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Satellite abundances around bright isolated galaxies – II. 
Radial distribution and environmental effects

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ABSTRACT
We use the Eighth Data Release of the Sloan Digital Sky Survey (SDSS/DR8) galaxy sample to study the radial distribution of satellite galaxies around isolated primaries, comparing to semi-analytic models of galaxy formation based on the Millennium and Millennium-II simulations. SDSS satellites behave differently around high- and low-mass primaries: those orbiting objects with $M_\ast > 10^{11} M_\odot$ are mostly red and are less concentrated towards their host than the inferred dark matter halo, an effect that is very pronounced for the few blue satellites. On the other hand, less massive primaries have steeper satellite profiles that agree quite well with the expected dark matter distribution and are dominated by blue satellites, even in the inner regions where strong environmental effects are expected. In fact, such effects appear to be strong only for primaries with $M_\ast > 10^{11} M_\odot$. This behaviour is not reproduced by current semi-analytic simulations, where satellite profiles always parallel those of the dark matter and satellite populations are predominantly red for primaries of all masses. The disagreement with SDSS suggests that environmental effects are too efficient in the models. Modifying the treatment of environmental and star formation processes can substantially increase the fraction of blue satellites, but their radial distribution remains significantly shallower than observed. It seems that most satellites of low-mass primaries can continue to form stars even after orbiting within their joint halo for 5 Gyr or more.

Key words: galaxies: abundances – galaxies: evolution – galaxies: haloes – dark matter.

1 INTRODUCTION
Satellite galaxies can contribute substantially to our understanding of galaxy formation. In the current structure formation paradigm, galaxies form by the cooling and condensation of gas at the centres of an evolving population of dark matter haloes that are an order of magnitude larger in both mass and linear size than the visible galaxies (White & Rees 1978). Comparable contributions to the growth of such haloes come from smooth accretion of diffuse matter and from mergers with other haloes spread over a very wide range in mass (Wang et al. 2011). The more massive accreting haloes will normally have their own central galaxies, and after infall these become ‘satellites’ of the galaxy at the centre of the dominant halo, orbiting it within their own ‘subhaloes’. Later, the satellites may merge with the central galaxy and so contribute to its growth.

High-resolution cosmological simulations predict not only the masses, positions and velocities of dark matter haloes but also those of the subhaloes they contain (e.g. Moore et al. 1999; Gao et al. 2004b, 2008, 2011; Springel et al. 2008). Linking such data over time then allows the construction of the assembly history of every system in the simulated volume. In combination with a model for galaxy formation, such halo/subhalo merger trees can be used to predict the development of the full galaxy population in the region considered. This can be compared directly with the properties of observed populations such as abundances, scaling relations, clustering and evolution (e.g. Springel et al. 2001; Bower et al. 2006; Croton et al. 2006; Guo et al. 2011). A particular strength of such ‘semi-analytic’ population simulations is that they enable evaluation of the relative sensitivity of these observables to cosmological and to galaxy formation parameters (e.g. Wang et al. 2008; Guo et al. 2013a). Satellite galaxies play an important role in such work because they are particularly sensitive to environmental effects and to the assembly history of haloes.

In Wang & White (2012, Paper I hereafter), we used the Sloan Digital Sky Survey (SDSS) to study the luminosity, mass and colour distributions of satellite galaxies as a function of the properties of their host. A comparison of our observational results to
semi-analytic galaxy formation simulations within the concordance 
ΛCDM cosmology showed good overall agreement for satellite 
abundances, inspiring some confidence in the realism of the par-
ticular galaxy formation model used (from Guo et al. 2011), but 
large discrepancies for satellite colour distributions confirmed 
earlier demonstrations that such models substantially overestimate 
the environmental suppression of star formation (e.g. Font et al. 2008; 
Weinmann et al. 2009). In this paper, we extend our earlier work 
through a detailed analysis of the radial distribution of satellites 
around their hosts. This enables further exploration both of the 
successes and of the failures of the galaxy formation model.

The observational study of satellite number density profiles ben-
efited enormously from the advent of wide-angle spectroscopic 
surveys such as the Two Degree Field Galaxy Redshift Survey 
(2dFGRS, Colless et al. 2001) and the SDSS (York et al. 2000). The 
availability of redshift measurements for almost all objects above 
some apparent magnitude limit allows the full three-dimensional 
distribution of objects to be studied (although in ‘redshift space’ 
rather than true position space) greatly facilitating the identification 
of host/satellite systems. Several studies concluded that the mean 
radial satellite distribution in such spectroscopic samples can be fit 
in (projection) by a power-law $\Sigma(r) \propto r^{-\alpha}$, although the range of 
indices quoted is quite broad $\alpha \sim 0.9$ to 1.7 (Sales & Lambas 2005; 
van den Bosch et al. 2005; Chen et al. 2006; Chen 2008). There 
is some indication that this index correlates with the properties of 
the primaries and/or satellites under consideration, but results are 
also rather noisy because of the relatively bright lower limit on the 
luminosity of the satellites which is enforced by the spectroscopic 
apparent magnitude limit.

In addition to being restricted to relatively bright objects, spec-
troscopic satellite samples are also subject to selection effects such 
as redshift incompleteness due to fibre–fibre collisions and survey 
geometry constraints which particularly affect their coverage of 
close pairs. In this context, photometric samples offer an interesting 
alternative, since they are complete at all separations and to appar-
ent magnitude limits which are typically 3–4 mag fainter than the 
corresponding spectroscopic surveys. For example, the SDSS/DR8 
data are effectively complete to $r$-band magnitudes $m_r = 17.7$ and 
m_v = 21 for the spectroscopic and photometric catalogues, respec-
tively (Aihara et al. 2011).

Inspired by this, several groups have recently analysed pri-
mary/satellite samples, where the primary galaxies are selected from 
spectroscopic surveys, ensuring their distances and environments 
are well characterized, but their satellite populations are identified 
in deeper photometric data and so must be corrected statistically 
for the inevitable foreground and background contamination (e.g. 
Lares, Lambas & Dominguez 2011; Guo et al. 2012; Nierenberg 
et al. 2011, 2012; Jiang, Jing & Li 2012; Tal, Wake & van Dokkum 
2012). This approach is reminiscent of the pioneering work in this 
field, where satellites were identified on photographic plates around 
relatively bright primary samples (Holmberg 1969; Lorrimer et al. 
1994). The projected satellite profiles measured in these hybrid 
studies are also consistent with power-laws $\Sigma(r) \propto r^{-\alpha}$, and 
again correlations are seen between the slope of the profiles and the 
colour/mass/type of the primaries and satellites.

Despite this superficial agreement, there are large discrepancies 
between recently published studies of satellite radial distributions. 
Some authors find satellite profiles to be steeper than the NFW 
profile (Navarro, Frenk & White 1996, 1997) predicted for the dark 
matter (Tal et al. 2012; Watson et al. 2012; Guo et al. 2014); others 
consider them as good tracers of the dark matter (Nierenberg et al. 
2012); yet others find them to be less concentrated than the dark 
haloes they inhabit (Budzynski et al. 2012; Wojtak & Mamon 2013).

The trends found with intrinsic properties of satellites/primaries 
also disagree between studies. For instance, whereas Watson et al. 
and Tal et al. find that bright satellites have steeper profiles, Guo 
et al. and Budzynski et al. conclude that faint companions are more 
strongly concentrated. Nierenberg et al. find no variation in profile 
slope with satellite mass.

Some of this disagreement can plausibly be traced to differing 
sample definitions. For example, Tal et al. (2012) studied satellite 
profiles around Luminous Red Galaxies at $0.28 < z < 0.4$, whereas 
both Watson et al. (2012) and Guo et al. (2012) used SDSS Main 
Sample galaxies at lower redshifts. The redshift range probed by 
Nierenberg et al. (2012) is $0.1 < z < 0.8$, based on data from the 
deeper Cosmological Evolution Survey, but their samples are 
relatively small so trends may be masked by counting noise. Fur-
thermore, Tal et al. (2012) and Watson et al. (2012) studied satellite 
radial profiles down to very small separations ($r_p \sim 30$kpc) and 
their inference of a steeper than NFW distribution depends on these 
scalps. Careful photometric corrections are needed in such work, 
because satellite magnitudes are systematically biased by their prox-
imity to a much brighter central galaxy. Deblending and background 
estimation effects can be substantial in this situation and are quite 
uncertain (e.g. Mandelbaum et al. 2006). Not all authors apply such 
corrections (e.g. Guo et al. 2012) and in consequence their results 
at the smallest separations may be compromised.

Variations in the radial distribution of satellites as a function of 
primary or satellite properties provide important clues to the 
processes driving galaxy evolution, in particular, to the influence 
of environmental effects. Tidal disruption and ram-pressure stripping 
are believed to be the main agents of structural change in satellites 
otherwise once they have fallen into their host haloes. Extended reservoirs 
of gas may be removed, causing the satellites to run out of fuel for 
star formation, or gas and stars may be removed directly from the 
visible regions of the galaxies. As a result, satellites are predicted 
and to be less active and redder than otherwise similar galaxies in the 
field.

There is clear observational evidence for effects of this kind. 
Studies of galaxy correlations show enhanced clustering of red 
objects at fixed stellar mass (see e.g. Li et al. 2006; Zehavi et al. 
2011) and there is a consensus among authors that the fraction of 
red and passive satellite galaxies is larger than for central galaxies 
(similar mass (see e.g. van den Bosch et al. 2008; Weinmann et al. 
2009; Yang, Mo & van den Bosch 2009). There are also, however, 
clear indications that this increased red fraction among satellites 
is a function of the stellar or halo mass of the primary, suggesting 
that environmental effects are weak or even negligible for satellites 
orbiting low-mass primaries (e.g. Weinmann et al. 2006; Prescott 
et al. 2011; Wetzl, Tinker & Conroy 2012).

Theoretical predictions based on semi-analytical models success-
fully reproduce several of these trends, but typically overproduce 
the fraction of red satellites (e.g. Coil et al. 2008). Recent improve-
ments in the modelling of gas removal and tidal stripping have 
Improved the situation (Font et al. 2008; Guo et al. 2011), but a 
significant problem still persists (Weinmann et al. 2011). The rad-
ial distributions of red and blue satellites and their relation to the 
properties of the primary galaxy give additional information about 
environmental influences on satellites, complementing the informa-
tion provided by the relative abundances of the two populations.

Despite difficulties in matching the observed colour distribu-
tion, simulations have proven useful for interpreting the observed 
properties of satellite galaxies. Kravtsov, Gnedin & Klypin (2004) 
and Gao et al. (2004a) used N-body simulations to argue that the
observed radial distribution of luminous satellites is more easily understood if these objects populate the most massive subhaloes at the time of infall, rather than the most massive today. The distribution of luminous satellites in both hydrodynamical and semi-analytic simulations suggests that they may be reasonable tracers of the underlying dark matter distribution of their host halo (e.g. Gao et al. 2004a; Nagai & Kravtsov 2005; Sales et al. 2007). Numerical simulations also show that the time of infall of satellites on to their host is correlated with their current distance from halo centre (e.g. Gao et al. 2004b), a relation that becomes tighter if we consider satellite orbital binding energy (Rocha, Peter & Bullock 2012). Thus, the radial distribution of satellites encodes information about the assembly of dark matter haloes that is not otherwise observationally accessible.

In this paper, we study the radial distribution of satellites in a hybrid primary/satellite sample selected from the spectroscopic + photometric SDSS/DR7 and DR8 catalogues. We go beyond previous work by comparing our results with a mock-galaxy catalogue generated from the Millennium and Millennium-II simulations (Springel et al. 2005; Boylan-Kolchin et al. 2009) using the semi-analytical model of Guo et al. (2011). The mock sample allows an improved assessment of the projection and sample selection effects, facilitating the physical interpretation of the observed profiles. At the same time, we are able to test the galaxy formation model by contrasting its predictions with observables it was not tuned to reproduce. This paper follows naturally from the analysis presented in Paper I which focused on the abundance and mass spectrum of satellites around isolated primaries.

This paper is organized as follows: our data sources and the selection criteria we apply to observed and simulated catalogues are described in Section 2. We report the trends found in the radial distribution of satellites according to primary/satellite colours and masses in Sections 3.2 and 3.3, while we discuss the implications for environmental modulation of star formation in Section 4. We summarize and discuss our main conclusions in Section 5. Throughout this paper, we adopt the cosmology of the original Millennium simulations ($H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.25$, $\Omega_{\Lambda} = 0.75$, $n = 1$). A discussion of the effect of cosmology on the satellite properties presented in this paper is included in Section 4.

2 DATA SELECTION

In this paper, we use the same primary and satellite samples as in Paper I. In the following, we briefly introduce the underlying observational and simulation catalogues and the selection criteria which define our samples, referring the reader to Paper I for further details.

2.1 Identification of primary and satellite galaxies

We select isolated primary galaxies from the spectroscopic catalogue of the New York University Value Added Galaxy Catalogue (NYU-VAGC), which is built by Blanton et al. (2005) based on the Seventh Data Release of the Sloan Digital Sky Survey (SDSS/DR7; Abazajian et al. 2009). Every galaxy with apparent (Petrosian) r-band magnitude brighter than $r = 16.6$ is a primary candidate. To ensure isolation, it must fulfil two further conditions: it must (i) be at least one magnitude brighter than any companion within a projected radius of $r_p = 0.5$ Mpc and a line-of-sight velocity difference $|\Delta z| < 1000$ km s$^{-1}$, and (ii) be the brightest object within $r_p < 1$ Mpc and $|\Delta z| < 1000$ km s$^{-1}$. This returns 66 285 isolated primaries.

The SDSS spectroscopic sample is incomplete due to fibre–fibre collision. For our selection criteria, we expect ~91.5 per cent completeness on average, varying with position on the sky and worse in dense regions such as the centres of galaxy groups or clusters. To ensure that none of our primaries is falsely identified as isolated due to incompleteness in the spectroscopic survey, we look for further companions using the photometric SDSS catalogue. In practice, we will reject a primary candidate if it has a photometric companion satisfying the position and magnitude cuts of (i) and (ii) which is absent from the spectroscopic catalogue but whose probability to have a redshift equal or less than the primary is larger than 10 per cent. For this last step, we use the photometric redshift distributions from Cunha et al. (2009). This reduces our sample of isolated primaries to 41 883 candidates. Lastly, we also consider survey boundaries to ensure that most of the companions of our primaries fall within the SDSS footprint. We use the spherical polygons provided on the NYU-VAGC web site to quantify the survey boundaries and masked areas around bright stars. We remove from the above primary sample all candidates for which more than 20 per cent of a surrounding disc with $r_p < 1$ Mpc lies outside the SDSS footprint. About 1.5 per cent galaxies are removed through this procedure, leading to our final primary sample with 41 271 isolated systems.

Satellites are identified in the SDSS/DR8 photometric catalogue (Aihara et al. 2011) and are corrected statistically for background contamination (see Paper I for details). We proceed as follows. For each isolated primary, we compute, as a function of projected distance $r_p$, the number of objects with apparent magnitude $r$ and colour $(g - r)$ in SDSS/DR8. For completeness, we only consider objects brighter than $r = 21$ (model magnitudes). For each bin in distance $r_p$, we subtract the average number of galaxies in the $(r, g - r)$ bin expected in this area of the sky, as estimated from the survey as a whole. The excess counts with respect to a homogeneous galaxy background are assumed to be satellites physically associated with the primary galaxy. Rest-frame colours and stellar masses can then be computed for these satellites by assigning them the redshift of the primary. Finally, results for different primaries can be averaged after making completeness, volume and edge corrections as set out in Paper I.

To aid the physical interpretation of these data, we use mock galaxy catalogues generated from the Millennium and Millennium-II simulations (Springel et al. 2005; Boylan-Kolchin et al. 2009). The formation of galaxies is simulated using the semi-analytic model of Guo et al. (2011) (hereafter G11). This is tuned to reproduce SDSS estimates of the mass and luminosity functions of low-redshift galaxies and also fits the measured autocorrelations of SDSS galaxies at high stellar mass. Autocorrelations of lower mass galaxies are significantly overestimated on small scales ($r_p < 1.0$ Mpc) but the abundances of satellites around primaries of the mass considered in this paper are in quite good agreement with direct measurements from SDSS (see Paper I). We create simulated galaxy catalogues by projecting the simulation ‘boxes’ in three orthogonal directions, i.e. parallel to their $x$, $y$ and $z$ axes. In each projection, we assign every galaxy a redshift based on its ‘line-of-sight’ distance and peculiar velocity. We then apply similar isolation criteria as in SDSS to identify a set of simulated primaries.

In addition, we analyse a sample of primary and satellite galaxies derived from a ‘light-cone’ mock catalogue which mimics
incompleteness due to fibre collisions as well the survey geometry of SDSS/DR7 (Henriques et al. 2012). This allows us to apply exactly the same selection criteria as described above for the SDSS sample and to compare with the simple projections used for our main analysis (which provide better counting statistics). Results of this comparison are shown in an appendix.

### 2.2 Satellite number density profiles

The background subtraction method explained above provides a measure of the cumulative number of satellites in fine grids of projected distance in the range \( r_p = [0, 0.5] \) Mpc. We group this data according to primary mass and colour. In Section 3.2, and to satellite mass and colour (Section 3.3) in order to study the average projected number density profile of satellites, \( \Sigma_{sat} \), defined as the mean number of satellites in some chosen magnitude range per primary and per unit area as a function of projected distance from the primary. Uncertainties are estimated from bootstrap re-samplings of each primary sample. Following Paper I, we divide our primaries into five disjoint stellar mass bins: log \( M_*/M_\odot \) = [10.2 – 10.5], [10.5 – 10.8], [10.8 – 11.1], [11.1, 11.4] and [11.4 – 11.7].

For every primary stellar mass bins, we consider eight equal-size logarithmic radial bins that extend up to the average virial radius, \( r_{vir} \), of the subsample (see Table 1). We estimate virial quantities using the relation between mean halo mass and primary stellar mass for all the isolated primaries in our semi-analytic catalogue. In SDSS, the luminosity of the primary galaxy affects the detectability of faint satellites at small projected radii. We thus expected that the stellar mass of the apparent companions according to

\[
(M/L)_g = -1.0819^{0.1}(g - r)^2 + 4.1183^{0.1}(g - r) - 0.7837, \tag{1}
\]

which is obtained through a fit to a flux-limited \((r < 17.6)\) galaxy sample from the NYU-VAGC. Stellar masses in the sample were estimated by fitting stellar population synthesis models to the K-corrected galaxy colours assuming a Chabrier (2003) initial mass function as in Blanton & Roweis (2007).

Notice that in contrast to the case when we take all satellites down to the magnitude limit, when computing satellite number density profiles as a function of satellite mass we need to account properly for completeness limitations. In these cases, we proceed as in Paper I: a primary is allowed to contribute counts to a given bin in satellite mass only if the K-corrected absolute luminosity corresponding to \( r = 21 \) for a galaxy at the redshift of the primary and lying on the red envelope of the intrinsic colour distribution is fainter than the lower luminosity limit of the bin.

Finally, we note that our primary selection criteria result in a sample of galaxies which are usually but not always the central galaxies of their dark matter haloes. In our simulated catalogue, the fraction of primaries which are not the central object of their friends-of-friends (FoF) dark matter halo is 0.1006, 0.1021, 0.0733, 0.0410 and 0.0156 for our five primary stellar mass bins (from most massive to least massive). This fraction increases strongly with primary stellar mass because of the concomitant increase in halo size (see Table 1). Note that the great majority (80 to 90 per cent) of these non-central primaries actually lie outside the virial radius of the FoF halo of which they are formally a satellite.

### 3 RESULTS

Throughout this paper, we will make extensive use of comparisons between results for the SDSS and for our simulated galaxy populations. Before starting systematic presentation and interpretation of the observed satellite profiles, we therefore use our two large simulations to demonstrate that the relevant quantities are numerically converged and that the observed, projected radial profile of satellites is related as expected to the mean three-dimensional

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**Table 1.** Average halo virial radius \( r_{vir} \) (following G11), scale radius \( r_s \) (following Zhao et al. 2009), inner radius \( r_{inner} \), and the \((g - r)\) colour cut separating blue from red satellites for the five primary stellar mass bins considered in our study. The final row gives the number of red and blue SDSS primaries in each of these bins.

| \( \log M_* / M_\odot \) | 11.4 – 11.7 | 11.1 – 11.4 | 10.8 – 11.1 | 10.5 – 10.8 | 10.2 – 10.5 |
|--------------------------|-----------|-----------|-----------|-----------|-----------|
| \( r_{vir} \) (kpc)      | 725       | 430       | 270       | 210       | 170       |
| \( r_s \) (kpc)          | 156.6     | 74.4      | 39.3      | 27.1      | 21.0      |
| \( r_{inner} \) (kpc)    | 50        | 50        | 30        | 20        | 10        |
| \((g – r)_{SDSS}\)       | 0.840     | 0.830     | 0.820     | 0.811     | 0.801     |
| \((g – r)_{mock}\)       | 0.627     | 0.618     | 0.609     | 0.600     | 0.591     |
| \( N_{SDSS} \) (red, blue) | 1651,35 | 6170,731 | 8518,4142 | 5453,5953 | 1625,3764 |

\( r_{vir} \) as the radius where the average enclosed density is 200 times the critical value.

\( r_{inner} \) is the inner (kpc) 50 50 30 20 10

\( (g – r)_{SDSS}\) is the \((g – r)\) colour cut separating blue from red satellites and \((g – r)_{mock}\) is the \((g – r)\) colour cut separating blue from red satellites.

\( N_{SDSS} \) is the number of red and blue SDSS primaries in each of the bins.

\( M/L \) is the stellar mass to light ratio.
distribution around the primary galaxies. For brevity, we focus on primaries with stellar mass in the range, $10.8 < \log M_*/M_\odot < 11.1$ and satellites more massive than $\log M_*/M_\odot > 9$, but we emphasize that we have checked explicitly that similar results are found for other choices of primary and satellite mass, as well as for samples split by primary or satellite colour.

Fig. 1 shows the 3D and 2D satellite number density profiles in the Millennium and Millennium-II simulations. Both panels, solid black dots show the three-dimensional number density of satellites as a function of distance $r$ from their primary, normalized to the average $r_{\text{vir}} = 270$ kpc for primaries of this stellar mass (see Table 1). These measurements agree essentially perfectly given the counting statistics (there are 125 times fewer primaries in the MS-II) and are very well represented by an NFW profile (black solid line) with concentration parameter $c = 6.87$, the value expected for haloes of virial mass $M_{\text{vir}} = 10^{12.5} M_\odot$ (Zhao et al. 2009), which is the mean halo mass for simulated primaries in this stellar mass bin.

In the simulations, there are two different kinds of satellites which combine to give these number density profiles, those which have an associated dark matter subhalo (type-1, blue solid squares in Fig. 1) and those whose dark matter subhalo has fallen below the resolution limit of the simulation (type-2, magenta solid triangles). The positions and velocities of the latter ‘orphan’ galaxies are set to the current values for the particles which were the most bound at the centre of their subhaloes at the last time these were identified in the simulation. Orphan galaxies are removed from the galaxy catalogues when one of two conditions is fulfilled: either the time since disruption of the subhalo exceeds the time estimated for dynamical friction to cause a merger with the primary, or the estimated tidal forces from the host exceed the binding energy of the satellite so that it is disrupted (see G11 for further details).

In the Millennium Simulation (the left-hand panel of Fig. 1), satellites with a dark matter subhalo are comparable in number to the orphans only near the virial radius. Throughout the inner halo, satellite numbers are entirely dominated by orphans. In the Millennium-II, however, (the right-hand panel) orphans are much less numerous and dominate the population only at the smallest radii ($r < 0.2r_{\text{vir}}$). To facilitate a direct comparison, we repeat the type-1 and type-2 data from the left-hand panel as dashed blue and magenta lines in the right-hand panel. The increase in mass resolution in the MS-II increases the number of satellites with resolved subhaloes by factors between 3 and 30 in the inner halo and reduces the number of orphans to compensate. Despite this, the total number of satellites agrees very well and their profile is very similar to that of the dark matter. Note that even at the high resolution of MS-II it is important to include the orphans to get a reliable and numerically converged estimate of the number density profile. Similar conclusions were drawn by G11 and by Guo & White (2014) from the study of small-scale correlations and by Moster et al. (2010) from their abundance matching work.

Fig. 1 also explores projection effects in the model. Black empty dots in the left-hand panel show the average profile obtained when systems are projected along their $x$, $y$, and $z$ axes. In practice, we count all apparent companions around our primaries and correct statistically for unassociated objects that happen to be projected near them, based on the mean surface number density of galaxies times the area of each annular bin. This projected number density profile, $\Sigma_{\text{sat}}$, is also shown as a function of projected distance $r_p$ normalized to $r_{\text{vir}}$, and again is very well represented by an NFW fit to the (projected) dark matter distribution (dashed black line). Thus, the simulations suggest that satellite profiles should closely parallel the mean dark matter distributions around isolated galaxies, a result that could be checked directly using galaxy--galaxy lensing.

In what follows, we will study projected number density profiles of satellites around isolated SDSS galaxies, comparing directly with simulation results. We have checked that numerical convergence between the two simulations is as good as in Fig. 1 for all the other plots we show, and hence, unless otherwise stated, we show only results based on the Millennium Simulation, since these have better counting statistics.

### 3.1 Satellite number density profiles: dependence on primary stellar mass

The thick black lines in the left-hand column of Fig. 2 show the mean projected number density of satellites around isolated SDSS primaries, $\Sigma_{\text{sat}}$, as a function of projected separation ($r_p$), normalized by mean inferred virial radius ($D = r_p/r_{\text{vir}}$). Each row corresponds to primaries in a different stellar mass range, as indicated by the listed values of $\log M_*/M_\odot$. Satellite number density profiles $\Sigma_{\text{sat}}$ are computed by summing the satellite counts (after background correction) in each radial bin, and then dividing by the number of contributing primaries per mass bin (see Table 1). The error bars correspond to the dispersion among 100 bootstrap re-samplings of each primary sample. We maximize the statistics by including all satellites down to the apparent magnitude limit $m_r = 21$ of the SDSS photometric catalogue. Because of the large number of
Figure 2. Projected number density profiles for satellites brighter than $r$-band apparent magnitude $r = 21$ and for primaries in different stellar mass bins (the quoted numbers indicate the interval in log $M_\ast/M_\odot$). The profiles correspond to the satellite number counts per primary and per unit surface area that we indicate in the $y$-axis with units $N^{-1}$ and $D = r_p/r_{\scriptscriptstyle V}$, respectively. Dashed lines indicate the expected distribution of dark matter around the hosts, computed by projecting the average NFW profile with mass following the $M_\ast-M_{\scriptscriptstyle V}$ relation from G11 and concentration from Zhao et al. (2009). The shape of the distribution of SDSS satellites (left-hand column) varies with primary stellar mass: for satellites of low-mass centrals (log $M_\ast/M_\odot < 11.1$), the profile agrees well with the expected dark matter distribution. In contrast, satellites of the most massive primaries have a noticeably shallower distribution than predicted for the dark matter. Error bars are almost invisible and correspond to the scatter among 100 bootstrap re-samplings of each primary sample. For comparison, the right-hand column shows results of a similar analysis performed on our simulation catalogue. Satellites are here counted down to an $r$-band absolute magnitude corresponding to $r = 21$ at the median redshift of the SDSS primaries in the corresponding left-hand panel. Note the excellent agreement in the absolute numbers of satellites in SDSS and in the simulation. The dependence of the shape of the satellite profiles on primary stellar mass is not, however, present in the simulation where satellites trace the underlying dark matter distribution regardless of primary stellar mass.

satellites included (including background galaxies, there are about \( \sim 7000000 \) photometric companions projected within 500 kpc of these primaries), the error bars are almost invisible in most cases.

We find that the shape of satellite profiles around our isolated SDSS primaries depends significantly on primary stellar mass, with a shallower radial distribution around high-mass primaries than around primaries with log $M_\ast/M_\odot < 11.1$. This is most clearly seen by comparing with the expected mean dark matter profiles, which we indicate as dashed lines in each plot. These are computed by using the stellar mass of each primary to estimate its halo mass according to the mean $M_\ast - M_{\scriptscriptstyle 200}$ relation in the semi-analytic catalogue of G11. We then compute the average halo mass in each bin and use the concentration--mass relation of Zhao et al. (2009) to get the mean projected NFW profile expected for the dark matter. Finally, we re-adjust the normalization to obtain a good fit to the amplitude of the simulation results in the right-hand panel of each row (the dashed curves are identical in each pair of panels). We have explicitly checked that stacking the DM particles directly around the simulated galaxy sample gives almost identical results.

Massive primaries with log $M_\ast/M_\odot > 11.1$ show a satellite profile that is inconsistent with the predicted dark matter profile. In contrast, the satellite distribution agrees well with the predicted dark matter distribution around lower mass primaries. In the lowest mass bin (the bottom-left panel), the satellite profile declines more steeply than the predicted dark matter profile at large radii. However, our tests indicate that at these radii the satellite counts around low-mass primaries become sensitive to background subtraction and are artificially steepened because our isolation criteria cause a slight suppression of the number of background galaxies around our primaries compared to randomly selected points on the sky. We show in the appendix that the measured satellite profiles in a light-cone mock catalogue decline more steeply in the lowest mass bin than those measured directly from the projected simulation box. Such uncertainties in background subtraction do not affect our profile measurements at smaller radii or around more massive galaxies, because of the higher mean densities expected there.

The right-hand column of Fig. 2 compares our SDSS results with analogous results for satellites surrounding isolated primaries in our mock catalogue based on the G11 simulation. For these plots, simulated satellites are counted down to an $r$-band absolute magnitude corresponding to $r = 21$ at the median redshift of the SDSS primaries in the corresponding left-hand panel. As noted above, the
Figure 3. Projected number density profiles for satellites in SDSS split according to satellite stellar mass: log \( M^*/M_\odot = [10.2, 11.2], [9.2, 10.2] \) and [8.2, 9.2] from left to right. Samples divided by satellite stellar mass require the use of volume-limited samples, unlike Fig. 2. For a given primary mass bin, we find no strong dependence of satellite profiles with satellite stellar mass. Simulated satellites show a similar behaviour in the mock catalogue but are not shown here.

The excellent agreement in normalization in each pair of panels thus repeats the result of Paper I, that the G11 simulation does a good job in reproducing the observed abundance of satellites as a function of primary mass. However, in the simulation, satellites follow the dark matter distribution for primaries of all stellar masses. This is inconsistent with the shallower slope found for massive SDSS primaries.

This disagreement is puzzling in view of the good match between model and SDSS found by G11 for the small-scale autocorrelations of massive galaxies, and the significantly poorer agreement in shape found for the autocorrelations of lower mass galaxies (see fig. 20 in G11). Apparently, although massive primaries have the right spatial distribution in the mock catalogue, their satellites are somewhat too concentrated to small radii in comparison to SDSS. We show in the appendix that more relaxed isolation criteria result in flatter satellite profiles in the outer regions (since satellites associated with other nearby primaries are now allowed to contribute), but the change is only significant for low/intermediate mass primaries. The overall shallower profile of satellites around massive primaries in SDSS seems robust to changes in isolation criteria and its physical explanation remains unclear. More efficient tidal disruption associated with massive primaries could provide a viable explanation for the inner shallow slopes. More definitive conclusions will require a better treatment of this process in the models, together, perhaps, with studies of the intergalactic light (e.g. Conroy, Wechsler & Kravtsov 2007; Contini et al. 2014; Presotto et al. 2014) systems.

We conclude that SDSS satellite galaxies are, in the mean, distributed in the same way as the dark matter around isolated galaxies like the Milky Way or M31, but are somewhat less centrally concentrated around more massive systems. The latter feature is not well reproduced in the model, where satellites follow the dark matter profile for primaries in all mass bins.

We investigate this further in Fig. 3 by splitting our SDSS satellites according to their stellar mass. As explained in Section 2.2, the completeness corrections needed to build unbiased, satellite-mass-limited subsamples reduce the primary sample by \( \sim 50 \) per cent overall. As a result, the uncertainties in Fig. 3 are larger than in the previous figure, especially for the less massive satellites where

\[\text{Equation} \]

Figure 3. Projected number density profiles for satellites in SDSS split according to satellite stellar mass: log \( M^*/M_\odot = [10.2, 11.2], [9.2, 10.2] \) and [8.2, 9.2] from left to right. Samples divided by satellite stellar mass require the use of volume-limited samples, unlike Fig. 2. For a given primary mass bin, we find no strong dependence of satellite profiles with satellite stellar mass. Simulated satellites show a similar behaviour in the mock catalogue but are not shown here.

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The volume surveyed is considerably smaller. Fig. 3 shows that the shallower profiles around massive primaries are quite pronounced for massive satellites (left-hand and middle columns) but are not significantly detected for the lowest mass satellites (right-hand column) where the data are much noisier. Nevertheless, variations of satellite profile with satellite mass are weak or undetected for all primary masses.

3.2 Satellite number density profiles: dependence on primary colour

We explore the dependence of satellite radial profile on primary colour in Fig. 4. We split primaries according to their \((g - r)\) colour at a value that varies weakly with primary stellar mass (see Table 1). These cuts are the same as used in Paper I (see Fig. 2 there) and reflect the position of the trough between the red and blue peaks in the colour distribution of isolated primaries in each \(M^*\) bin. Because the colour distributions of observed and simulated primaries differ slightly, we list separately in Table 1 the colour cuts used in the SDSS and the mock galaxy samples, \((g - r)_{\text{SDSS}}\) and \((g - r)_{\text{mock}}\), respectively.

When comparing satellite abundances, it is important to account for the different redshift distributions of red and blue primaries. Red primaries are located at systematically lower redshift, resulting in an offset in the intrinsic luminosities of satellites between the two primary populations if satellites are counted to a fixed apparent magnitude limit (e.g. \(r = 21\) as above, see Section 2). To make the comparison unbiased, we count satellites down to \(r = 21\) around blue primaries, but only down to \(r = 20.76, 20.75, 20.61, 20.66\) and 20.44 around red primaries in the most massive to least massive stellar mass bins quoted in Table 1. We compute these limits from the difference in distance modulus between the median redshifts of red and blue primaries (0.24, 0.25, 0.39, 0.34 and 0.56) which was then subtracted from \(r = 21\).

We show in the left-hand column of Fig. 4 the average satellite number density profiles for red and blue SDSS primaries (solid orange and light-blue curves, respectively). The normalizations of the curves in Fig. 4 depend on primary colour in all stellar mass bins. Red primaries have systematically more satellites at every radius, particularly for the most massive bins (log \(M^*/M_\odot > 10.8\)). This is consistent with the results in Paper I, where we reported a larger total number of satellites around red than around blue primaries at fixed stellar mass. Fig. 4 shows that these ‘excess’ companions are distributed more or less evenly across the full radial range. An excess of satellites around red primaries at fixed luminosity had previously been reported in a number of other studies (Sales et al. 2007; Guo et al. 2012; Wang et al. 2012).

Black dashed curves in Fig. 4 show the predicted dark matter profiles, obtained as in Fig. 2 and Fig. 3. Since the halo mass differs between red and blue primaries of similar stellar mass, we...
Satellite radial distribution

Figure 5. Satellite number density profiles split according to satellite colour. Red and blue curves refer to red and blue satellites, respectively. Primaries are grouped by their stellar mass as before (rows). In the observed sample (left), the radial profile of red and blue satellites varies with primary stellar mass. For massive primaries, blue satellites have significantly shallower profiles than the red population and also than predicted for the dark matter (black dashed curves). However, for primaries with log $M_*/M_\odot < 11.1$, red and blue satellites have comparably steep profiles, which are similar to that expected for the dark matter. Blue satellites dominate in number at all radii for these lower mass primaries. The semi-analytic catalogue (right-hand column) fails to reproduce any of these trends: blue satellites in the model always have a very shallow radial profile and are sub-dominant for all primary stellar masses. Environmental effects are apparently too strong in the semi-analytic model, particularly in low-mass haloes. Red satellite profiles are similar to the dark matter predictions at all masses both in SDSS and in the simulations.

estimate dark matter profiles for red and blue primaries separately using the $M_*-M_{200}$ relations for red and blue primaries in our semi-analytic catalogue. These have been re-normalized to fit the amplitude of the measured satellite profiles. For primaries more massive than log $M_*/M_\odot = 11.1$, satellites around red primaries have significantly shallower profiles than predicted for the dark matter. The profiles around blue primaries are noisier and steeper, but still show some tendency to be shallower than predicted for the dark matter.

In the right-hand column of Fig. 4, we show predictions from our simulated catalogue for comparison with the observed profiles. Overall, the qualitative agreement between models and data, is quite good although the difference in the normalization between red and blue primaries is more pronounced in the models than in the SDSS for primaries less massive than log $M_*/M_\odot = 11.1$. Note that the shapes of the dark matter profiles in the left-hand column of Fig. 4 are based on those of the simulated primaries in the right-hand column, and so may be biased by this difference in colour dependence.

There appears to be an excess of companions at large radii around blue primaries with $10.8 < \log M_*/M_\odot < 11.4$, especially in the right-hand column of Fig. 4. We have checked and found that this is mostly due to the small fraction of our primary sample which, despite passing all our isolation criteria, are nevertheless actually satellite galaxies in massive groups or clusters. The excess counts reflect a contribution from fainter galaxies within these groups/clusters. A similar bump in the SDSS data may have been weakened due to the oversubtraction of background counts at large distances (see the appendix for more details): it still can be seen around primaries with $11.1 < \log M_*/M_\odot < 11.4$. The excess count is substantially weakened if we additionally require all our simulated primaries to be the central galaxies of their FoF haloes. We have checked and found that this bump in the satellite distribution parallels a similar excess at large radii in the mean profiles for the dark matter stacked around these hosts, in good agreement with our previous conclusion that simulated satellites trace the underlying dark matter in considerable detail (see also the appendix).

3.3 Satellite number density profiles: dependence on satellite colour

We explore the radial distribution of satellites according to their colour in Fig. 5. The left-hand column shows results for the SDSS sample. We consider all primaries in a given $M_*$ bin, splitting the satellites into red and blue subsamples (solid red and blue curves, respectively). For this, we use a colour boundary that depends on satellite stellar mass and corresponds to the trough between the blue and red peaks of the satellite colour distributions. Table 2 lists the satellite stellar mass bins and colour cuts used in our study.
Table 2. \((g − r)\) colour cuts for the three satellite stellar mass bins considered in our study.

|        | 10.2–11.2 | 9.2–10.2 | 8.2–9.2 |
|--------|------------|----------|----------|
| \(g − r\)SDSS | 0.796      | 0.731    | 0.666    |
| \(g − r\)mock | 0.606      | 0.526    | 0.446    |

The left-hand column of Fig. 5 shows that the dependence of number density profile on satellite colour is complex. For massive primaries \((\log M_*/M_\odot > 11.1)\), red satellites have steeper profiles than blue ones, and only the former are an approximate tracer of the expected dark matter distribution (black dashed line). Blue satellites have a shallow profile and are sub-dominant at almost all radii. This behaviour changes, however, for lower primary mass. For \(\log M_*/M_\odot < 11.1\), the red and blue satellite populations have similar profiles and both are similar to the expected halo dark matter distribution. At these primary masses, the dominant satellite population is blue.

These results suggest that environmental effects are a strong function of primary stellar mass in our SDSS sample, or equivalently, of host halo mass. Satellites orbiting massive primaries tend to be red, particularly if they are close to the primary. As a result, there is a deficiency of blue objects relative to red in the inner regions. On the other hand, for primaries with \(M_* < 10^{11} M_\odot\), environmental effects are sufficiently weak that satellites can continue to form stars even if they are close to their primaries. The blue population thus maintains the steep profile characteristic of the dark matter and dominates by number at all radii.

This result can be seen more clearly in Fig. 6, which shows the fraction of red satellites as a function of radius in each of our primary stellar mass bins. Because galaxy colours depend intrinsically on stellar mass, we show \(f_{\text{red}}\) separately for satellites in three different stellar mass ranges: \(\log M_*/M_\odot = [8.2 − 9.2]\), \([9.2, 10.2]\) and \([10.2−11.2]\) in blue, green and red, respectively. In agreement with Fig. 5, \(f_{\text{red}}\) is larger than 0.5 only for the most massive primary bins; most satellites remain blue for primaries with \(\log M_*/M_\odot < 10.8\). Notice that although \(f_{\text{red}}\) decreases with radius, the dependence is weak, indicating that environmental effects on satellite colour depend relatively little on distance to the primary.

We compare these SDSS results with profiles from our simulation catalogue in the right-hand column of Fig. 5. Despite the relatively good agreement seen in previous figures, the models do very poorly at reproducing profiles split by satellite colour. This is primarily because, as already noted in Paper I, the fraction of satellites around low-mass primaries which are blue is substantially too low, the discrepancy reaching an order of magnitude at the lowest masses. The profiles for the few blue satellites which remain in the simulation are much shallower than the dark matter profiles, regardless of primary stellar mass. Clearly, satellite colours – and presumably related properties such as specific star formation rates, morphologies, gas fractions – are poorly reproduced by the model, indicating that it is substantially overestimating the effects of environment on these properties of satellites. A similar conclusion was

![Figure 6](http://nras.oxfordjournals.org/)

**Figure 6.** The fraction of red satellites, \(f_{\text{red}}\), as a function of projected distance from isolated SDSS primary galaxies. Each panel corresponds to primaries in a different range of \(\log M_*/M_\odot\), as indicated. Results for satellites in three different stellar mass ranges are shown as curves of different colour. Red satellites are more common around high-mass primaries and also at smaller distances, although the trends with radius are rather weak. Error bars correspond to 100 bootstrap re-samplings of the primary samples.
reached by Guo et al. (2013b) for a different simulation of similar type to the one we analyse here.

3.4 Satellite number density profiles: comparison with previous work

A number of recent studies have examined the distribution of satellites in hybrid samples from spectroscopic + photometric catalogues using methods similar to our own (Lares et al. 2011; Nierenberg et al. 2011, 2012; Guo et al. 2012, 2014; Jiang et al. 2012; Tal et al. 2012). Most of them agree with us in finding the abundance of satellites to depend strongly on primary mass (see also Paper I). However, in several cases the detailed trends we find with primary and satellite properties do not all agree with those published previously. For instance, the very weak dependence of the shape of satellite profiles on primary colour and satellite mass agrees well with Nierenberg et al. (2012), Wang et al. (2011) and Jiang et al. (2012), but is contrary to some of those in Tal et al. (2012), Watson et al. (2012) and Guo et al. (2014), who find bright satellites to be more radially concentrated. Our results are also in partial disagreement with Guo et al. (2012), who found the radial distribution of bright satellites to be less radially concentrated.

Some of these discrepancies can be explained by differences in sample definition. Our selection of isolated primaries discards all galaxy systems where the difference of r-band magnitude between the central object and the satellites is smaller than 1. This makes the comparison of our results with those found in groups and clusters more difficult to interpret. However, comparisons with Guo et al. (2012) are more interesting since their analysis uses similar selection criteria to our own and is also applied to objects in the SDSS/DR7 and DR8 catalogues.

The approaches to quantifying satellite radial distributions differ between our work and Guo et al. (2012): we use abundance matching arguments to infer the expected mean distribution of dark matter around our primary samples, and we compare this with the mean number density profiles we find for satellites, whereas Guo et al. fit NFW profiles directly to their estimated satellite distributions without reference to expectations for the host dark matter haloes. The shapes of the number density profiles they measure for satellites of different luminosity agree for $r_p > 0.12 r_{\text{vir}}$, but differ at smaller radii (see their fig. 6). The variations in the inner profiles are thus not totally unexpected, given the different choices and cuts applied to each sample. Here, we assume a fixed projected radius cut for all primaries in a given mass bin (see Table 1), whereas Guo et al. (2012) deal with the inner regions by excluding annuli that are within 1.5 times the Petrosian radius of the primary galaxy. This is typically a smaller radius than the cut we impose. For example, the luminosity range of primaries in Guo et al. (2012) corresponds roughly to the second most massive primary stellar mass bin in our analysis, for which we use $r_{\text{max}} = 50$ kpc $\approx 0.12 r_{\text{vir}}$ (see Table 1), while the mean inner cut of Guo et al. (2012) is $r_{\text{max}} = 23$ kpc and differs from galaxy to galaxy. On scales smaller than 0.1$r_{\text{vir}}$ systematics caused by proximity to the primary image are argued to be important by both Tal et al. (2012) and Watson et al. (2012), whereas no photometric corrections are made by Guo et al. (2012), which perhaps accounts for the different conclusions about inner profiles in these three studies. We chose such a more conservative inner radius cut because we have tested that satellite profiles at these radii are sensitive to photometric systematics (see the appendix of Paper I for more details). We exclude these radii from our analysis specifically to avoid the need to correct for such effects.

![Figure 7. Cumulative distribution of (look-back) infall times $t_{LB}$ for satellites with $\log M_*/M_\odot > 9$ in the semi-analytic galaxy catalogue.](http://mnras.oxfordjournals.org/)
stellar mass bins defined above. Note that we only consider ‘true’
satellites, defined as objects with 3D positions within the virial
radius of each host halo, when we make this plot, although we bin
as a function of projected radius to enable more direct comparison
with observed systems.

As expected, satellites in the inner regions typically have a longer
time since infall than those at large radii, consistent with inside-out
growth of the satellite population. Interestingly, we find that the time
since infall is also typically longer in more massive haloes. This
is surprising, because dark matter concentrations and formation
redshifts are typically lower for more massive haloes. The trend
we see is in part due to the fact that our isolated primaries are
usually the central galaxies of fossil groups (galaxy groups with a
large magnitude difference between the first and second brightest
galaxies) and these assemble earlier than typical groups of their
mass. The second brightest companions in our mock catalogue are
typically 1.9, 2.4, 2.8, 2.8 and 2.5 mag fainter in r-band than their
primaries in the most- to least- massive stellar mass bin, respectively.

Fig. 7 shows that around isolated galaxies similar in mass to the
Milky Way (the blue curves), half of all satellites that today have
\( r_p < 0.3 \, r_{\text{vir}} \), first fell within the virial radius of the primary more than
5 Gyr ago, whereas for satellites with \( r_p > 0.6 \, r_{\text{vir}} \) the median time
since infall is =\~2 Gyr. Figs 5 and 6 show that most observed satellites
of primaries with \( \log M_*/M_\odot < 11.1 \) are blue, even at small radii,
so the time-scale for shutting-off star formation apparently needs to
be at least 5 Gyr in such systems. For comparison, in the G11
model analysed here, the mean time since infall for blue satellites
of primaries with \( \log M_*/M_\odot = 11.1 \) is only =\~0.9 Gyr.

If satellites in the G11 model redden too quickly compared to
observation, could overly early collapse and halo assembly (due to
an overly large \( \sigma_s \) value) be responsible? We show in Fig. 8 the
effect of cosmology on satellite profiles split by colour. Thick solid
lines correspond to the Guo et al. (2013a) model (G13), which
is the same as G11 except that it corrects the cosmological parameters
to be consistent with Wilkinson Microwave Anisotropy Probe 7
(WMAP7). The differences from the original G11 model (the thin
dotted lines) are small, indicating that the assumed background
cosmology has little effect on the properties of satellites and thus
cannot explain the discrepancy between the semi-analytic model
and the SDSS data.

We take a closer look at the impact of different physical as-
sumptions on the predicted profiles of red and blue satellites by
analysing predictions from an updated model specifically targeted
at improving the treatment of satellite and low-mass galaxies. This
model (Henriques et al., in preparation) is based on G13 and adopts
most of its physical prescriptions. An important modification is an
increase in the time-scale for reincorporation of material ejected
to large radius by supernova explosions, particularly in low-mass
systems and early times. This follows Henriques et al. (2013) and
extends star formation to later times in low-mass galaxies. It has
a large impact on the properties of central galaxies but the strong
environmental effects in G11/G13 prevent it from substantially in-
creasing the number of blue satellites.

To address this problem, the updated model also reduces the
threshold for star formation and removes the effects of ram-pressure
stripping in galaxy groups. (Tidal stripping is assumed to act in
groups of all masses, whereas ram-pressure effects are eliminated
for group masses \( M_{\text{vir}} < 10^{14} M_\odot \).) These changes cause satellites
in low-mass groups to retain their extended gas reservoirs for longer,
and to convert more of their cold gas into stars. Together these mod-
fications ensure that the bulk of low-mass satellites remains blue at
later times. This model also updates the cosmological parameters
to be consistent with Planck results, and modifies the scaling of the
active galactic nucleus radio-mode feedback to improve the proper-
ties of high-mass galaxies. These last two changes have a negligible
impact on the properties analysed here.

Fig. 9 shows the distribution of red and blue satellites in the
updated model (thick solid lines). Observations from SDSS are
indicated by thin dashed lines. The new recipes produce a significant
increase in the number of blue satellites around primaries of all
masses. As a result, the normalization of the predicted blue popula-
tion gets closer to observations. However, the profile shape for this
blue population is only similar to that observed for the two most
massive primary bins. Profiles are still significantly shallower than
observed for low-mass primaries.

These results, together with an extensive series of tests in which
we have arbitrarily suppressed individual environmental effects (not
shown here for brevity) seem to indicate that straightforward modi-
fication of standard environmental effects cannot lead to a satel-
lite population which remains predominantly blue at small separ-
atons. A possible solution might involve the enhancement of
star formation in satellites near halo centre, perhaps as a result of
tidal effects induced by the primary. There is some direct obser-
vational evidence that star formation can indeed be triggered by
close tidal interactions (e.g. Lambas et al. 2003; Ellison et al. 2008;
Li et al. 2008), and starbursts which may be tidally induced have slightly shallower profiles than are predicted for the dark matter in their host haloes, whereas for less massive primaries $10.2 < \log M_*/M_\odot < 11.1$ satellites follow quite closely the predicted dark matter profiles.

(ii) We find the shape of satellite number density profiles to depend at most weakly on satellite stellar mass.

(iii) Red primaries have more satellites than blue primaries of the same stellar mass, at least for $\log M_*/M_\odot > 10.8$.

(iv) Observed satellite number density profiles depend on satellite colour and behave differently for high- and low-mass primaries. For primaries with $\log M_*/M_\odot < 11.1$, the blue and red populations have profiles of similar shape, consistent in both cases with that predicted for the dark matter distribution. Blue satellites dominate at all radii. Around more massive primaries ($\log M_*/M_\odot > 11.1$), the blue population has a shallower profile and is subdominant at all radii.

We compare these observational results with satellite samples selected from the galaxy population simulation of G11. The number density profiles of the whole satellite population always parallel the dark matter profile of the host halo, regardless of primary mass; this disagrees with the SDSS result for massive primaries. This may reflect the need for more efficient tidal disruption of satellites in the model. Satellite colours remain the most important challenge to these theoretical models, however. In the model, the fraction of blue satellites is too small, particularly around low-mass primaries, and the few remaining blue satellites have an almost flat radial profile, in clear disagreement with the observations.

Given that observed satellites of low-mass primaries are predominantly blue at all projected radii, the distributions of time since infall that we find for simulated satellites imply that real satellites can remain actively star forming as much as 5 Gyr after they have fallen into their current host halo, even when their orbit takes them into its inner regions. This seems qualitatively consistent with earlier work reporting that the decline of star formation in satellites occurs over extended periods of time (e.g. Wang et al. 2007; Weimann et al. 2009; Trinh et al. 2013; Wetzel et al. 2013; Wheeler et al. 2014). The significantly shorter time-scales implied by our model (~0.9 Gyr) are responsible for its overabundance of red satellites. This indicates that the environmental suppression of star formation is overestimated by the model, particularly around low-mass primaries, and perhaps that the environmental stimulation of star formation needs to be included.

Indeed, from a series of experiments with differing treatments of environmental processes, we find that although the combined effect of suppressing ram-pressure stripping in low-mass haloes ($M_{\text{vir}} < 10^{14} M_\odot$) and decreasing the density threshold for star formation can bring the overall blue fraction into agreement with SDSS, the shape of the blue satellite profile remains much flatter than observed. The fact that SDSS satellites are still predominantly blue even a few tens of kpc from low-mass primaries, suggests that processes which enhance star formation during close encounters need to be introduced into the models. Progress in this area will require a better understanding of tidally or shock-induced star formation, as well as observational studies which resolve the structure of star-forming regions in typical satellite galaxies.

5 CONCLUSION AND DISCUSSION

We study the mean number density profiles of satellites around isolated primary galaxies selected from the spectroscopic catalogue of SDSS/DR7. We select satellites from the full photometric catalogue of SDSS/DR8, correcting statistically for contamination by unrelated foreground and background galaxies. Our sample contains about 41,000 isolated primaries with $\sim 7000 \text{,000}$ photometric companions (including background) projected within 500 kpc. We explore the dependence of these profiles on the stellar mass and colour of both primaries and satellites. Our results can be summarized as follows.

(i) The radial distribution of satellites depends on primary stellar mass. Satellites around massive primaries $\log M_*/M_\odot > 11.1$ have slightly shallower profiles than those observed in SDSS (the thin dashed curves). (thick solid lines) is increased significantly, but the profiles remain flatter than those observed in SDSS (the thin dashed curves).

Figure 9. Prediction from an updated semi-analytic model (from Henriques et al., in preparation) which, relative to the G11 model, has delayed reincorporation of gas ejected by supernovae, a lower star formation threshold, and no ram-pressure stripping in galaxy groups. The fraction of blue satellites (thick solid lines) is increased significantly, but the profiles remain flatter than those observed in SDSS (the thin dashed curves).

Satellite radial distribution

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APPENDIX A: PROJECTION EFFECTS IN A LIGHT-CONE AND THE LOCAL ENVIRONMENT OF ISOLATED GALAXIES

Throughout our paper, we have compared rectilinear projections of snapshots of the Millennium and Millennium-II simulations with observations from SDSS. Although most projection effects are taken care of in a realistic way in these mock galaxy samples (redshifts are computed using the line-of-sight distance within the box together with peculiar velocities), there are several factors affecting the SDSS data that are not properly represented. Among these, effects due to the fixed flux limit of a real survey and the $K$-corrections needed to obtain rest-frame magnitudes, fibre–fibre collision effects which make it difficult to obtain redshifts for close galaxy pairs, and the effects of the survey geometry stand out as possible sources of concern for our analysis. To address these issues, we have paralleled the analysis presented in the main body of our paper with the studies of satellite profiles obtained from a light-cone galaxy catalogue taken from Henriques et al. (2012).6 This light cone is generated from the same Millennium-based galaxy population simulation as our other model catalogues, but properly includes evolutionary and band-pass shifting effects, as well as the flux limits of the survey, a simplified model for the effects of fibre–fibre collision, and the geometry of the SDSS mask. The selection for primaries and satellites can be applied to this light-cone catalogue in exactly the same way as to the observed SDSS sample.

Overall, we find good agreement between our original mock catalogue and that generated from the light cone. We illustrate this by showing the projected number density profiles of satellites split according to primary colour from the light-cone sample in Fig. A1. Panels indicate different primary stellar mass bins, with the log $M_*/M_\odot$ ranges quoted at the top left of each box. As before, orange and light-blue curves correspond to satellites of red and blue primaries, respectively (colour cuts for each primary stellar mass bin are as quoted in Table 1). This figure should be compared with the right-hand column of Fig. 4. To guide the eye, the black dashed lines in Fig. A1 are exactly those in the right-hand column of Fig. 4. Agreement between the two samples is generally good, but for low-mass primaries, particularly blue ones, satellite profiles tend to fall off more rapidly at large radii than for the dark matter (black dashed lines). This effect is only marginally detected but appears to reflect a bias in the environment of our primaries (see the text for more details).

The probable source of this effect is an overestimation of the background subtraction in our light-cone samples (both observational and simulated). The isolation criteria for primaries used in this paper and also in Paper I is quite strict, and as a result objects that fulfil it are significantly biased towards low-density environments. Since our satellite profiles are estimated by subtracting the average projected number counts from the full catalogue, we over-correct for background at about the $\sim 1$ per cent level. Although this is not a large effect in the satellite population as a whole, it becomes noticeable when the signal is weak, i.e. at large distances from low-mass primaries.

We explore the local environment of isolated galaxies further in Fig. A2, where we have selected primary galaxies from SDSS with more relaxed isolation criteria, increasing the primary sample by

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6 This catalogue is available at http://www.mpa-garching.mpg.de/millennium
isolation criteria translate into significantly shallower satellite profiles at large radii than those we obtained in Section 3.2 (the slope differences are significant only for $r > 0.5r_{\text{vir}}$). We have checked that this excess is due to the inclusion of a larger fraction of primaries that are not central galaxies of their FoF halo, with the consequences for the satellite profiles discussed in Section 3.2. Interestingly, the mean dark matter profiles in the simulation for this new primary sample show a similar excess at large radius, further evidence for our claim that satellites do indeed trace the underlying dark matter distribution very well, at least in the simulation. We also notice slightly higher normalizations for the inner satellite profiles in this new sample compared to Fig. 4. Primaries with relatively bright companions have more faint satellites than those which do not, an effect that we traced back to their having slightly more massive haloes.

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