoes a transition when it becomes a satellite, but it does not matter whether it becomes a satellite of a small (Milky Way sized) halo, or of a massive cluster. We discuss the implication of this 'dearth' of environment dependence for the physical processes responsible for transforming satellite galaxies.

Key words: galaxies: clusters: general – galaxies: haloes – galaxies: evolution – galaxies: general – galaxies: statistics – methods: statistical

1 INTRODUCTION

In the current paradigm of galaxy formation, it is believed that virtually all galaxies initially form as disks due to the cooling of gas with non-zero angular momentum in virialized dark matter haloes. During their subsequent evolution, star-forming disk galaxies may be transformed into non star-forming early-types via a variety of transformation mechanisms. Two disk galaxies of roughly equal mass may merge to produce a spheroidal galaxy (Toomre & Toomre 1972; Negroponte & White 1983), or a disk galaxy may be transformed into a spheroid due to the cumulative effect of many high speed (impulsive) encounters, called harassment (Farouki & Shapiro 1981; Moore et al. 1996). When a small

halo is accreted by a larger halo its hot, diffuse gas may be stripped thus removing its fuel for future star-formation (Larson, Tinsley & Caldwell 1980; Kauffmann, White & Guiderdoni 1993; Balogh, Navarro & Morris 2000). Following Balogh & Morris (2000) we refer to this process, that results in a fairly gradual decline of the satellite's star formation rate, as strangulation. When the external pressure is sufficiently high, ram-pressure stripping may also remove the entire cold gas reservoir of the satellite galaxy (Gunn & Gott 1972; Quilis, Moore & Bower 2000), resulting in an extremely fast quenching of its star formation. Finally, along its orbit a satellite galaxy is subject to tidal forces which may cause tidal stripping and heating.

The efficiencies of all these various transformation mechanisms are expected to be strong functions of environment. Ram-pressure stripping requires a dense inter-galactic

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medium and is therefore believed to occur predominantly in massive clusters. The same holds for galaxy harassment, which requires the presence of many, relatively massive satellite galaxies in order to be efficient. Galaxy merging, on the other hand, is thought to be suppressed in massive clusters, and to preferentially occur in group-sized haloes, while tidal stripping and heating should play a role in all dark matter haloes with little dependence on their virial mass. Finally, strangulation can result from both ram-pressure and tides, and it is difficult to predict how its efficiency would scale with halo mass. The various transformation mechanisms also have very different outcomes: while mergers and harassment are thought to transform disk galaxies into spheroids, ram-pressure stripping and strangulation only affect the star formation activity of the galaxy without changing its global morphology. Therefore, an assessment of galaxy properties as function of their environment sheds light on which of these transformation mechanisms operates in what environment and with what efficiency.

Numerous authors have investigated the relation between environment and morphology (e.g., Hubble 1936; Oemler 1974; Dressler 1980; Postman & Geller 1984; Whitmore, Gilmore & Jones 1993; Hashimoto & Oemler 1999; Goto et al. 2003; McIntosh, Rix & Caldwell 2004; Kuehn & Ryden 2005; Blanton et al. 2005b), between environment and star formation rate (e.g., Hashimoto et al. 1998; Lewis et al. 2002; Domínguez et al. 2002; Gómez et al. 2003; Balogh et al. 2004a; Tanaka et al. 2004; Kauffmann et al. 2004; Kelm, Focardi & Sorrentino 2005), and between environment and colour (e.g.,Tanaka et al. 2004; Balogh et al. 2004b; Hogg et al. 2004; Weinmann et al. 2006a; Blanton & Berlind 2007). These and other studies have clearly established that galaxies in denser environments are more massive, redder, more concentrated, less gas-rich and have an older stellar population. Within the paradigm outlined above, the transformation mechanisms thus seem to preferentially occur in denser environments. However, a more detailed interpretation of these findings is complicated by the fact that various galaxy properties are strongly correlated even at a fixed environment. An important outstanding question, therefore, is which relationships with environment are truly causal, and which are just reflections of other more fundamental correlations that are not environment dependent.

With the advent of large redshift surveys, such as the Two-Degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) and the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002), several authors have started to address these questions using multi-variate statistics. Most of these studies agree that morphological properties are less strongly related to environment than star-formation related properties such as colour and emission-line flux (Kauffmann et al. 2004; Blanton et al. 2005b; Quintero et al. 2006). This is also in line with recent results indicating that the relation between star formation indicators and environment is at least partially independent of galaxy morphology (Balogh et al. 1998; Koopmann & Kenney 1998; Poggianti et al. 1999; Christlein & Zabludoff 2005).

A physical interpretation of all these results in terms of the transformation mechanisms discussed above is hampered by two shortcomings. First of all, in most studies of environment dependence, especially those based on large redshift surveys such as the 2dFGRS or the SDSS, one does not split the galaxy population into central galaxies (those at rest at the centers of their dark matter haloes) and satellite galaxies (those orbiting a central galaxy). This is important since most of the transformation mechanisms discussed above (tidal stripping and heating, strangulation, ram-pressure stripping, and harassment) mainly operate on satellite galaxies. However, satellite galaxies only make up roughly 20 to 40 percent of the entire galaxy population (Mandelbaum et al. 2006; van den Bosch et al. 2007a; Tinker et al. 2007; Cacciato et al. 2008). Therefore, unless one specifically focuses on satellite galaxies, the environmental impact of the aforementioned processes may not be apparent.

A second problem that hampers a physical interpretation of the results is the use of non-intuitive environment indicators. Most studies parameterize 'environment' through the projected number density of galaxies, either within some fixed metric aperture, or out to the distance of the $n^{\rm th}$ nearest neighbor (with n typically in the range 5-10). Although these environment indicators are relatively easy to measure from large galaxy redshift surveys, they are difficult to interpret in terms of more physical quantities (see discussions in Kauffmann et al. 2004 and Weinmann et al. 2006a). Arguably the most natural environment indicators are the halo mass and the halo-centric distance, with the virial radius $R_{\rm vir}$ being the natural scale of environment dependence. This is supported by various observational studies which have shown that the environment dependence of galaxies seems to be restricted to scales $R < R_{\rm vir}$ (e.g., Mo et al. 2004; Kauffmann et al. 2004; Quintero et al. 2005; Blanton et al. 2006; Blanton & Berlind 2007). Galaxy properties as function of halo mass can be studied using either clustering data or using galaxy group catalogues. The former is less direct as it requires modelling in order to translate an observed correlation function into a description of halo occupation statistics. Nevertheless, a great deal of progress in this area has been made in recent years (e.g., Yang et al. 2003; van den Bosch et al. 2003, 2007a; Scranton 2003; Magliochetti & Porciani 2003; Zehavi et al. 2005; Tinker et al. 2005; Collister & Lahav 2005; Li et al. 2006; Wang et al. 2007a; Cacciato et al. 2008). Galaxy group catalogues allow a more direct study of the relation between the properties of galaxies and their dark matter haloes. In particular, it assigns a halo to each individual galaxy, whereas the clustering method only assigns haloes to galaxies in a statistical sense. Another advantage of using galaxy group catalogues is that it is straightforward to separate the galaxy population into centrals and satellites and to compute their halo-centric distances (in projection).

In van den Bosch et al. (2007b, hereafter Paper I), we used a large galaxy group catalogue constructed from the SDSS to study the impact of satellite specific transformation processes. We compared the colours and concentrations of satellites galaxies to those of central galaxies of the same stellar mass, adopting the hypothesis that the latter are the progenitors of the former. On average, satellite galaxies were found to be redder and more concentrated than central galaxies of the same stellar mass, indicating that satellite specific transformation processes do indeed operate. Central-satellite pairs that are matched in both stellar mass and colour, however, show no average concentration difference, indicating that the transformation mechanisms

operating on satellites affect colour more than morphology. We also showed that the colour and concentration differences of matched central-satellite pairs are completely independent of the mass of the host halo (not to be confused with the subhalo) of the satellite galaxy, indicating that satellite specific transformation mechanisms are equally efficient in host haloes of all masses. In this paper we extend this study by investigating the ecology of satellite galaxies. In particular, we investigate how the colours and concentrations of satellite galaxies are correlated with their stellar mass, their halo mass, and their (projected) halo-centric distance. We believe that this is the optimal strategy to investigate the effects of satellite-specific transformation mechanisms such as strangulation, ram-pressure stripping and harassment. Throughout we adopt a flat ΛCDM cosmology with $\Omega_m = 0.238$ and $\Omega_\Lambda = 0.762$ (Spergel et al. 2007) and we express units that depend on the Hubble constant in terms of $h \equiv H_0/100 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$.

2 DATA

The analysis presented in this paper is based on the SDSS DR4 galaxy group catalogue of Yang et al. (2007; hereafter Y07). This group catalogue is constructed applying the halo-based group finder of Yang et al. (2005a) to the New York University Value-Added Galaxy Catalogue (NYU-VAGC; see Blanton et al. 2005), which is based on SDSS DR4 (Adelman-McCarthy et al. 2006). From this catalogue we select all galaxies in the Main Galaxy Sample with an extinction corrected apparent magnitude brighter than $r = 18$, with redshifts in the range $0.01 \leq z \leq 0.20$ and with a redshift completeness $\mathcal{C} > 0.7$. As described in Y07, we use this sample of galaxies to construct three group samples: Sample I, which only uses the 362356 galaxies with measured redshifts from the SDSS, Sample II which also includes 7091 galaxies with SDSS photometry but with redshifts taken from alternative surveys, and Sample III which includes an additional 38672 galaxies that lack a redshift due to fiber-collisions, but which we assign the redshift of its nearest neighbour (cf. Zehavi et al. 2002). Unless specifically stated otherwise the present analysis is based on Sample II, which consists of 369447 galaxies distributed over 301237 groups.

The magnitudes and colours of all galaxies are based on the standard SDSS petrosian technique (Petrosian 1976; Strauss et al. 2002), have been corrected for galactic extinction (Schlegel, Finkbeiner & Davis 1998), and have been K-corrected and evolution corrected (hereafter E-corrected) to $z = 0.1$, using the method described in (Blanton et al. 2003a). We use the notation $^{0.1}M_r$ to indicate the resulting absolute magnitude in the r-band. In addition, for each galaxy we compute a stellar mass, M_*, using the relations between stellar mass-to-light ratio and colour of Bell et al. (2003; see Y07 for details). In addition to the magnitude and stellar mass, we also use the $^{0.1}(g-r)$ colour of each galaxy as well as its concentration $C = r_{90}/r_{50}$. Here r_{90} and r_{50} are the radii that contain 90 and 50 percent of the Petrosian r-band flux, respectively. In what follows, we interpret the $^{0.1}(g-r)$ colour as an indicator of the galaxy's star formation history (mean stellar age), though we acknowledge that because of dust attenuation this connection may not be very tight. In addition, we interpret the concentration pa-

rameter as reflecting the galaxy's mass-assembly history. As shown by Strateva et al. (2001), C is a reasonable proxy for Hubble type, with $C > 2.6$ corresponding to an early-type morphology. The link to the mass-assembly history owes to the common belief that a galaxy's morphology (in particular its disk-to-bulge ratio), is related to the importance of major mergers (and other violent disturbances) during its mass assembly.

For each group in our catalogue we have two estimates of its dark matter halo mass M_h: one based on the ranking of its total characteristic luminosity, and the other based on the ranking of its total characteristic stellar mass. As shown in Y07, both halo masses agree very well with each other, with an average scatter that decreases from ~ 0.1 dex at the low mass end to ~ 0.05 dex at the massive end. In addition, detailed tests with mock galaxy redshift catalogues have demonstrated that our group masses are more reliable than those based on the velocity dispersion of the group members (Yang et al. 2005b; Weinmann et al. 2006a; Y07). Further support for the accuracy of our group masses comes from an analysis of their clustering properties (Wang et al. 2007b). In this paper we adopt the group masses based on the stellar mass ranking. We have verified, though, that none of our results change significantly if we adopt the luminosity-rank based masses instead (see §4.1)

Finally, for each group member we determine the projected radius R_{proj} from the luminosity weighted group center using the angular separation and the angular diameter distance at the redshift of the group. We normalize these projected radii by the characteristic radius of the group, R_{180}, which is defined as the radius inside of which the dark matter halo associated with the group has an average overdensity of 180. This radius is computed from the mass and redshift of the group using equation (5) in Y07.

2.1 Sample definition

From Sample II we select all satellite galaxies, defined as all group members that are not the most massive group member, of groups with an assigned halo mass in the range $12.0 \leq \log[M_h/(h^{-1} \, \mathrm{M_\odot})] \leq 15.0$. In addition, the satellites are required to have stellar masses in the range $9.0 \leq \log[M_*/(h^{-2} \, \mathrm{M_\odot})] \leq 11.5$ and normalized projected radii $R_{\mathrm{proj}}/R_{180} \leq 1.0$. Neither of these criteria is particularly restrictive, so that the vast majority ($\sim 88\%$) of all satellite galaxies in our group catalogue make it into the sample used here. The resulting sample consists of 60245 satellite galaxies, which we use to study the interrelations between colour, concentration, halo mass, stellar mass, and projected halo-centric radius.

Note that this is not a volume-limited sample. Consequently, the sample suffers from Malmquist bias, causing an artificial increase of the average luminosity (and also stellar mass) of the satellite galaxies with increasing redshift. To correct for this bias, we weight each galaxy by $1/V_{\mathrm{max}}$, where V_{max} is the comoving volume of the Universe out to a comoving distance at which the galaxy would still have made the selection criteria of our sample. In what follows all distributions are weighted by $1/V_{\mathrm{max}}$, unless specifically stated otherwise
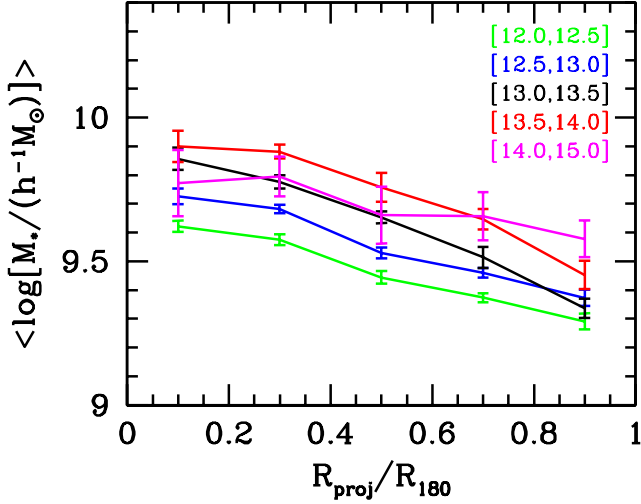
Figure 1. The average satellite mass as a function of the normalized, projected radius from the group center. Different lines correspond to different bins in halo mass, as indicated. Two trends are evident. First of all, at a given R_{proj}/R_{180} more massive haloes contain, on average, more massive satellites. Secondly, there is clear evidence for mass segregation, with more massive satellites (in a given halo mass), residing at smaller (projected) radii.

3   RESULTS

The main aim of this paper is to investigate the conditional probability functions $P(^{0.1}(g-r)|M_*, M_h, R_{proj})$ and $P(C|M_*, M_h, R_{proj})$ of satellite galaxies. In particular, we wish to establish which of the conditionals, M_*, M_h or R_{proj}/R_{180}, is most relevant for setting the colours (related to the star formation histories) and concentrations (related to the mass-assembly histories) of satellite galaxies.

In order to facilitate the interpretation of these probability functions and their moments we first focus on the interrelations between the three conditionals. These are nicely summarized in Fig. 1, which plots the average stellar mass of the satellite galaxies, $\langle \log[M_*/(h^{-2}\ M_\odot)]\rangle$, as function of R_{proj}/R_{180} for different bins in halo mass. Two trends are clearly apparent: at fixed R_{proj}/R_{180}, the average satellite mass increases with increasing halo mass, while at fixed M_h, the average satellite mass decreases with increasing R_{proj}/R_{180}. The former simply reflects that the characteristic mass (or luminosity) of satellite galaxies increases with increasing halo mass (cf., Yang et al. 2005c; Zheng et al. 2005; Skibba, Sheth & Martino 2007; Yang, Mo & van den Bosch 2008). The latter indicates that the spatial distribution of satellite galaxies in dark matter haloes has undergone some mass segregation, and is consistent with the luminosity segregation observed in galaxy clusters (e.g., Rood & Turnrose 1968; Quintana 1979; den Hartog & Katgert 1996; Adami, Biviano & Mazure 1998; Lares, Lambas & Sánchez 2004; McIntosh et al. 2005). As we will see below, these two trends are essential for understanding the various relations between colour and concentration on the one hand and halo mass, stellar mass, and halo-centric radius on the other.

3.1   First Moments

As a first step in our investigation of $P(^{0.1}(g-r)|M_*, M_h, R_{proj})$ and $P(C|M_*, M_h, R_{proj})$ of satellite galaxies we focus on their first moments. Fig. 2 shows the relations between the $^{0.1}(g-r)$ colour of satellite galaxies and their halo mass M_h, their stellar mass M_*, and their normalized, projected, halo-centric radius, R_{proj}/R_{180}. The upper panels show contour plots of the various distributions, while the solid lines reflect the average colour. Panel (a) shows that the colour distribution of satellite galaxies has a remarkably weak dependence on halo mass: over the entire range of halo masses probed the colour distribution is clearly skewed, with a relatively narrow peak near $^{0.1}(g-r) = 0.85$ and an extended wing to bluer colours. There is a weak trend, though, that the average satellites are somewhat bluer in less massive haloes.

The colour-stellar mass distribution, shown in panel (b), reveals a pronounced and narrow red sequence which is clearly tilted with more massive red sequence satellites being redder. In fact, this colour-stellar mass relation of satellite galaxies looks very similar to that for the entire galaxy population (cf. Fig. 7 in Paper 1). We emphasize that this is not a trivial result since satellite galaxies only contribute between 20 and 40 percent of the entire galaxy population (see §1). As discussed in Paper I, it implies that centrals and satellites of the same stellar mass have very similar colour distributions, which already puts tight constraints on the efficiencies with which the various satellite specific transformation processes operate.

Panel (c) of Fig. 2 shows the distribution of satellite galaxies as function of $^{0.1}(g-r)$ and R_{proj}/R_{180}. First of all, the number of satellites seems to peak around $R_{proj}/R_{180} = 0.15$; the rapid decline toward smaller radii, however, is an artefact of the data sample, and owes to the problem of fiber collisions in the SDSS. Since galaxies lost from the survey due to fiber collisions do not have any specific colours or concentrations, this has no impact on our results, as we demonstrate in §4.2. The steady decline in the number of satellites at larger radii is genuine, and simply reflects the fact that the number density of satellites decreases with increasing halo-centric radius faster than r^{-1} (e.g., Beers & Tonry 1986; Carlberg, Yee & Ellingson 1997a; van der Marel et al. 2000; Lin, Mohr & Stanford 2004; van den Bosch et al. 2005; Chen 2007). Finally, there is also a clear indication that satellites at larger halo-centric radii are, on average, bluer. Again, this is consistent with numerous other studies (e.g., Biviano et al. 1996; Colless & Dunn 1996; Carlberg et al. 1997b; Lares et al. 2004).

The lower six panels of Fig. 2 show the average $^{0.1}(g-r)$ colour of satellite galaxies as function of M_h (left column), M_* (middle column) and R_{proj}/R_{180} (right column). Lines of different colours correspond to different bins in one of the other two parameters, as indicated at the top of each panel. Errorbars (often barely visible) reflect the standard deviations obtained using the jackknife technique. To that extent we divide the group catalogue in $N = 20$ subsamples of roughly equal size, and recalculate the mean colour 20 times, each time leaving out one of the 20 subsamples. The jackknife estimate of the standard deviation then follows from
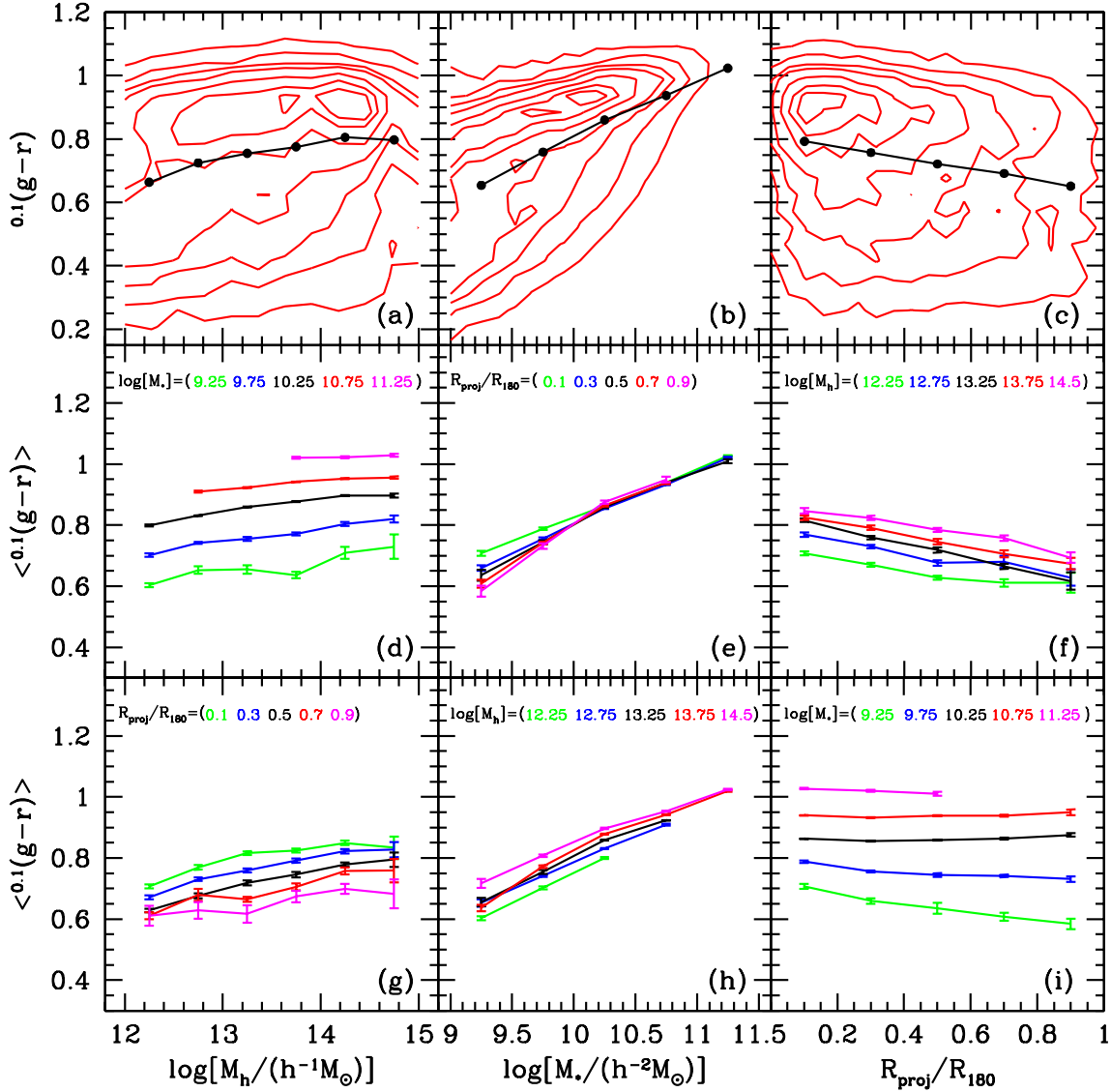
Figure 2. The contours in the upper panels reflect the $1/V_{\mathrm{max}}$-weighted distributions of satellite colours as functions of halo mass M_h (left), stellar mass M_* (middle) and normalized, projected radius $R_{\mathrm{proj}}/R_{180}$ (right). The connected solid dots indicate the average satellite colour as function of these quantities. The lower six panels show the average colour again as function of these three quantities, but this time split in bins of one of the other two quantities, as indicated. The values at the top of each panel indicate the central values of each bin. In particular, for $R_{\mathrm{proj}}/R_{180}$ we consider bins of $[0.0, 0.2]$ (green lines), $[0.2, 0.4]$ (blue lines), $[0.4, 0.6]$ (black lines), $[0.6, 0.8]$ (red lines) and $[0.8, 1.0]$ (magenta lines). For the stellar mass we adopt bins in $\log[M_*/(h^{-2}\,\mathrm{M_\odot})]$ of $[9.0, 9.5]$ (green lines), $[9.5, 10.0]$ (blue lines), $[10.0, 10.5]$ (black lines), $[10.5, 11.0]$ (red lines) and $[11.0, 11.5]$ (magenta lines). And finally, for the halo mass we use bins in $\log[M_h/(h^{-1}\,\mathrm{M_\odot})]$ of $[12.0, 12.5]$ (green lines), $[12.5, 13.0]$ (blue lines), $[13.0, 13.5]$ (black lines), $[13.5, 14.0]$ (red lines) and $[14.0, 15.0]$ (magenta lines). Note that the last bin in M_h is twice as broad as the other bins, which is done to assure a sufficient number of satellite galaxies to be able to calculate reliable statistics. Errorbars (sometimes barely visible) indicate the standard variance obtained from 20 jackknife samples. Note how the average colours of satellite galaxies at fixed stellar mass are virtually independent of their environment (halo mass and halo-centric radius).

$$\sigma_x = \sqrt{\frac{N-1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{1}$$

with x_i the average colour obtained from jackknife sample i.

Panel (d) of Fig. 2 shows that at fixed stellar mass the average colour of satellite galaxies depends only very weakly on halo mass. On the other hand, at fixed halo mass, there is a very strong dependence on stellar mass, with more massive

satellites being redder. The same trend is also visible from panel (h), which shows the average colour as a function of stellar mass for different bins in halo mass. Panels (f) and (g) show that the average satellite colour becomes slightly bluer with increasing halo-centric radius at fixed halo mass. At the same time, satellites at a fixed $R_{\mathrm{proj}}/R_{180}$ are also somewhat redder if they reside in more massive haloes. However, as is evident from panel (e), at fixed stellar mass there is no discernable dependence of the average satellite colour on $R_{\mathrm{proj}}/R_{180}$.
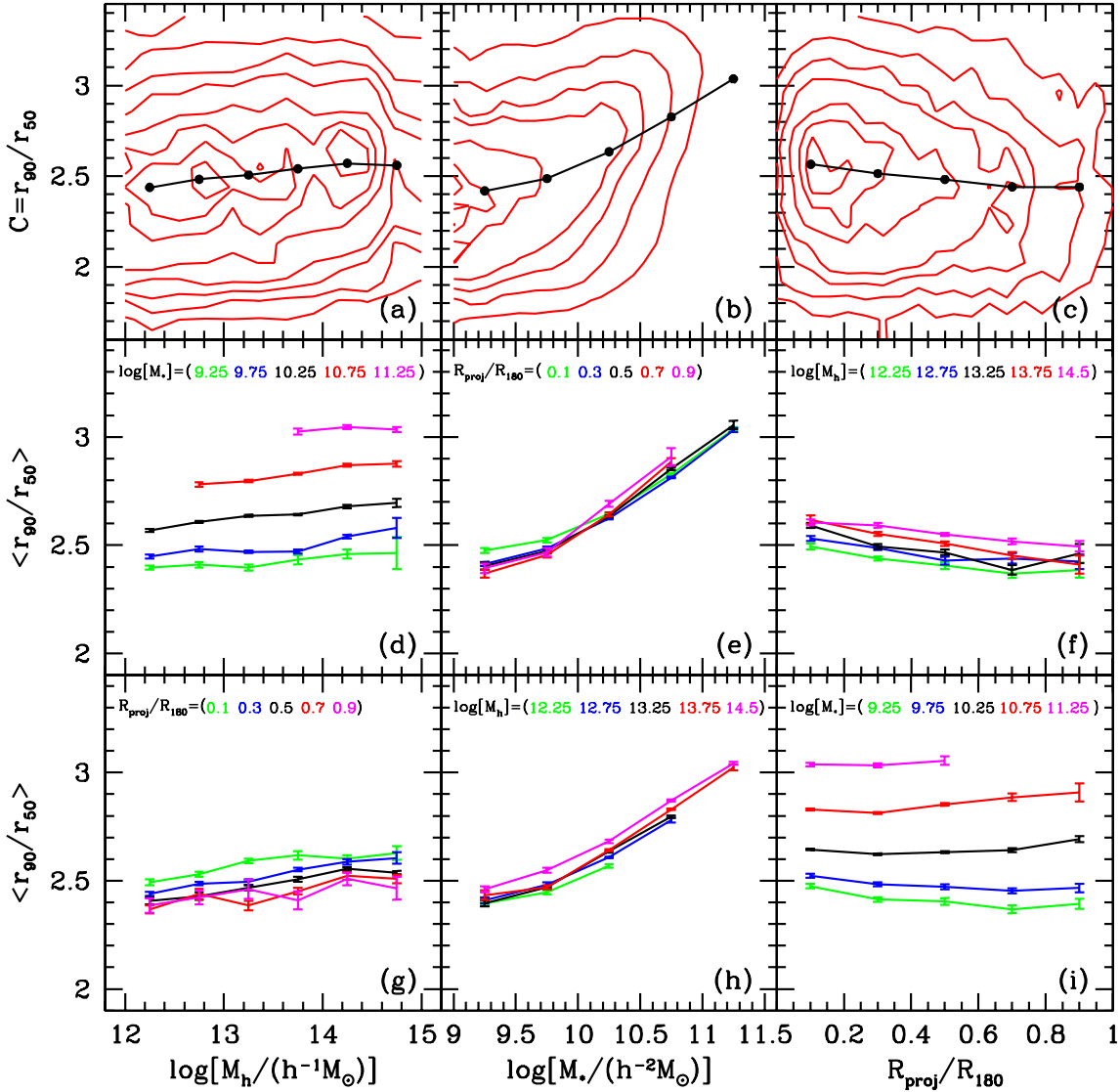
Figure 3. Same as Fig. 2 but for the concentration parameter $C = r_{90}/r_{50}$ rather than the colour. Note that the overall trends are remarkably similar. In particular, at fixed stellar mass the average concentration of satellite galaxies is virtually independent of their environment (halo mass and halo-centric radius). See text for a detailed discussion.

Fig. 3 shows the same as Fig. 2 but now for the average concentrations of the satellite galaxies, rather than their colours. Note that the overall behavior is remarkably similar to the case of the average colours: (i) at fixed halo mass there is a strong dependence on stellar mass (more massive satellites are more centrally concentrated), while at fixed stellar mass there is almost no halo mass dependence; (ii) at fixed halo mass there is a weak (barely significant) dependence on halo-centric radius (satellites at larger $R_{\rm proj}/R_{180}$ are less concentrated), and at fixed $R_{\rm proj}/R_{180}$ there is a similarly weak dependence on M_h; (iii) at fixed $R_{\rm proj}/R_{180}$ satellite concentrations depend strongly on stellar mass, while at fixed stellar mass there is no discernable dependence on $R_{\rm proj}/R_{180}$.

To summarize, the average colours and concentrations of satellite galaxies show almost no sign of intrinsic environment dependence. Rather, they seem to be completely determined by their stellar masses: to good accuracy Figs. 2

and 3 can be used to read off the average colours and concentrations of satellite galaxies of a given stellar mass *without having to know anything about their environment*. At least a significant part of the (already weak) dependence on halo mass is not causal, but merely owes to the fact that more massive haloes contain more massive satellites (cf. Fig. 1). Similarly, the mild dependence on $R_{\rm proj}/R_{180}$ seems to owe mainly to mass-segregation, rather than to a causal relation between colour and halo-centric radius. This remarkable dearth of environment dependence for satellite galaxies is the main results of this paper. As we discuss in §6, it has profound implications for theories of galaxy formation. The remainder of this paper is therefore concerned with addressing the robustness and statistical significance of these findings, and with reconciling them with previous, at first sight antithetical, results.
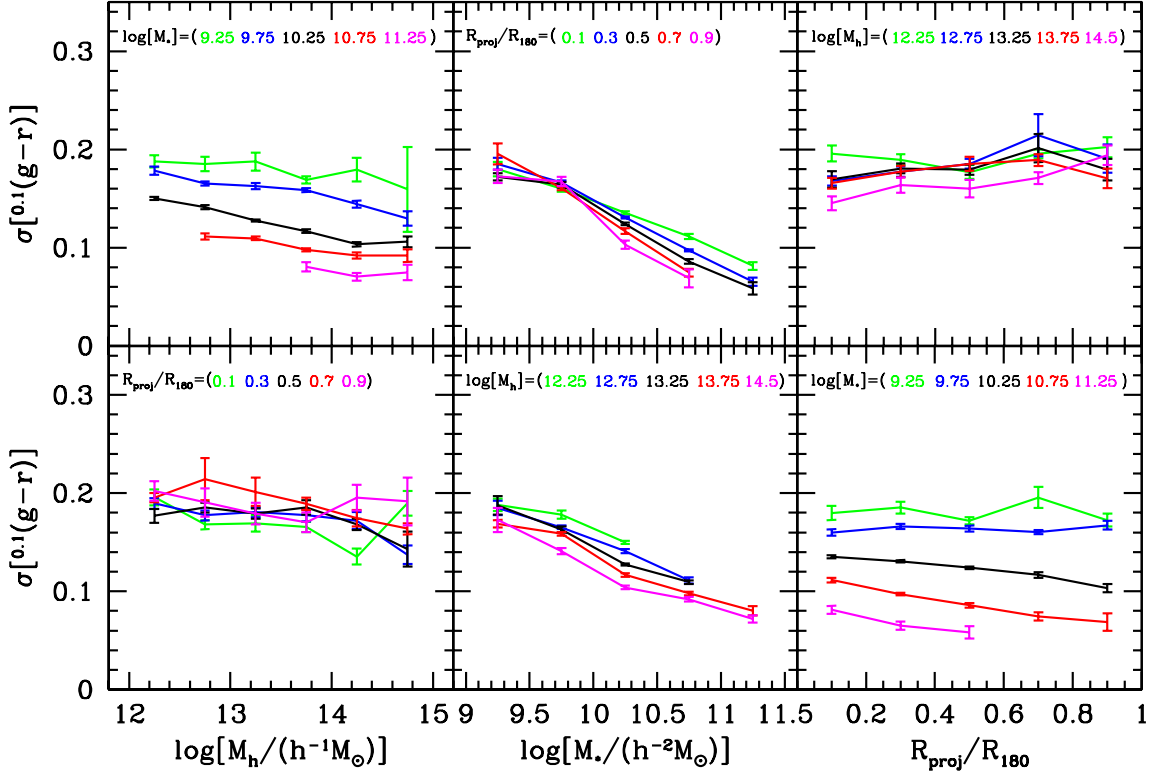
Figure 4. The standard deviations $\sigma[^{0.1}(g-r)]$ of the colour distribution of satellite galaxies as function of halo mass (left panels), stellar mass (middle panels) and projected radius (right panels). Lines of different colour correspond to different bins in one of the other three conditionals, as indicated. The values at the top of each panel indicate the central values of each bin, and the colour coding is the same as in Fig. 2. Errorbars reflect the standard deviations obtained from 20 jackknife samples.

3.2 Higher order moments

The above analysis, based on the average colours and concentrations, suggests that the star formation histories and morphologies of satellite galaxies are virtually independent of their environment. Instead, they seem to be governed almost entirely by their stellar masses. However, the averages only reflect the first moments of the full probability distributions $P(^{0.1}(g-r)|M_*, M_h, R_{\mathrm{proj}})$ and $P(C|M_*, M_h, R_{\mathrm{proj}})$. Since two distributions can be very different and yet have the same average, the above conclusion is only valid for the first moments of the colour and concentration distributions of satellite galaxies.

As a logical next step, we therefore now focus on the second moments. Fig. 4 shows the standard deviations $\sigma[^{0.1}(g-r)]$ as functions of the three conditionals. The overall behavior is very similar as for the averages: (i) at fixed halo mass there is a strong dependence on stellar mass, while at fixed stellar mass, the dependence on halo mass is much weaker, (ii) at fixed $R_{\mathrm{proj}}/R_{180}$ there is a strong dependence on M_*, but at fixed stellar mass there is virtually no dependence on projected radius. Thus the second moments of $P(^{0.1}(g-r)|M_*, M_h, R_{\mathrm{proj}})$ depend most strongly on M_*, with only a weak dependence on M_h, and virtually no dependence on $R_{\mathrm{proj}}/R_{180}$. Fig. 5 shows the same but now for the satellite concentrations. Contrary to the colours, the standard deviations of $P(C|M_*, M_h, R_{\mathrm{proj}})$ seem to be almost independent of stellar mass. In fact, within the errors,

there is no really significant dependence on any of the three conditionals.

We can therefore conclude that the statement that the star formation histories and morphologies of satellite galaxies are (virtually) independent of their environment remains valid up to the second moments of their respective distribution functions.

Expanding this investigation, we could next present similar plots for the third moments, the fourth moments, etc. However, already for the third moment (or equivalently, the skewness) we find that the results become too noisy (i.e., the jackknife errors are too large) to make any quantitative assessment. Therefore, we choose to show (a subset of) the full probability distributions instead. The upper panels of Fig. 6 show the full colour distributions of satellite galaxies of a given stellar mass (indicated at the top of each panel) for three different bins in halo mass (indicated by the values in square brackets). The lower panels, on the other hand, show the colour distributions of satellites in haloes of a given mass for three different bins in stellar mass. The small vertical bars near the top of each panel indicate the averages of the corresponding distributions. Only two distributions are shown in the upper right-hand and lower left-hand panels, since haloes with $12 \leq \log[M_h/(h^{-1}\,\mathrm{M_\odot})] \leq 12.5$ do not contain satellite galaxies with $\log[M_*/(h^{-2}\,\mathrm{M_\odot})] \geq 11$. As is clear from a comparison of the upper and lower panels, the colour distributions of satellite galaxies are far more dependent on stellar mass than on halo mass. However, it is also clear that satel-
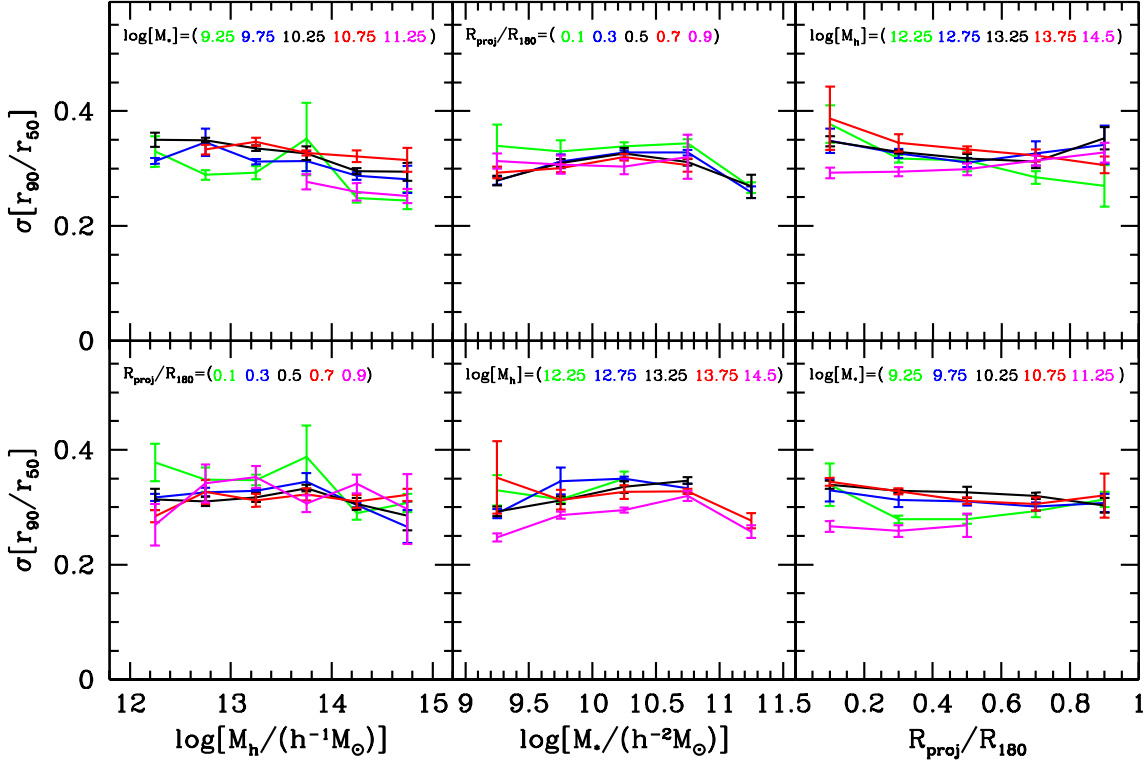
Figure 5. Same as Fig. 4 but for the concentrations of satellites rather than their colour.

lite galaxies of the same stellar mass that reside in haloes of different masses have colour distributions that are not exactly the same. In fact, there are significant differences, though they typically relate to higher order moments of the distributions. For example, in the upper left panel, the distributions for $\log[M_h/(h^{-1}\,M_\odot)] \geq 13.0$ are clearly negatively skewed, while that for $12 \leq \log[M_h/(h^{-1}\,M_\odot)] \leq 12.5$ has a positive skewness. We therefore conclude that the dependence of satellite colour on environment is extremely mild, and only apparent from the higher-order moments of the colour distributions.

Finally, Fig. 7 shows the distributions of satellite concentrations for the same bins in halo mass and stellar mass as in Fig. 6. The conclusions are the same as for the colours: at fixed stellar mass the distributions only depend very weakly on halo mass (even more weakly than in the case of the colour distributions), while at fixed halo mass, the distributions depend very strongly on stellar mass.

4 TESTING THE ROBUSTNESS

In order to check the robustness of the above results, we perform a number of tests, which we now describe in turn.

4.1 Group masses

As mentioned in §2 each group in our catalogue has two estimates for the mass of its corresponding dark matter halo: one based on its ranking of the characteristic luminosity, defined as the total luminosity of all group members with $^{0.1}M_r - 5\log h \leq -19.5$, and one based on its ranking of the

characteristic stellar mass, defined as the total stellar mass of all group members with $^{0.1}M_r - 5\log h \leq -19.5$ (see Y07 for details). Thus far we have used the latter. Since the stellar masses are determined from the colours of the galaxies, one could potentially be worried that this has somehow influenced the dependence of satellite colour on halo mass. To test this, we repeat our analysis using the halo masses based on the luminosity ranking. We also change the definition of a satellite galaxy: previously a satellite galaxy was defined as any group member that is not the most massive, while now a satellite galaxy is any group member that is not the most luminous. In a few cases this turns a satellite galaxy into a central galaxy, and vice versa. The left-hand column of Fig. 8 shows the results thus obtained, and which should be compared to the middle column of Fig. 2. Since we only consider satellite galaxies that reside in groups with an assigned halo mass in the range $12.0 \leq \log[M_h/(h^{-1}\,M_\odot)] \leq 15.0$, the satellite samples in both cases are not exactly the same. In fact, when using the group masses based on the luminosity ranking we obtain a sample of 60835 satellites, compared to 60245 in the case of the stellar mass ranking. This difference, however, is extremely small, so that the upper two panels in the first column of Fig. 8 are almost identical to those in the middle column of Fig. 2. The more interesting comparison regards the lower panels in these columns, where the average colours as function of stellar mass are shown for different bins in halo mass. As can be seen, the results are almost indistinguishable, indicating that our results are extremely robust to whether we use the halo masses based on the luminosity ranking or the stellar mass ranking. We have verified that this is also the case for all other statistics presented in this paper.
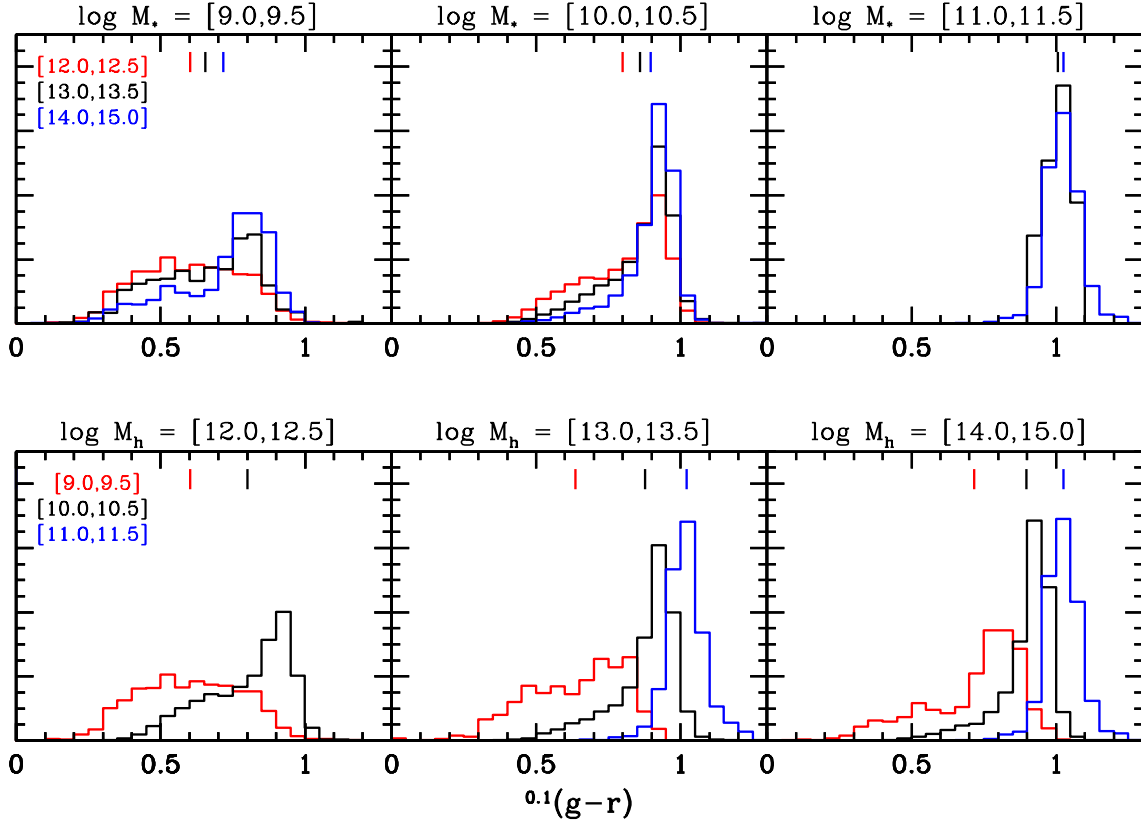
Figure 6. Histograms of the colour distributions of satellites for various bins in halo mass and stellar mass. In the upper panels different colours correspond to satellites of the same stellar mass (indicated at the top of each panel) but residing in groups of different halo mass (indicated by the values in square brackets). In the lower panels different colours correspond to satellites in haloes of the same mass (indicated at the top of each panel) but of different stellar mass (indicated by the values in square brackets). The small vertical bars near the top of each panel, indicated the averages of the corresponding distributions. See text for a detailed discussion.

4.2   Fiber Collisions

As discussed in Y07, the galaxy sample on which group Sample II is based suffers from incompleteness due to fiber collisions: no two fibers on the same SDSS plate can be closer than 55 arcsec. Although this fiber collision constraint is partially alleviated by the fact that neighboring plates have overlap regions, ~ 7 percent of all galaxies eligible for spectroscopy do not have a measured redshift (Blanton et al. 2003d). Since fiber collisions are more frequent in regions of high (projected) density, they are more likely to occur in richer groups, thus causing a systematic bias. In Sample III we (partially) correct for this by assigning galaxies that lack an observed redshift due to fiber collisions (hereafter fiber-collision galaxies) the redshift of the galaxy with which it collided. As shown in Zehavi et al. (2002), roughly 60 percent of the fiber-collision galaxies have a redshift within $500\,\mathrm{km\,s^{-1}}$ of their nearest neighbor, which justifies the above procedure. However, there are also cases in which the fiber-collision galaxy has a true redshift that is very different from that of its nearest neighbor. In this case the above procedure will cause the group finder to falsely identify the fiber-collision galaxy as a group member (and with the wrong absolute magnitude and stellar mass). In order to avoid these failures from impacting on our results, we have used Sample II as our fiducial sample in the present study (see §2). Nevertheless, since the above method seems

to work well for ~ 60 percent of the fiber-collision galaxies, it is worthwhile to check if our results are sensitive to whether we include fiber-collision galaxies or not. We therefore repeat our analysis using Sample III. The selection criteria discussed in §2.1 now yield a sample of 92546 satellite galaxies (32301 more than for Sample II). Yet, the results, shown in the middle column of Fig. 8, are almost identical to those obtained from Sample II: once again, at fixed stellar mass the average satellite colour is almost independent of M_h and $R_{\mathrm{proj}}/R_{180}$. The main difference with respect to Sample II regards the tails of the colour-stellar mass distribution, as can be seen from the contour plot in the upper panel. In Sample III there is a tail of faint, very red galaxies, which is absent in Sample II. These galaxies are most likely fiber-collision galaxies for which the assigned redshift has a large error. Another difference, which is not shown here, is that in Sample III there is no decline in the number of satellites for $R_{\mathrm{proj}}/R_{180} \lesssim 0.15$ as in the upper right panels of Figs. 2 and 3. However, since the fiber-collision galaxies do not have any preferred colour, this has no impact on the average colour of satellite galaxies at these small radii.

4.3   Malmquist Bias

As mentioned in §2.1, the sample of groups and galaxies used for our analysis is flux-limited, not volume-limited. In or-
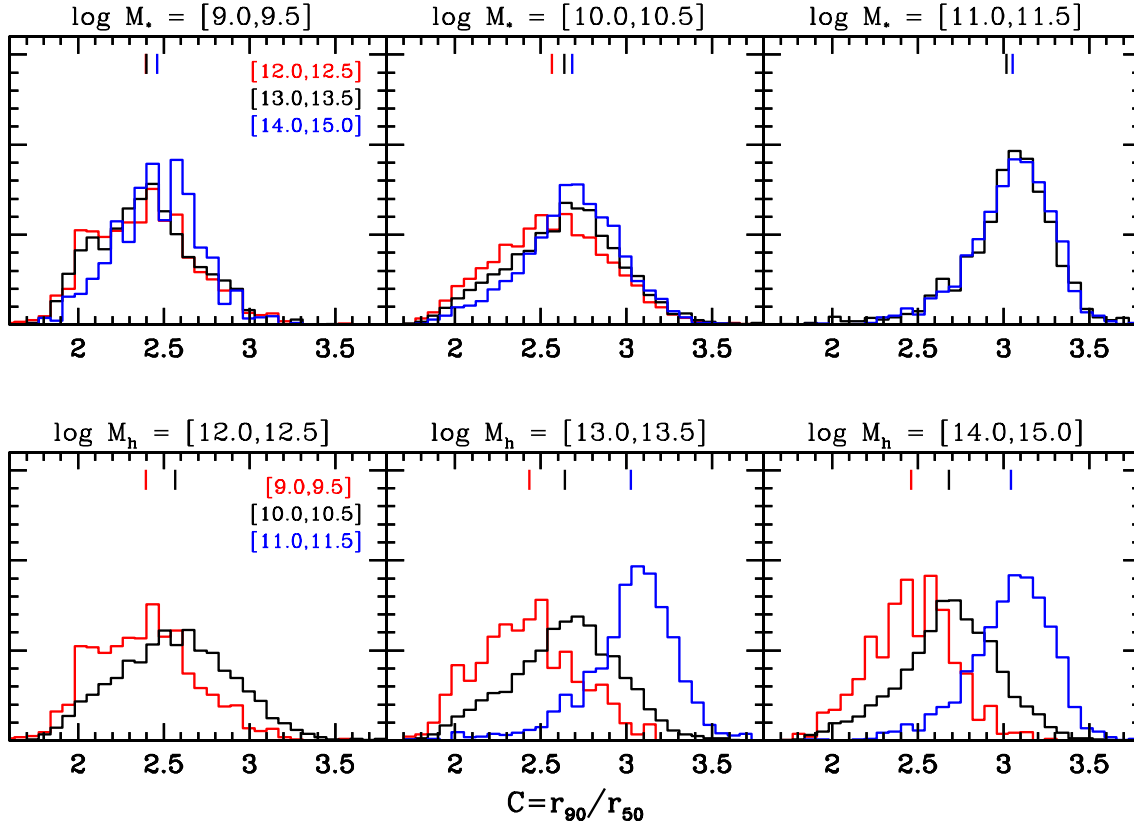
Figure 7. Same as Fig. 6 but for the concentrations of satellites rather than their colour.

der to correct for the consequential Malmquist bias we have weighted each galaxy by $1/V_{\max}$, the inverse of the comoving volume out to which the galaxy would have made it into our sample. However, in computing $V_{\max}$ we did not account for the fact that the flux-limit of the SDSS varies mildly with the position on the sky (see for example Blanton et al. 2003b). In order to investigate how sensitive our results are to the $1/V_{\max}$ weighting scheme adopted, we now repeat our analysis without any weighting. The results are shown in the right-hand column of Fig. 8. As expected the distribution of galaxies in the plane of colour *vs.* stellar mass is significantly different, showing a relatively larger contribution from massive (and hence red) galaxies. As can be seen from the black solid line in the upper panel, at the low mass end satellites are about 0.1 magnitude bluer on average than in the case with weighting. A galaxy of a given stellar mass that is bluer will also typically be brighter, and can therefore be seen out to a higher redshift. In other words, by not applying the $1/V_{\max}$ weighting one artificially overestimates the fraction of blue galaxies at a given stellar mass, thus causing the average colour to be too blue (but only mildly so). Yet, despite the fact that the average colours at a given stellar mass are somewhat different, even in this extreme case without any weighting to correct for Malmquist bias one finds that there is only a very mild halo mass dependence of $\langle^{0.1}(g-r)\rangle$ at fixed M_* and no significant dependence on $R_{\mathrm{proj}}/R_{180}$ at all, in good agreement with our fiducial results in Fig. 2.

For brevity we only show the above tests for the average satellite colours as function of stellar mass. However, the average colours as function of halo mass or halo-centric radius,

as well as the average concentrations, all point to the same conclusion: the results presented in §3 are extremely robust. They do not depend on our choice of the group mass indicator, they are not influenced by sample incompleteness due to fiber-collisions, and they are not affected by an imperfect correction for Malmquist bias.

5   COMPARISON WITH PREVIOUS STUDIES

The analysis presented above shows that at fixed stellar mass the colours and concentrations of satellite galaxies are only weakly dependent on their environment. This differs substantially from several previous studies, which have argued for a strong environment dependence of galaxy colours or star formation indicators (e.g., Hogg et al. 2004; Kauffmann et al. 2004; Blanton et al. 2005b; Weinmann et al. 2006a)

Our study differs from most of these on the following grounds:

(i) we have used halo mass and halo-centric radius as environment indicators, as opposed to a projected number density of galaxies.

(ii) we have split our galaxy population in centrals and satellites and only focused on the latter.

(iii) we have used broad-band colours, rather than more sophisticated star formation activity indicators, such as the equivalent width of various emission lines or the 4000Åbreak strength, which are less sensitive to dust attenuation.

The second of these issues is probably the most important one. For example, as shown by Hogg et al. (2004)
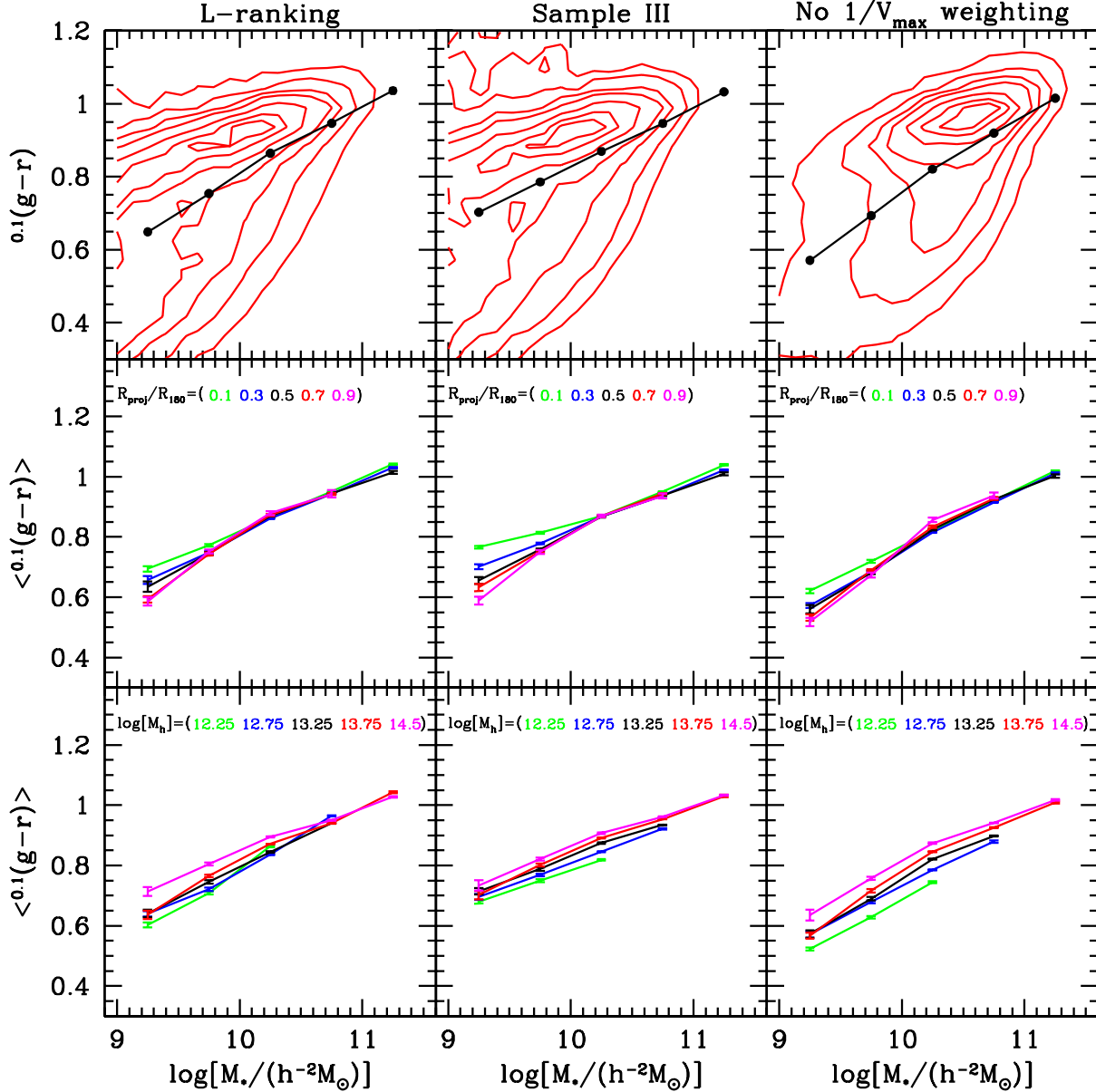
Figure 8. Same as the middle column of Fig. 2 but using halo masses based on the luminosity ranking, rather than the stellar mass ranking (left-hand column), using Sample III rather than Sample II (middle column), and using no $1/V_{max}$ weighting (right-hand column). In all cases, the average colours as function of stellar mass are very similar, indicating that our results are robust to uncertainties in halo mass, incompleteness due to fiber collisions, and inaccuracies in the correction for Malmquist bias. In particular, in all cases the average colour of satellite galaxies depends strongly on stellar mass with no or very little dependence on environment (halo-centric radius, as shown in the middle row of panels, or halo mass, shown in the lower panels). See text for a detailed discussion.

and Kauffmann et al. (2004), the colour-magnitude relation of galaxies is strongly environment dependent, with lower density environments showing a far more pronounced blue sequence than high density environments. Our results, however, suggest that the colour-magnitude relation of *satellite galaxies* has only a very weak environment dependence. We believe, though, that these results are not inconsistent with each other, but merely reflect that different environments have different satellite fractions: in high density environments, such as clusters of galaxies, the (vast) majority of all galaxies are satellites. In low density environments, however, most galaxies are central galaxies in low mass haloes. In

paper I we have shown that central galaxies are, on average, bluer than satellite galaxies of the same stellar mass, and we believe that this is largely responsible for the environment dependence noticed in the studies mentioned above.

The study whose results seems most antithetical to those presented here is that of Weinmann et al. (2006a; hereafter W06), who used a SDSS galaxy group catalogue very similar to that used here in order to study the fractions of red and blue satellite (and central) galaxies as a function of halo mass and absolute r-band magnitude (see Hester 2006b for a similar analysis, though they did no split their sample in centrals and satellites). W06 find that at fixed absolute

magnitude the fractions of red and blue satellites are strong functions of halo mass, while at fixed halo mass there is only a very mild dependence on luminosity. At first sight these results are completely opposite to the results presented here[†]. However, the following two reasons show that they are, in fact, consistent with each other.

First of all, the fact that W06 found no significant luminosity dependence of the red fraction of satellites, $f_{\rm red}$, owes entirely to the fact that they used a red/blue dividing line that is magnitude dependent. Clearly, for each magnitude bin one can always identify a colour so that the satellite fraction red-ward of this colour is independent of luminosity. Apparently, this is roughly what happens when using the magnitude-dependent cut adopted by W06. However, since the dependence of colour on luminosity is now 'absorbed' by the magnitude dependence of the colour-cut, one can not use the absence of a luminosity dependence of $f_{\rm red}$ to argue that colour does not depend on luminosity.

Secondly, the fact that W06 found a significant halo mass dependence for $f_{\rm red}$ is consistent with our results. This is most easily seen from the upper left-hand corner of Fig. 6. If we define the red satellite fraction, $f_{\rm red}$, as the ($1/V_{\rm max}$-weighted) fraction of satellites red-ward of $^{0.1}(g-r) = 0.7$, one obtains values of 0.33, 0.47, and 0.66 for the halo mass bins $[12.0, 12.5]$ (red histogram), $[13.0, 13.5]$ (black histogram) and $[14.0, 14.5]$ (blue histogram), respectively. Thus, in agreement with W06, we find that $f_{\rm red}$ increases with increasing halo mass. Upon closer inspection, it is clear that this largely owes to the fact that the colour-distributions for these different halo mass bins have a different skewness. However, as we have shown, the first and second moments are very similar. What really matters are the actual distribution functions, and there is no doubt from Fig. 6 that these depend more strongly on stellar mass than on halo mass.

We therefore conclude that our results are not inconsistent with previous studies. We do caution, though, that one has to be careful not to overinterpret trends (or the absence thereof) in red or blue fractions. Since colour is an actual physical quantity, while $f_{\rm red}$ is not (and is sensitive to a somewhat arbitrary colour cut), we believe that our study presented here is more useful for gaining insight regarding the physical processes at work.

6 CONCLUSIONS

Using a large SDSS galaxy group catalogue, we have examined the ecology of satellite galaxies. In particular, we have studied how the colours and concentrations of satellite galaxies depend on their stellar mass and their environment. The latter is 'parameterized' in terms of the mass of the host halo and the halo-centric radius. Our main result is that both the colour and the concentration of a satellite galaxy are almost completely determined by their stellar mass, with only a very mild dependence on environment. Or, to put it

in different words, in order to predict the (average) colour and concentration of a satellite galaxy, all one needs to know is its stellar mass. No information regarding its environment (halo mass or halo-centric radius) is required.

There is a weak trend that satellites at smaller halo-centric radii and in more massive haloes are, on average, redder and more concentrated. However, we argue that neither of these are reflections of a causal environment dependence. Rather, they owe to mass segregation (more massive satellites reside on smaller halo-centric radii) and to the fact that more massive satellites on average reside in more massive haloes. These two trends, combined with the fact that more massive satellites are redder and more concentrated, explain the weak environment dependencies evident in the data; they almost completely disappear when using stellar mass as a control variable (i.e., when only considering satellite galaxies in a narrow bin in stellar mass).

It is interesting to combine these results with those of Paper I, in which we used the same SDSS group catalogue to investigate the colour and concentration differences between central and satellite galaxies, in a statistical sense. That analysis has shown that satellite galaxies are, on average, redder and somewhat more concentrated than central galaxies of the same stellar mass. In addition, it was shown that the average magnitude of this difference is independent of halo mass, in excellent agreement with the lack of environment dependence presented here. Combining all these results, the following picture emerges: galaxies become redder and somewhat more concentrated once they fall into a bigger halo (i.e., once they become a satellite galaxy). This is a clear manifestation of environment dependence. However, there is no indication that the magnitude of the transformation (or its timescale) depends on environment; a galaxy undergoes a transition when it becomes a satellite, but it does not matter whether it becomes a satellite of a small (Milky Way sized) halo, or of a massive cluster. In that respect there is no (significant) environment dependence, and this is the 'dearth' of environment dependence we are referring to in the title of this paper.

This dearth of environment dependence puts interesting constraints on the physical processes responsible for transforming satellite galaxies. As discussed at length in Paper I, the data are most consistent with a picture in which strangulation, i.e., the removal of the (hot) gas reservoir of satellite galaxies, is the main mechanism that operates on satellite galaxies, and that causes their transformation from the blue to the red sequence. The fact that satellites in clusters have the same properties as satellites of the same stellar mass in galaxy-sized haloes, strongly argues against mechanisms that are thought to operate only in very massive haloes, such as ram-pressure stripping or galaxy harassment. Note, though, that we are not claiming that these processes do not occur, after all, clear-cut example of ram-pressure stripping have been observed (e.g., Gavazzi et al. 1995; Kenney, van Gorkum & Vollmer 2004). We mainly argue that they are not the *dominant* processes causing satellites to undergo a blue-to-red sequence transition. We also emphasize that we have used the term 'ram-pressure stripping' to refer to a (rapid) stripping of the *entire* cold gas reservoir of a galaxy. Although we claim that this can not be the main cause for satellite transformations, our data is perfectly consistent with a picture in which ram-pressure stripping operates on

[†] Although the results of W06 are based on r-band magnitudes, while those presented here are based on stellar masses, we have verified that our results hold if we were to use the r-band magnitudes instead.

the cold gas, but only manages to strip the outer layers of the gas disk (i.e., the gas at large galacto-centric radii, where no or very little star formation occurs). Such a stripping, after all, has basically the same effect as strangulation (the removal of the hot gas), as it effectively removes the fuel for *future* star formation (Hester 2006a,b). In fact, the observed HI deficiency of cluster galaxies (e.g., Warmels 1988; Cayatte et al. 1990; Bravo-Alfaro et al. 2000; Levy et al. 2007) strongly suggests that a mechanism is stripping some, but not all, of the HI gas[‡].

Our results also argue against 'pre-processing' in groups as an important process: as argued above, the only way in which a cluster is a 'special' environment, is that it has a larger fractional population of satellites than the 'field', and that the average satellite mass is higher than in the field. It has been suggested, though, that cluster galaxies are different from their field counterparts because they were part of an intermediate mass group prior to falling into the cluster (Zabludoff & Mulchaey 1998; Zabludoff 2002). Since merging is more effective in groups than in either clusters or the field, this "pre-processing" could explain the morphology-density relation. However, our results show that there is no difference between satellite galaxies in clusters and satellite galaxies *of the same stellar mass* in any other environment. This indicates that pre-processing in groups can not be the dominant cause for differentiating the cluster galaxy population from that of the field. A similar conclusion was recently reached by Berrier et al. (2008), who used numerical simulations to show that the vast majority of cluster galaxies ($\sim 70\%$) fall into the cluster potential directly from the field, without having been a satellite in an intermediate mass group environment.

We conclude by postulating, based on our results, that galaxy properties depend predominantly on stellar mass. The second most important 'parameter' for a galaxy is the distinction between centrals and satellites. When using these two parameters as control variables, there is virtually no environment dependence left. This conclusion has recently received support from various directions. Kauffmann et al. (2004) have shown that at fixed stellar mass, there is nearly no dependence of structural properties like Sérsic index or concentration parameter on local galaxy density. Pasquali et al. (2007) have shown that the trends of the isophotal shapes of elliptical galaxies ('disky' vs. 'boxy') with environment can be completely explained in terms of a pure stellar mass dependence. Using the same group catalogue as that used here, Pasquali et al. (2008) have shown that the star formation and AGN activity of galaxies has a much stronger dependence on stellar mass than on halo mass. Mouhcine, Baldry & Bamford (2007) find no dependence of the relationship between galaxy stellar mass and gas-phase oxygen abundance on local galaxy density. Blanton et al. (2005b) and Kauffmann et al. (2004) find that there is only a very weak dependence of galaxy size on local

density at fixed luminosity, which, as shown by Weinmann et al. (2008), is mainly a reflection of a difference between centrals and satellites.

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[‡] Although this is often attributed to ram-pressure stripping, viscous stripping (Nulsen 1997) or stripping due to tidal forces could also play an important role. In addition, the deficiency may also simply be a reflection of the fact that star-formation has used up a large fraction of the HI gas, without being replenished with new gas since its hot gas reservoir has been removed.

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