Local and global environmental effects on galaxies and active galactic nuclei

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ABSTRACT
We study the properties of Sloan Digital Sky Survey (SDSS) galaxies with and without active galactic nucleus (AGN) detection as a function of the local and global environment measured via the local density, mass of the galaxy host group (parametrized by the group luminosity) and distance to massive clusters. Our results can be divided into two main subjects: the environments of galaxies and their relation to the assembly of their host haloes, and the environments of AGNs. (i) For the full SDSS sample, we find indications that the local galaxy density is the most efficient parameter to separate galaxy populations, but we also find that galaxies at a fixed local density show some remaining variation in their properties as a function of the distance to the nearest cluster of galaxies (in a range of 0–10 cluster virial radii). These differences seem to become less significant, if the galaxy samples are additionally constrained to be hosted by groups of similar total luminosity. If instead of fixing the local density, the mass of the host group is held fixed at a given value, the fraction of red galaxies also increases as the distance to clusters diminishes, indicating that neither the local density nor the host halo mass contains all the information on the environment. (ii) In AGN host galaxies, the morphology–density relation is much less notable when compared to the behaviour of the full SDSS sample, indicating a lack of sensitivity to the host group mass during the AGN phase, probably due to the higher typical luminosities of the AGN hosts. In order to interpret this result, we analyse control samples constructed using galaxies with no detected AGN activity with matching distributions of redshifts, stellar masses, r-band luminosities, g − r colours, concentrations, local densities, host group luminosities and fractions of central and satellite galaxies; the aim in using the control sample is to detect any correlations between the AGN detection and other AGN host properties that are unrelated to the AGN selection. The control samples also show a similar small dependence on the local density, indicating an influence from the AGN selection, but their colours are slightly bluer compared to the AGN hosts, regardless of the local density. Furthermore, even when the local density is held fixed at intermediate or high values, and the distance to the closest cluster of galaxies is allowed to vary, AGN control galaxies away from clusters tend to be bluer than the AGN hosts. However, AGN in bright, low-concentration hosts (i.e. discy morphologies) are bluer than galaxies in the control sample, connecting the presence of discs to AGN activity even under a controlled comparison between active and inactive galaxies.

Key words: surveys – galaxies: active – galaxies: clusters: general – large-scale structure of Universe.

1 INTRODUCTION
The description of the large-scale structure in the Universe and how it relates to the properties of galaxies in different environments has become more intricate in the last few years. In order to understand the environmental dependence of galaxy properties, it is now necessary to combine results, where the environment comes from local density estimates, the host halo mass, the distance to cluster centres, together with a theoretical understanding of what could influence the star formation (SF) activity and morphological transformations in galaxies. This introduction will first review the assembly effects

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on the galaxy population of haloes of equal mass, then the results from the literature on the environment studies of galaxies, and finally the properties of the hosts of active galactic nuclei (AGNs) and their dependence on the environment.

1.1 Properties of galaxies in equal-mass haloes: assembly effects

Up to only a few years back it was believed that the mass of a dark matter (DM) halo was the only important parameter that defined its clustering properties (see, for instance, Mo & White 1996; Sheth, Mo & Tormen 2001; Padilla & Baugh 2002) and galaxy population (e.g. Cole et al. 2000). The latter has been studied in the framework of the Halo Model (Jing, Mo & Börner 1998; Peacock & Smith 2000; Cooray & Sheth 2002; Cooray 2005, 2006), whereby the typical number of galaxies per DM halo, typical central and satellite luminosities, SF activity and possibly their colours depend solely on the host halo mass (Weinmann et al. 2006; Wang et al. 2008). However, recent studies on the clustering of DM haloes found that the age and assembly history of haloes of similar mass also play a role in their clustering amplitude. The dependence on the halo age was first reported by Gao, Springel & White (2005) and has been studied in more detail, finding a general dependency on the way in which a halo is assembled by Gao & White (2007), Jing, Suto & Mo (2007), Croton, Gao & White (2007), Wechsler et al. (2006) and Li, Mo & Gao (2008). The assembly bias has also been detected in observations by Wang et al. (2008); their studies only concentrate on the clustering amplitude of different samples selected according to the group colour, which they associate with the group age. In addition to a difference in the clustering amplitude, Zapata et al. (2009) demonstrated that groups of similar mass and different assembly histories also show important differences in their population of galaxies, an aspect that can be added to the present halo model and conditional luminosity functions and that can also be used to improve the modelling and understanding of the evolutionary processes that shape galaxies in the observed Universe.

Extending this particular problem, Wang et al. (2009a) found a subpopulation of red, dwarf isolated galaxies that are not satellites of larger haloes, but are concentrated around their nearest massive halo. Such isolated dwarfs are expected to be able to form stable haloes and therefore show blue colours. These red, dwarf galaxies would fit within the galaxy formation scenario, if they inhabit subhaloes that have been expelled from clusters and have acquired their red colours earlier, when they were under the effects that satellites suffer in clusters, such as strangulation, ram-pressure and tidal stripping, processes that quench the SF activity. On the theoretical side, Wang, Mo & Jing (2009b) found that some small fraction of the assembly bias effect comes from such subhaloes.

These results, however, concern only the population of galaxies inside individual DM haloes (or ejected subhaloes).

1.2 Measurements of environment and the properties of galaxies

On the large-scale structure side, starting with the pioneering work of Dressler (1980), the location of a galaxy has been shown to have an influence on its average properties. Using large redshift surveys, Balogh et al. (2004) found a smooth transition from high-density regions populated with red galaxies towards blue-dominated low-density regions. These results pointed to the density of the region, where galaxies live as being responsible for important characteristics of the galaxy population. This was also confirmed at higher redshifts in the Sloan Digital Sky Survey (SDSS, York et al. 2000) by O’Mill, Padilla & Lambas (2008). Numerical simulations following the evolution of DM, with galaxy populations imprinted on them via semianalytic models, have shown that the prevalence of red galaxies in high-density regions can be naturally achieved in a Lambda cold dark matter ($\Lambda$CDM) hierarchical cosmology (Bower et al. 2006; Cattaneo et al. 2006, 2008; Croton et al. 2006; Lagos, Cora & Padilla 2008; Lagos, Padilla & Cora 2009). The remaining question with respect to this general behaviour resides in whether this population change was due to local or global effects, that is, whether the dependence of properties on the local density responds mainly to the dependence on halo mass alone or also to assembly and other effects, such as ejection from hosts.

Kauffmann et al. (2004) found little evidence of a dependence of star formation (SF) indicators on the environment measured over scales larger than $1 \ h^{-1}\ Mpc$. However, more recent results around voids in the SDSS by Ceccarelli, Padilla & Lambas (2008) suggested that the local density is not the only parameter defining a galaxy population. They showed that at a fixed local density, the fraction of blue galaxies increases towards the regions corresponding to void walls; this represented a first measurement of a large-scale modulation of SF in galaxies. This behaviour was later confirmed in numerical simulations by González & Padilla (2009), who analysed semianalytic galaxies from the semi-analytic galaxies (SAG) model (Lagos et al. 2008, 2009) and found that this was also the case for galaxies with a fixed local density, at increasingly larger distances from clusters of galaxies or closer to voids. Furthermore, they found that this change at a fixed local density is mostly due to the effect of the mass of the host halo, with a remnant variation that can be tied to the assembly history of the haloes hosting these galaxies. The reason for a dependence on mass is related to the different physical processes taking place in haloes of different masses. For instance, at very low halo masses, $M < 10^{10} \ h^{-1} \ M_{\odot}$, reionization from a ultraviolet radiation field plays an important role in the photoionization of baryons; this effect along with stellar feedback significantly reduces the baryon fraction available to form stars in such low-mass haloes (Tassis et al. 2002). The reason for a dependence on the assembly is that, for instance, more recent merger activity can have an important impact on the colours of galaxies. Therefore, even though local processes may extend out to $\sim 1 \ h^{-1} \ Mpc$, global processes affecting the underlying mass function and the rate of growth of haloes (assembly) help extend the variation of galaxy properties to much larger scales, up to tens of Mpc.

1.3 AGN host properties and their dependence on the environment

Regarding the environmental dependence of galaxies with AGNs, there is still a debate on the frequency of occurrence of AGNs as a function of the local density. For instance, Miller et al. (2003) found that the fraction of galaxies with AGNs appeared to be constant with local density, even when dividing the sample according to the host morphology into spiral and elliptical galaxies (see also Dressler et al. 1999). Using the SDSS, Kauffmann et al. (2004) confirmed this result only for AGNs with weak emission in the O$_{\alpha}$ line. They claim that for high O$_{\alpha}$ emitters the fraction of galaxies with AGNs decreases as the local density increases (see also Popesso & Biviano 2006). It should be noted that these studies do not reach densities as high as those in clusters of galaxies. Pasquali
et al. (2009) studied the variation of the SF and AGN activity of central and satellite galaxies as a function of their host DM halo mass (ranging from low mass groups to clusters of galaxies) to find a smooth and continuous transition from SF to AGNs and to radio activity as the halo mass and the stellar mass increase, for both centrals and satellites, the latter showing lower activity than the former at all halo masses; furthermore, they show that the dependence on the environment (as indicated by the halo mass) is weaker than on the stellar mass of the host galaxy. Other studies of AGNs in clusters show a higher frequency of X-ray sources than in the field (Cappi et al. 2001; Martini et al. 2002; Molnar et al. 2002). Furthermore, using clustering analyses, Gilli et al. (2003) also found higher correlation amplitudes for X-ray-selected AGNs. Additionally, Martini, Sivakoff & Mulchaey (2009) found that the fraction of AGNs in clusters of galaxies decreases for lower redshifts; this could help obtain a smooth transition between the results from these X-ray-detected AGNs and those by Kauffmann et al. (2004).

There are also studies of the environment in which AGNs are embedded, which focus on the morphology and other characteristics of their hosts and their neighbours (including their local density, colours, etc.). Choi, Woo & Park (2009) studied AGN hosts in the SDSS Data Release 5 (DR5, Adelman-McCarthy et al. 2008). They found that late morphological types are the dominant hosts, regardless of the AGN power, and that bluer late types host the most powerful AGNs (also in agreement with Coldwell et al. 2009), confirming earlier results by Kauffmann et al. (2003a), who additionally showed that the young stars in the powerful AGNs reside preferentially away from the nucleus and that their hosts have suffered a starburst in the recent past. Additionally, Kauffmann et al. (2003a) showed that these results do not depend on the Seyfert type (for equal \( L_L/\text{edd} \)). Going into more detail on the different AGN types, Kewley et al. (2006) showed that the hosts of low-ionization narrow emission-line regions (LINERs, characterized by low luminosities with respect to the Eddington value) are older, more massive, less dusty, less concentrated and have higher velocity dispersions than Seyfert galaxies (characterized by higher \( L_L/\text{edd} \)). Waskell et al. (2005) found that the environments of AGNs at \( 0.4 < z < 0.6 \) are similar to those of normal galaxies at the same redshifts and consist of group-like environments. Gilmour et al. (2007) confirmed this result finding that AGNs in bright galaxies at \( z = 0.17 \) (in a region corresponding to a supercluster) show a preference for intermediate environments and are preferentially surrounded by blue galaxies. More recently in zCOSMOS (Lilly et al. 2007), Silverman et al. (2009) confirmed that AGNs tend to prefer intermediate environments, such as groups, and also found AGNs hosted by massive galaxies with stellar masses \( M_\ast > 2 \times 10^{10} \text{M}_\odot \) that occur preferentially in low-density environments, where disruptive processes (mergers) are lessened. Results on the environment of high-redshift AGN sources (detected via X-ray counterparts of ACS images) are presented by Martel et al. (2007), who found that \( z \approx 1 \) AGNs prefer regions that are more crowded than for the typical galaxy in the field, giving clues on the possible nature of the hosts of these AGNs; however, they also warned about possible systematic effects in their results. More recently, von der Linden et al. (2010, see also Montero-Dorta et al. 2009) studied the variation in the fraction of AGN hosts as a function of the distance to cluster centres in the SDSS. They analysed the time-scale over which the AGN activity shuts down and found that this coincides roughly with the crossing time-scale of the clusters, and that this is similar to the time-scale of general SFR shut-down; note that their analysis does not discriminate the changing local density as the distance to the cluster centres varies.

Centring mostly on low-accretion-rate AGNs, these studies have helped shed light on the feeding and growing mechanisms of AGNs and their influence on the SF activity of the host galaxies. For instance, Koulouridis et al. (2006) studied the origin of the AGN activity in relation to their immediate environment. Their analysis of bright \( I/\text{RS} \) galaxies in comparison to that of AGNs helped them to conclude that close interactions drive fuel to the AGNs, which produces obscured AGN activity. They inferred that only when the close neighbour moves away, the AGN becomes unobscured. Martini (2004) presents an extended review on the relation between AGN fueling and environment. These results are in good agreement with morphological studies by Pasquali, van den Bosch & Rix (2007), who found that the AGN activity is associated with an increase in the fraction of galaxies with stellar discs, and Hao et al. (2009), who detected an increase in the fraction of barred hosts with the presence of AGNs. Along the same lines, Donoso et al. (2009a) found, via clustering studies of radio-loud AGNs, that there is an influence of the gaseous content on scales of the host DM halo on the probability that an AGN is radio-loud and on the jet luminosity (see Donoso, Best & Kauffmann 2009b) for a study on the evolution of radio AGNs with redshift.

1.4 The object of this work

In this paper, we will focus on the variation of galaxy properties at different global environments as traced simultaneously by the local density and by the distance to the nearest clusters of galaxies, which as mentioned above should include both a dependence on the host DM halo mass, halo assembly and other effects, such as, for instance, dynamical coherence or ejection from larger haloes. We will study galaxy colours, concentrations and colour–magnitude relations for normal galaxies, on the one hand, and for galaxies with AGNs, on the other, with the aim to provide further clues on the interplay between large-scale structure, assembly history and galaxy evolution. The reader should bear in mind that the environmental behaviours of normal galaxies and of AGN hosts will not be compared to one another due to the different selection effects in play, but will be used to try to improve our understanding of the galaxy formation process. In the case of AGN hosts, we want to stress the fact that we will focus our analysis of the environmental dependence via variations with the environment instead of studying the fraction of galaxies hosting AGNs. In order to overcome the possible influence from selection effects associated with the detection of AGN signatures in the spectra of the galaxies, we will rely on the definition of control samples that match several properties of the AGN hosts to mimic their selection function as best as possible. Finally, we will use the galaxy colour as an indicator of SF activity, bearing in mind that this quantity also depends on SF history, metallicity and reddening.

This paper is organized as follows. Section 2 presents the sets of observational data and definition of samples used in this work; in Section 3, we explore distributions of galaxy colours and concentrations for the full sample of galaxies and for AGNs. We present our results and compare them to the literature in Section 4, which also contains our conclusions.

2 DATA

2.1 SDSS galaxies and AGNs

We study galaxies from the spectroscopic SDSS Data Release 7 (DR7, Abazajian et al. 2009), which consists of \( \sim 686,000 \) galaxies
with measured spectra and photometry in five photometric bands $ugriz$. In our analysis, we restrict the full sample of SDSS galaxies to $z < 0.1$, which leaves a total of 307,254 galaxies. This redshift limit reduces the effects from flux incompleteness; we correct for the remaining incompleteness effects by weighting each galaxy by the inverse of the maximum volume out to which it can be detected.

Several galaxy parameters are provided by the automated SDSS pipeline out of which we make use of the Petrosian magnitudes and the radii containing 50 and 90 per cent of the total flux of each galaxy, calculated in the r photometric band. We define the bulge concentration parameter

$$c_b = \frac{r_{50}}{r_{90}}$$

which has been proposed as a morphological discriminator such that low (high) concentration galaxies consist preferentially of spiral (elliptical) types (Shimasaku et al. 2001; Strateva et al. 2001).

We use the $O\alpha$, $N\alpha$, $H\beta$ and $H\alpha$ line ratios measured by Kauffmann et al. (2003b) initially for the SDSS Data Release 1 (DR1, Abazajian et al. 2003) updated to the Data Release 4 (DR4), to select AGNs in our sample, to compare their characteristics with that of the full galaxy population. We follow Kauffmann et al. (2003b) and define a galaxy as an AGN, if

$$\log \left( \frac{[O\alpha]}{H\beta} \right) > \frac{0.61}{\log([N\alpha]/H\alpha)} - 0.05 + 1.13,$$

with all four lines satisfying signal-to-noise ratio >3. There are 36,107 AGNs with $z < 0.1$ in this sample. According to Kauffmann et al. (2003b), none of the AGN emission features affect the r-band photometry or the concentration parameter of the galaxies in our samples. Our analysis of AGN hosts will also take into account the redshift-dependent detection limit by weighting each galaxy by the maximum volume out to which it would be detected, given the magnitude limit of the survey $r = 17.77$. Hao et al. (2005) noted that this limit would only be slightly different for the detection of the AGN spectral lines, estimating corrections of less than a 10 per cent.

In the remainder of this paper, we will consider galaxies with no (or undetected) AGN activity as those with null luminosity in the $O\alpha$ emission line in the spectroscopic DR4 sample (130,828 galaxies out to $z = 0.1$).

### 2.2 SDSS Group catalogue

We use the group catalogue constructed from the SDSS-DR6 by Zapata et al. (2009), updated to the full DR7. This catalogue is based on a friends-of-friends (FOF) algorithm, which uses a varying projected linking length $\sigma_i$ with $\sigma_i = 0.239 h^{-1}$ Mpc and fixed radial linking length $\Delta V = 450 \, \text{km s}^{-1}$. These parameters correspond to the values found by Merchán & Zandivarez (2005) to produce a reasonably complete sample (95 per cent) with low contamination ($\lesssim 8$ per cent). The quality of the group catalogue has been analysed by applying the same group identification algorithm to an SDSS mock catalogue (Zapata et al. 2009). We acknowledge previous group compilations using the FOF technique on the SDSS DR3 (Merchán & Zandivarez 2005) and DR4 (Yang et al. 2007) and using percolation algorithms (Berlind et al. 2006) on the NYU-VAGC (Blanton et al. 2005). We adopt the Zapata et al. groups, since this choice allows us to control the measurements of the group centre, mass (or group luminosity) and membership. In addition, we are also able to use a larger sample of galaxies, that of the SDSS DR7. The sample of groups extends out to $z = 0.12$, with a total of 15,140 groups with at least four galaxy members.

Due to the flux limit affecting the galaxy sample from which the groups are identified, the number of galaxies per group does not correlate well with mass. We use the virial theorem to compute the virial mass of groups, which is given by

$$M_{\text{vir}} = \frac{3\sigma_v^2 R_{\text{vir}}}{G},$$

where $\sigma_v$ is the line-of-sight velocity dispersion and $R_{\text{vir}}$ is estimated as in Merchán & Zandivarez, (2005):

$$R_{\text{vir}} = \frac{\pi N_g(N_g - 1)}{2 \sum_{i>j} R_{ij}},$$

where $N_g$ is the number of galaxy members and $R_{ij}$ are the relative projected distances between galaxies. In order to ensure a high completeness for our sample of groups, we apply a second cut in the group mass of $M > 3 \times 10^{12} h^{-1} M_{\odot}$.

We divide our sample of groups in (i) a cluster sample, comprising all groups with virial masses $M_{\text{vir}} > 10^{14} h^{-1} M_{\odot}$, to be used as landmarks of high-density regions for a global density estimator and (ii) the rest of the groups, called hosts sample; a proxy for their masses will be used as indicators of the immediate environment of galaxies.

The cluster sample is used to define the global environment of galaxies as follows. For each galaxy, we compute the distance to all clusters in units of the cluster virial radius. The shortest distance is used to tag each galaxy so that samples at different distances from clusters can be constructed using this parameter. In the case where a galaxy falls within one virial radius of a cluster, in projection, and its velocity difference is $\Delta v < 500 \, \text{km s}^{-1}$, we consider the galaxy to lie within the cluster. The velocity difference is adopted to take into account the ‘finger-of-god’ effect.

We use the hosts sample to assign individual galaxies a host DM halo mass. If a galaxy lies within a group – if it has a host group or host DM halo – its virial mass is assigned to the galaxy. Galaxies outside groups are assumed to be hosted by groups of masses below the completeness limit of the catalogue (groups with four or more members), $M_{\text{host}} < 3 \times 10^{12} h^{-1} M_{\odot}$. In turn, once all the galaxies are assigned to groups, a group luminosity is measured for each group in the sample by summing the luminosities of the four brightest galaxy members in each group. This quantity is a better proxy for the true, underlying group mass than the virial mass (Eke et al. 2004, Padilla et al. 2004) and it is our parameter of choice to place further cuts on our samples of galaxies (the stellar mass of member galaxies could be a better proxy for the group mass than the galaxy luminosity; e.g. More et al. 2010). Out of our full samples of DR7 galaxies and DR4 AGN hosts, 66 and 69 per cent reside in groups above the completeness limit, respectively.

### 2.3 Control samples for AGN hosts

Given the possible selection biases affecting the AGN hosts, we construct samples of control galaxies by randomly selecting those with no detected AGN activity in the SDSS-DR4, such that they

1. The choice of minimum mass can be varied with only minor effects on our conclusions. We tested limits as low as $M_{\text{vir}} > 10^{13} h^{-1} M_{\odot}$ consistent with the lower limit adopted by González & Padilla (2009).

2. In González & Padilla (2009), it was shown that for fixed local density environments, most of the remaining global variation in galaxy properties were due to variations in the host halo mass; the dependencies shown by the galaxy properties after fixing their local density and host halo mass could be due to the assembly history of their host haloes (a minor effect).
reproduce (to a ~10 per cent or better) the normalized distributions of redshifts, absolute magnitudes (rest-frame \( r \) band), stellar masses, local density \( \sigma_5 \) and \( r_{90}/r_{50} \) \( r \)-band concentrations of the AGN hosts. Additionally, we require that the distributions of host group luminosity are the same between control and AGN samples. In the case of AGN hosts with no associated groups, we force the control samples to have the same fraction of such objects. The control samples also contain the same fractions of central, brightest, second brightest and faint satellites as the AGN hosts; in our case, the brightest galaxy (\( r \) band) in the group is considered the central galaxy. This procedure is similar to the one adopted by Pérez et al. (2009a) to study the variations of galaxy properties as a function of the environment when these are in pairs. As we are interested in the variations in galaxy properties when these host an AGN, our selection of the control sample uses the stellar masses as well; for the general galaxy population, this is not expected to produce important changes after the luminosity, local density and host halo mass are constrained Pérez et al. (2009a). Pérez, Tissera & Blaizot (2009b) claimed that an adequate control sample can help disentangle morphological and environmental effects on the galaxy population.

As we will show later in this work, the distance to the nearest cluster of galaxies produces only mild changes in the galaxy properties, and therefore we have not used this parameter to place further constraints on the control samples.

As a result of these constraints, of the full sample of non-AGN galaxies containing 130 828 galaxies, a total of 7311 galaxies comprise the final control sample. Fig. 1 shows in different panels the resulting normalized distributions of parameters used to define the control samples. The dashed lines correspond to the AGN hosts, solid lines correspond to the control sample and dotted lines correspond to the full galaxy population. As can be seen, the distributions of properties for the AGN and control samples match each other in shape, even for the distance to the closest cluster in units of virial radii, which was not used to define the control sample.

By comparing the distributions for the full galaxy population (dotted lines) to that of the AGN hosts, it can be seen that the latter are concentrated towards the red peak of the colour distribution, and are characterized by higher luminosities (the peak of the distribution of absolute magnitudes is about 1 mag brighter) and stellar masses (consistent with e.g. Silverman et al. 2009) and therefore higher redshifts. It can be seen that the normalized distribution of host group luminosities is lower in amplitude for the full sample of galaxies at this range of luminosities. This is due to a higher fraction of galaxies with no host group in comparison to the AGN host samples, also consistent with Silverman et al. (2009), who found that AGN hosts are preferentially found in groups of higher mass. Also, the fraction of central galaxies in the full sample is (14.0 ± 0.1) per cent compared to a higher fraction of (16.4 ± 0.4) per cent in the AGN sample (as in Pasquali et al. 2009). It should be borne in mind that these differences may be due, at least in part, to selection effects associated to the detection of AGN features. The local density and the distance to the closest galaxy clusters show similar distributions for the full and AGN host samples, indicating constant fractions of AGNs as a function of these two environment measurements. The grey long-dashed line in the lower left-hand panel shows the distribution of local densities for high \( O \) luminosity AGNs [\( \log_{10}(L_{\text{O}}/L_{\odot}) > 6.4 \), corresponding to the median luminosity of the sample and the LINER limit], which shows a lower abundance of bright AGNs at higher densities, in agreement

**Figure 1.** Comparison between AGN hosts (dashed lines), control galaxy (solid lines) and full galaxy population properties (dotted lines) indicated in each panel (the distributions are normalized to ensure unit integrals). The parameters used to constrain the members of the control sample are the \( g - r \) colour, \( M_r \) rest-frame absolute magnitude, redshift, stellar mass, local density (in this subpanel, the grey long-dashed line corresponds to the high \( O \) in luminosity AGNs), luminosity of the host group and fractions of central galaxies, brightest, second brightest and faint satellites (corresponding to satellite hierarchies of 0, 1, 2 and 3). A satellite hierarchy of -1 indicates galaxies not associated to any group with masses above the chosen minimum mass threshold. The distributions of the distance to the nearest cluster of galaxies (in units of virial radii) are also shown, but are not used to define any membership for the control sample.

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with the results by Kauffmann et al. (2004) and Popesso & Biviano (2006).³

Finally, a word of warning should be put in with respect to the BH population of the galaxies that comprise the control sample. Some unknown fraction of these galaxies could harbour dormant BHs and their distribution of masses could well reproduce that of the AGN sample (even if the distributions of concentrations are similar). However, there could also be a population of galaxies with central black holes (BHs) of completely different masses (even zero mass). We will bear this in mind when comparing the properties of the AGN hosts and galaxies in the control sample.

3 GALAXY SEQUENCES AND THE COLOUR–CONCENTRATION DIAGRAM

In this section, we show results on one- and two-dimensional distributions of galaxy properties (colours, bulge concentration and galaxy luminosities) for samples of galaxies limited by intrinsic luminosity, concentration, host halo mass, local density, distance to the nearest cluster of galaxies, and by whether they present an AGN. Our sample is not volume limited, since it comprises galaxies in the SDSS DR7 out to $z = 0.1$, with $-23 < M_r < -18$. We correct for this incompleteness by using a 1/$V_{\text{MAX}}$ weighting scheme (as in Padilla & Strauss 2008), bearing in mind the possible effect of a large-scale structure on our results not taken into account in the weighting procedure.

We will follow previous works by González & Padilla (2009) and Ceccarelli et al. (2008), and define two proxies for the galaxy environment: (i) the local density, $\sigma_s$, designed to follow local effects, such as galaxy–galaxy interactions, measured using the cylindrical volume with a radius equal to the distance to the fifth nearest neighbour. The length of the cylinder corresponds to a redshift difference of 500 km s$^{-1}$ and neighbours are required to satisfy $M_r < -20.5$ (neighbours are drawn from a volume-limited subsample out to $z = 0.1$); this method has been widely used in the literature (Balogh et al. 2004; Baldry et al. 2006; among others); and (ii) a quantity that is related to larger scales and therefore to the history of mass buildup of the region, where the galaxy resides, rather to the interaction history of the galaxy (modulo correlations between these two quantities). For this quantity, González & Padilla (2009) proposed to use the distance to the nearest cluster of galaxies (in simulations) and Ceccarelli et al. (2008) used the distance to void centres on SDSS-DR6 galaxies. In both works, it is shown that the galaxy population shows variations as a function of the global densities, even when the local density is held fixed at a given value. For instance, González & Padilla (2009) showed that at intermediate galaxy densities of $-0.5 < \log (\rho/10^{10} \text{M}_\odot/\text{h}^{-2} \text{Mpc}^3) < 0.5$, the fraction of red galaxies decreases from $0.45 \pm 0.10$ to $0.21 \pm 0.02$ as the distance to clusters of galaxies increases from $d/r_{\text{vir}} < 2$ to $d/r_{\text{vir}} > 9$, where $r_{\text{vir}}$ corresponds to the virial radii of the closest cluster to any given galaxy. This indicates that the local galaxy density as traced by $\sigma_s$ does not necessarily probe the widest dynamical range of the dependence of galaxy properties on the environment due to residual global variations (also suggested by Weinmann et al. 2006, using the SDSS-DR2). One of the main objectives of this paper will be to provide a firm statistical confirmation (or not) of this effect, which was only marginally found by Ceccarelli et al. Note that the mass of the host halo does not probe the widest dynamical range in local environmental effects, as it has been shown that the properties of galaxies in equal-mass haloes depend on their assembly or SF history (Zapata et al. 2009).

3.1 Colour–magnitude relations

We start our analysis by studying the colour–magnitude diagram (CMD) for different local density environments and different host group luminosities. The CMDs for restricted samples of galaxies are shown in Fig. 2. The colour-scale corresponds to the full galaxy sample, and the black solid and white dashed lines correspond to the AGN and AGN control samples, respectively. The left-hand panels correspond to two different ranges of local density and the right-hand panels correspond to galaxies in groups of different total luminosity measured in the $r$ band ($M'_r$, used as a proxy for group mass). In both cases, there is a clear red sequence, which becomes tighter for higher galaxy luminosities. This sequence has been thoroughly used as a tool to detect clusters at both low and high redshifts (e.g. Gladders & Yee 2005). We note that we obtain similar CMDs for low densities and low host group luminosities (shown in the right-hand panel), and for high densities and high group luminosities. In the former, there are clear blue clouds, which almost completely disappear for the latter. This behaviour is well documented and can be explained via the density–morphology relation (e.g. Dressler 1980; Postman & Geller 1984; Whitmore & Gilmore 1991; Goto et al. 2003; Postman et al. 2005). The individual error bars on the left-hand side of each panel show the 68 per cent width of the red sequence; it is clear that for higher densities and higher host group luminosities, the red sequence is more sharply defined (has a smaller dispersion).

Both, AGN hosts and galaxies in the AGN control sample, show wider distributions in colour than the red sequence shown by the full sample of galaxies due to the effect noted earlier while inspecting Fig. 1 that the AGN host colour distribution is similar to the red part of the bimodal colour distribution of the full galaxy sample, although slightly wider and shifted towards bluer colours. We note that the width of the distributions of AGN colours does not change significantly when the density or the host group luminosity increases (there is a marginal narrowing of the AGN colour distribution at higher densities). AGN hosts show a slight tendency to become redder and brighter at higher local densities (a correlation in agreement with a colour–magnitude relation also present in AGN hosts). Since this effect is also visible for the control samples, it must be a result of the morphology and environment of the AGN hosts.

When comparing AGN hosts and control samples, there are some notable differences between them. Regardless of the local density and host group luminosity, the hosts of AGNs tend to be slightly redder, compared to galaxies in the control sample; this will be confirmed in the following subsections. As a function of the local density, it can be seen that the AGN hosts become brighter relative to control galaxies as the density increases. This is more clearly seen as a function of the host group luminosity. These two results are consistent with a picture in which AGNs are hosted by larger galaxies in clusters, which are likely to host higher mass BHs and also are more efficient in retaining gas in spite of the adverse intra-cluster conditions in comparison with low-mass objects, which are likely to be gas stripped; we remind the reader that the proportion

³To provide the statistical significance of this result, we calculated the fraction of AGN hosts located in local density environments characterized by $\sigma_s > 10 h^{-2} \text{Mpc}^3$ and found $(8.0 \pm 0.2) \text{pc}$ per cent for bright AGNs and $(9.6 \pm 0.2) \text{pc}$ per cent for the full AGN sample, indicating a $>5\sigma$ detection of this effect.

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of central and satellite galaxies is the same for the samples of AGN hosts and their control galaxies.

3.2 Dependence on the local density

With the aim of understanding the changes in the galaxy population in different large-scale environments, we measure the variations in the galaxy sequences in a $g - r$ colour versus bulge concentration diagram. This is shown in Fig. 3, where in the frequency scale bluer colours indicate a large concentration of objects ($1/V_{\text{MAX}}$ weighted) and yellow shows regions with a lack of galaxies. The left-hand panels show galaxies with no restriction on luminosities ($-23 < M_r < -18$), and low, intermediate and bright galaxies are shown in the right-hand panels; higher local densities, $\sigma_5$, are shown in the top panels.

The plots show two distinct populations, one containing blue, low bulge concentration galaxies, and another with red galaxies with a wider range of bulge concentration values. The red galaxy population shows an elongated sequence in this figure, which due to the colour–magnitude relation appears slightly narrower in colour when the range of intrinsic luminosities is restricted. The red long-dashed lines in the figure correspond to $g - r = 0.75$, which is used to divide the population into blue and red galaxies. The number at the bottom of each panel shows the fraction of blue galaxies (the error corresponds to Poisson uncertainties). For the left-hand panels, which consider the full intrinsic luminosity range, there is a clear trend of a lower fraction of galaxies in the blue, low bulge concentration population as the local density increases. As can be seen on the columns to the right, this effect is present at all galaxy luminosities. These results are in agreement with a number of studies.
Environmental effects on galaxies and AGNs

Figure 3. Distribution ($1/V_{\text{MAX}}$ weighted) of galaxies in the $r_{\text{90}}/r_{\text{50}}$ versus $g-r$ colour plane, for different galaxy luminosities (ranges indicated on top of the upper subpanels) and located in regions with different local densities [ranges indicated on the right-hand side, $L_\sigma$ is shorthand for $\log (\sigma_5/\text{h}^{-2}\text{Mpc}^2)$]. The frequency of galaxies increases as the colour progresses from yellow to blue. Lines enclose a 68 per cent of the population of $\text{OIII}$ bright (solid line) and faint (dashed line) AGN galaxies. The white dashed line shows the same contour for the full AGN control sample. The dashed red lines indicate the value of $g-r$ used to compute the fraction of blue galaxies shown near the bottom of each panel.

of the dependence of galaxy properties on the environment, including Balogh et al. (2004), Baldry et al. (2006) and Weinmann et al. (2006). Consistent results were also obtained for galaxies in voids (low local densities), which were found to be bluer and with higher SF activity than galaxies in average environments (e.g. Goldberg et al. 2005; Hoyle, Vogele & Rojas 2005; Padilla, Ceccarelli & Lambas 2005; Rojas et al. 2005; Ceccarelli et al. 2006, 2008), and for clusters of galaxies on the high local density end, where galaxies show the well-known clustercentric radius–morphology relation (e.g. Dressler 1980; Domínguez et al. 2002; Postman et al. 2005).

Our study of the environmental dependence of AGN activity will centre on the colours and concentrations of AGN hosts instead of analysing the fraction of galaxies hosting AGNs as done in several works (Kauffmann et al. 2004; Martini et al. 2009). Our results will be comparable to those presented by Choi et al. (2009) (see also Waskett et al. 2005; Gilmour et al. 2007; Coldwell et al. 2009; Pasquali et al. 2009), who studied the morphological types of the hosts. The black line contours in Fig. 3 enclose 68 per cent of the AGN population in this diagram. The solid lines correspond to the brightest half (in extinction corrected $\text{OIII}$ luminosity) of the AGN sample; the dashed lines correspond to the galaxies with the fainter $\text{OIII}$ emission half of the sample. The median $\text{OIII}$ luminosity of the AGN sample is $\log_{10}(L_{\text{OIII}}/L_\odot) = 6.4$ (which roughly corresponds to the LINER limit). As can also be seen, AGNs in our sample tend to prefer hosts with colours redwards of the blue population, in qualitative agreement with Choi et al. (2009) and also Schawinski et al. (2007). It can also be seen that there are no strong trends in either the $\text{OIII}$ bright or faint AGN samples with the local density (for this reason, we do not produce control samples for AGN divided by $\text{OIII}$ luminosity), except for a mild tendency to reach lower...
host bulge concentrations and bluer host colours in environments characterized by lower local densities, for both high and low O\textsc{iii} luminosity AGN hosts. The white dashed lines show the regions, where the AGN control samples lie in this diagram. As can be seen, most of the behaviour shown by the AGN comes from the morphology and environment of their hosts; in comparison to the AGN hosts, particularly those with low $r$-band luminosities, the control samples show a more noticeable shift from low to high concentrations and $g-r$ colours as the local density increases; for instance, for $-19.5 < M_r < -18$, the control sample is a good match to the high O\textsc{iii} luminosity AGN hosts at low densities, but a better match for the low O\textsc{iii} luminosity AGNs at the highest densities probed. We will come back to this point later in this section.

The O\textsc{iii} bright AGN sample consistently shows bluer colours (occupying the ‘green’ valley) and lower concentrations than the faint AGNs. This result can be understood in terms of the effect described by Kewley et al. (2006), who also found that LINERs (faint O\textsc{iii} AGNs) are more concentrated than Seyferts (bright O\textsc{iii} AGNs), which they interpret as the latter being likely associated with gas-rich disc galaxies, where gas can supply SF and AGN activity independently, whereas LINERs may have switched off their SF long ago and have maintained their AGN status using gas supplied by mass-loss from their stellar population or via mergers. Another possibility comes from the work by Schawinski et al. (2007). They claimed that AGNs are triggered by the same processes as the SF in a galaxy and that the effect of AGN activity is that of shutting off the SF in a galaxy. Therefore, if the AGN activity is strong, that is, the central accretion disc is acquiring mass at high rates, the SF shutdown may still be in process, whereas once the fuel has been consumed (low nuclear luminosity), the SF burst has already been quenched by the previous high-activity phase of the AGN, and the galaxy appears redder. This is also in agreement with estimates of stellar ages (the time since the last SF episode) by Schawinski et al. of more recent SF events for bluer AGN hosts. However, it has been argued (e.g. Kewley et al. 2006) that other processes could be more likely the source of the SF quenching, such as hot and cold gas stripping in satellites.

At the high galaxy luminosity ($r$ band) and low-density end, there is some evidence for a reversal of this relation, namely, high O\textsc{iii} luminosity AGNs tend to have higher $g-r$ colours and concentrations than low O\textsc{iii} AGNs, on average. This is mainly due to the extension of the sequence shown by the low O\textsc{iii} luminosity AGNs, which tends to cover the full range shown by the general galaxy population. This shows that the relation between AGN activity and SF (as traced by galaxy colours) is not exactly one-to-one; at the very least, it depends on the host luminosity and concentration, since for a fixed galaxy luminosity and colour, we see that when the local density decreases, the AGN activity shifts towards more extended, possibly disc-like objects. The control sample shows the latter behaviour independently of the local density. We quantify these observations in Section 3.3.

The top left-hand panel of Fig. 4 shows the $g-r$ colour distribution for galaxies with $-23 < M_r < -18$ at different local density environments (different line-types, indicated in the figure key). The distributions show a clear bimodality with peaks located at roughly fixed positions, with the red and blue peaks separated by $\Delta(g-r) = 0.43 \pm 0.02$. There is a clear shift towards the red galaxy population as the local density increases (consistent with previous studies e.g. O’Mill, Padilla & Lambas 2008). This trend is quantified in the lower left-hand panel, where the black dashed lines show the fraction of red ($g-r > 0.75$) galaxies as a function of $\sigma_5$ (error bars correspond to Poisson fluctuations and are only shown for the sample with no restriction on the concentration to improve clarity). We also show this fraction in the dotted lines for low-concentration galaxies and in the dashed lines for high concentration galaxies; as can be seen, the bluer colours of low-concentration galaxies are also confirmed by these ratios.

The top centre panels of the figure show the colour distributions of AGN hosts, for the full range of nuclear O\textsc{iii} luminosity. As can be seen in the colour distributions, as well as in the red fractions shown in the lower centre panel, AGN hosts show a milder but significant trend towards redder colours, when embedded in higher density environments, as well as higher red fractions as the concentration of the hosts increases.

The right-hand panels show these results for the AGN control sample. As can be seen, the colour distributions and their variation on local density is qualitatively similar to that shown by the AGN hosts. The lower right-hand panel shows in a solid line the fraction of red galaxies for the AGN sample (repeated from the lower centre panel) and in dashed lines that of the control sample. The variation of this fraction over the three orders of magnitude in the local density, shown in the figure, is equal in amplitude for the control galaxies and AGN hosts ($0.32 \pm 0.02$ and $0.31 \pm 0.01$ increases in red fractions, respectively; Poisson errors) and lower than that for the full galaxy sample (a red fraction variation of $0.58 \pm 0.01$). A significant difference between galaxies in the control sample and AGN hosts is that the former are characterized by a lower average red fraction, that is, $0.415 \pm 0.014$ and $0.470 \pm 0.013$, respectively (with a $2.9\sigma$ significance level). Bearing in mind the BH versus bulge mass relations (e.g. Magorrian et al. 1998; Häring & Rix 2004), this difference in colours may be due to the presence of larger bulges in the AGN hosts (which on average will have higher mass BHs at their centres in order to have been detected as AGNs). Alternatively, as the control sample may include galaxies with BHs with masses similar to those of the AGN hosts, but in their dormant phase, this could also point to a recovery of the SF activity in the control sample after their last AGN cycle; this last speculative interpretation would also allow to understand that this difference is not significantly detected at the highest local densities due to the higher difficulty for gas cooling in such environments.

Several works on the dependence of the AGN population on the environment study the fraction of galaxies that host active nuclei. For example, in a combined study of high- and low-redshift galaxies using DEEP2 (Faber et al. 2007) and SDSS, respectively, Montero-Dorta et al. (2009) found that galaxies in the SDSS show a decreasing fraction of AGNs in the red sequence towards high-density environments. Our result is complementary to this approach, indicating that, regardless of the fraction of active galaxies, their hosts show a slight tendency to become redder as the local density increases.

Later in this section, we will study whether the colours of galaxies show any dependence when the local density is held fixed and the distance to clusters is allowed to vary.

### 3.3 AGN and galaxy sequences

In this subsection, we quantify the behaviour of AGNs and how it compares to that of their control sample and the full galaxy population at different local densities, and for different intrinsic host galaxy luminosities. Pasquali et al. (2009) indicated that the AGN activity is more likely to be found in central galaxies; in the following comparisons, we will verify whether the fraction of central galaxies of subsamples of the full, control and AGN populations under comparison is similar, as we will also do with their
average stellar masses. In order to estimate the total number of central galaxies in our samples, we use the satellite hierarchy shown in Fig. 1, which is equal to 0, if a galaxy is central in an SDSS group in the hosts sample (which comprises groups with masses $M > 3 \times 10^{12} h^{-1} M_\odot$), hierarchy > 0, if a galaxy is a satellite in one of these groups, and -1, if no group is associated to the galaxy. Therefore, the sample of galaxies with satellite hierarchy 0 does not represent the full central galaxy population. Zehavi et al. (2004) used the halo model (Cooray & Sheth 2002) to measure the minimum DM halo mass from which haloes start to contain satellites brighter than $M_r = -21$ and found it to be $M \approx 10^{13} h^{-1} M_\odot$. On the other hand, Zheng et al. (2005) extended the study of the halo occupation model to lower luminosities using models of galaxy formation. Combining their results with those by Zehavi et al., we expect that less than 5 per cent of $-21 < M_r < -19$ galaxies in haloes below the lower mass limit of the hosts sample will be satellites. Therefore, from this point onwards, we will consider as central galaxies those with satellite hierarchies of 0 and -1 (for $M_r < -19$).

Fig. 5 shows the colour distribution of high- and low-concentration galaxies and AGN hosts in two different luminosity ranges. As can be seen, galaxies selected this way show almost exclusively unimodal colour distributions, which will allow us to study average colours for each subsample. The results for objects with $-19.0 < M_r < -18.0$ and $-23.0 < M_r < -20.5$ (top and bottom panels, respectively) clearly show that faint AGN hosts show more similar fractions of blue galaxies between high and low concentrations than high-luminosity AGN hosts. In the case of no restriction on AGN activity, galaxies with similar luminosities show a similarly strong behaviour of much lower values of $g-r$ for low concentrations, regardless of the galaxy luminosity. These results are supported by the fractions of blue galaxies and blue AGN hosts (shown in the panels and in Table 1) and the average $g-r$ colours for each of the populations studied in the figure (shown as circles with error bars, dashed and solid lines for high and low concentrations, and in Table 1). Namely, we find a clear difference between the SF activity (traced by the $g-r$ colour) and that of AGNs, indicating that low-concentration (disc-like) hosts are characterized by bluer colours for AGN hosts of higher luminosities. Instead, the control AGN samples (and normal galaxies) show redder colours for higher galaxy luminosities. With respect to AGN hosts, control galaxies show redder colours (lower fractions of blue galaxies). It is possible that control galaxies contain similar BH masses in a dormant phase, such that their SF activity has been quenched during the previous cycle of activity. One exception is the
Figure 5. Weighted distributions of \(g - r\) colour for galaxies (lower lines), AGN hosts (middle lines in each panel, displaced vertically by a constant value) and the AGN control sample (upper lines, displaced further up vertically), for low and high values of concentration (solid and dashed lines, respectively). The top and bottom panels correspond to low and high galaxy luminosities. The luminosity and concentration ranges are indicated in the legend. The circles show the average colour for the different samples (error bars are the Poisson errors of the mean) and are used to allow a statistical comparison between the distributions (see values in Table 1). The fraction of blue galaxies is shown in black (grey) for the low (high) concentration sample. This fraction is obtained using a limit of \(g - r = 0.75\) in all cases and are also shown in Table 1.

Table 1. Average \(g - r\) colour, fraction of blue galaxies (\(g - r < 0.75\)), stellar masses \((M^* = \log_{10}(M/M_\odot))\) and fraction of central galaxies (satellite hierarchies \(-1\) and 0), for the full galaxy sample, the AGN hosts and the AGN control sample, for two different ranges of \(r\)-band luminosities. The quoted errors correspond to the errors on the mean, calculated using Poisson statistics.

| Sample   | Luminosity | \(\langle g-r \rangle\) | Fraction of blue galaxies | Fraction of central galaxies |
|----------|------------|-------------------------|---------------------------|-----------------------------|
| AGN      | Low        | 0.21 ± 0.01             | 0.04 ± 0.01               | 0.70 ± 0.02                 |
|          | High       | 0.33 ± 0.03             | 0.04 ± 0.01               | 0.74 ± 0.03                 |
| Control  | Low        | 0.35 ± 0.02             | 0.03 ± 0.01               | 0.74 ± 0.03                 |
|          | High       | 0.65 ± 0.01             | 0.01 ± 0.01               | 0.59 ± 0.01                 |
| Full     | Low        | 0.21 ± 0.01             | 0.04 ± 0.01               | 0.70 ± 0.02                 |
|          | High       | 0.33 ± 0.03             | 0.04 ± 0.01               | 0.74 ± 0.03                 |

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low-concentration, low-luminosity case, where we may argue that the larger fraction of central galaxies in the control sample causes their bluer colours. The mean and its associated error for each of the presented distributions of galaxy colours (circles with error bars and Table 1) confirm all the trends mentioned above with high statistical confidence levels.

The average values of stellar mass are comparable between normal, control and AGN host galaxies for samples of similar luminosities and concentrations (see columns 7 and 8 in Table 1) and even though the fraction of central galaxies shows significant differences in a few cases, these do not affect our conclusions. The cases are (i) for low luminosities and low concentrations, normal galaxies show a slightly larger central galaxy fraction, but even though this may correlate with the bluer colours shown by these galaxies (central galaxies in this range of luminosity tend to be bluer than equal-luminosity satellites), this cannot produce such a large difference in colour; (ii) in the same subsamples, the fraction of central control galaxies is higher than for the AGN hosts, but this would only indicate that the colours of control galaxies with equal fractions of central galaxies would be more similar to those of the AGN hosts; and (iii) the remaining case corresponds to high-concentration, low-luminosity objects, where control galaxies show a larger fraction of centrals than AGN hosts; however, if these fractions were forced to be similar, the colour difference would be even more significant.

3.4 Remotion of local galaxy density and local halo effects

In this section, we explore whether at fixed values of the median local density there are residual variations of galaxy properties as a function of the distance to the closest galaxy cluster, and if so, whether the constraining of the host group luminosity is able to remove this residual dependence. Several works (e.g. Wang et al. 2009a) have reported a dependence of the red galaxy fraction with the distance to clusters; however, it has been reported that there is a tight correlation between the local environment and the distance to clusters (e.g. Balogh et al. 2004). Therefore, our aim is to find out whether there are residual variations in the galaxy colours with the distance to clusters, once the local density is controlled; as shown by González & Padilla (2009), there is a remaining variation in a sample of ΛCDM semianalytic galaxies.

Fig. 6 shows concentration versus colour diagrams in four panels divided in six subpanels, each corresponding to different combinations of parameters. The top and bottom panels correspond to bright and faint galaxies (−20.5 < M_r < −23 and −18 < M_r < −19.5, respectively), and the left-hand and right-hand panels correspond to unrestricted host group mass and host groups with M_{vir} > 20, respectively. In turn, each panel shows two columns: the left-hand column is for low local densities, −0.8 < log_{10}(σ_r h^{-2} Mpc^2) < −0.4, and the right-hand column is for high local densities, 0.6 < log_{10}(σ_r h^{-2} Mpc^2) < 1; the three rows in each panel correspond to different distances to the centres of clusters (indicated to the right-hand side of the figure).

As can be seen in Fig. 6, when the local density is restricted to a narrow range, there is a small remnant of the dependency reported from Fig. 3. Namely, for low local densities, −0.8 < log_{10}(σ_r h^{-2} Mpc^2) < −0.4, a small but significant blue population appears in the diagram for faint galaxies, as the distance to the nearest cluster increases (left-hand subpanels of the bottom panel in Fig. 6); this is quantified by the fraction of blue galaxies shown in each subpanel, which increases systematically with d/r_{vir}. For the higher density samples, 0.6 < log_{10}(σ_r h^{-2} Mpc^2) < 1, there are only small variations in the bulge concentration versus colour diagrams (second column of panels from the left-hand side); for faint galaxies (bottom left-hand panels), the same effect is present with a higher statistical significance as indicated by the systematically increasing relative fraction of the blue, low-concentration population with respect to that of red galaxies as the distance to clusters increases (indicated in each panel). The fact that a dependency on the clustercentric distance is still marginally visible in the samples with a fixed local density indicates that the morphology–density relation found in previous works, such as Balogh et al. (2004), Baldry et al. (2006) and O’Mill et al. (2008), are, in principle, detecting only part of the possible dynamical range of variations in the galaxy population. A more fundamental parametrization should at least involve the global environment of the galaxy as well as the local density. Here, we parametrized the former by the distance to clusters of galaxies. This result is in agreement with the study of the residual variations in the fraction of blue galaxies at fixed local densities, but at increasingly larger distances from cluster centres in semianalytic models (González & Padilla 2009). It is also in agreement with studies of the colours of satellite galaxies around groups in the SDSS by van den Bosch et al. (2010), where at a fixed stellar mass, satellites tend to be redder than central galaxies; this could be the reason behind the decrease in blue fractions as the distance to clusters decreases modulo local density effects.

The option of additionally fixing the mass of the DM host halo could provide the alternative parametrization needed to remove the dependence on clustercentric distance. This was pointed out by González & Padilla (2009), who found that the local and global density dependencies of the galaxy population can be seen in the distributions of galaxy colours, but also as variations in the mass of their DM halo hosts. They also found a smaller residual effect coming from the assembly of groups that we will not consider in the present analysis. González & Padilla estimated that, to some degree, this is in accordance with new results, where it is found that the evolution of galaxies takes place, while they are part of groups, which later merge to form larger structures, such as clusters of galaxies (Wilman et al. 2008; McGee et al. 2009).

We adopt our proxy for host halo mass for the individual galaxies described in Section 2.1, which consists of an assignment of the added luminosity of the four brightest group members. We use the group luminosity as previous findings point out that the group luminosity is a better proxy for the DM mass of a group than its virial estimate (e.g. Eke et al. 2004). The two right-most columns of subpanels in Fig. 6 show the resulting galaxy populations in the bulge concentration versus colour plane, for the same local density limits as used in the left-hand panels, but for groups with faint luminosities (M_{vir} > 20). The measured median group luminosities are indistinguishable for both the low and high local density samples and at different distances from clusters. The results are shown for two different ranges of galaxy luminosity (top and bottom panels). As can be seen, for low group luminosities (right-hand panels), it is slightly less clear (as evidenced by analysing the fractions of blue galaxies and their errors, indicated in the top left-hand side of each subpanel), that there are systematic shifts in the populations of galaxies as the clustercentric distances increase, regardless of the local density and galaxy luminosity (the only exception is that of...
Figure 6. Variations of galaxy properties as a function of distance to cluster centres for fixed values of projected local density. Weighted distributions of galaxies (colours are as in Fig. 3) and AGN hosts (solid lines containing 68 per cent of the total) for high, $-23 < M_r < -20.5$, and low, $-19.5 < M_r < -18$, galaxy luminosities (top and bottom sets of panels, respectively). Left-hand and centre left-hand panels correspond to different ranges of the local projected galaxy density (the legends on the top indicate the ranges). The centre right-hand and right-hand panels correspond to the same local densities as in the two left-most panels, with an additional constraint on the total host group luminosity of $M_{Gr} > -20$. The numbers near the top of each panel show the fraction of blue galaxies with $g - r < 0.75$; the errors are Poisson, on the mean.

faint galaxies in low-density environments). However, due to the larger errors involved in this analysis, it is only marginally preferred, at best, to use the host DM halo mass in addition to the local density as the ideal double parameter to separate different galaxy populations. Larger data sets will be needed to rule out a possible dependence on assembly.

Finally, the AGN population does not show any obvious trends with the clustercentric distance, when the local density or the host halo mass is constrained. However, this may be the result of low number statistics.

Fig. 7 quantifies these points; in all the panels, the local density is held fixed at $\sigma_5 = 1/\hbar^{-2}\text{Mpc}^2$ (median value). The left-hand
Figure 7. Top panels: 1/V$_{\text{MAX}}$ weighted distributions of colour for galaxies in equal local density environments, but different clustercentric distances (shown in different line types indicated in the figure key). The left-hand panels are for non-AGN galaxies; centre panels correspond to the full AGN population; and right-hand panels correspond to the AGN control samples. In all cases, the local density is fixed at equal average values by limiting $-0.3 < \log (\sigma_5/h^{-2}\text{Mpc}^2) < 0.3$. Lower left-hand and lower centre panels: fraction of red galaxies as a function of distance to the closest cluster of galaxies (solid lines), regardless of the concentration, and for high (dashed line) and low (dotted line) concentrations. The cuts in the colour and concentration are shown in the key. The additional grey solid line in the lower left-hand panel shows the fraction of red galaxies as a function of distance to cluster centres for galaxies with an additional cut in host group luminosity of $M_{\text{Gr}}^\text{r} > -20$. The lower right-hand panel shows the fraction of red galaxies for the control sample (dashed line) and for the AGN hosts (solid line, repeated from the lower centre panel). Error bars correspond to Poisson uncertainties on the mean.

The top left-hand panel shows the $g-r$ colour distribution for galaxies with $-23 < M_r < -18$, but this time corresponding to different distances from clusters (see the figure key), and only for galaxies in the fixed moderate density environment to avoid variations in galaxy properties coming from their local density. The distributions show only a moderate bimodality with peaks located at roughly fixed positions, with the red and blue peaks separated by $\Delta (g-r) = 0.43 \pm 0.04$ as found in the analysis of samples in different local densities. There is a hint of a shift towards higher red galaxy fractions as the clustercentric distance diminishes. This trend is quantified in the lower left-hand panel, where the solid lines show the fraction of red $(g-r > 0.75)$ galaxies as a function of $r/r_{\text{vir}}$ (error bars show Poisson errors only for the sample with no restriction on concentration), where this fraction drops by $0.099 \pm 0.011$ (Poisson uncertainty) between 0 and 10$r_{\text{vir}}$ from the clusters of galaxies. We also show this fraction in the dotted lines for low-concentration galaxies and in the dashed lines for high-concentration galaxies; we again find bluer colours of lower concentration galaxies. Given that it has been pointed out that the host-halo mass may be a better indicator of the local environment than $\sigma_5$ (e.g. Weimann et al. 2006, in observations; González & Padilla 2009, in simulations), we have also measured the fractions of red galaxies as a function of distance to cluster centres for fixed values of the host halo mass (average total group luminosity of $M_{\text{Gr}}^{\text{r}} = -20.0$). The result is shown as a black long-dashed line in the lower left-hand panel of the figure, and as can be seen, we recover the results obtained by fixing the local density (a variation in the red fraction of $0.096 \pm 0.019$).

We make an additional subsample by requiring fixed local densities $\sigma_5 = 1/h^{-2}\text{Mpc}^2$ and low host group luminosities, $M_{\text{Gr}}^{\text{r}} > -20$, and show the dependence of the red fractions with the distance to clusters as a grey solid line. In this case, the dependence is almost
null, although the error bars are considerably larger than for the black solid line (for the grey line, the local density is also held fixed). Therefore, the simultaneous constraint on the local density and the group luminosity (proxy for mass) is able to marginally improve the selection of a galaxy population fully independent of global environment, a result that is definitely not achieved by fixing the local galaxy density or the host halo mass alone. Due to low number statistics, we do not place further limits on the masses of the host groups for AGNs or in the AGN control sample.

The top centre panel of the figure shows the $g - r$ colour distributions of AGN hosts for the full range of nuclear O III luminosity, but with the same restriction on the local density. As can be seen, both in the distributions and in the red fractions (shown in the lower centre panel), AGN hosts are consistent with no change in their colours as a function of distance to clusters, once the local density is held fixed, at least to the degree of statistical certainty allowed by these observational data. An interesting feature in the fraction of red galaxies as a function of the distance to cluster centres is the bump at $r/r_{\text{vir}} \sim 2$. This would coincide with results from Coldwell et al. (2009), who also found an excess of AGNs with red hosts in the outskirts of clusters. However, the significance of this feature in our analysis is only marginal and it does not improve by changing the range of masses of the cluster sample (we varied the low mass limit from $10^{13}$ to $5 \times 10^{14} h^{-1} M_{\odot}$).

Galaxies in the control sample show a clear dependence of colours as a function of the distance to clusters (at fixed local density) as can be seen in the right-hand panels (a total variation of 0.56 ± 0.07 in the fraction of red control galaxies). The lower right-hand panel shows in a dashed line the dependence of the red galaxy fraction on the distance to clusters for the control sample, which can be compared with the dependence obtained for the AGN sample (shown in this panel as a solid line, repeated from the lower centre panel). It is clear that the colours of AGN control galaxies (at a fixed local density, $\sigma_5$) show a clear variation towards bluer colours as the distance to the centres of clusters of galaxies increases. Even though AGNs show almost constant red fractions as a function of distance to cluster centres, relative to control galaxies, AGN hosts are significantly redder for $r/r_{\text{vir}} > 2$, where the fraction of red galaxies is $0.313 \pm 0.015$ and $0.394 \pm 0.014$ for the control and AGN samples, respectively, and significantly bluer for $r/r_{\text{vir}} < 2$, with fractions of red galaxies of $0.63 \pm 0.11$ and $0.39 \pm 0.14$, respectively, with comparable stellar masses and fractions of central galaxies. In particular, 100 and 93 per cent of AGN hosts and control galaxies at $r/r_{\text{vir}} < 1$ are satellites (72 and 80 per cent, respectively, at $r/r_{\text{vir}} > 5$) in this figure. This could indicate that towards the centres of clusters, satellite galaxies at fixed local density environments need to be more capable of feeding a central BH, to be detected as an AGN, than outside clusters (consistent with the constant red fractions as a function to cluster centres shown by AGN hosts); this would point towards the known SF–AGN activity relation (Kauffmann et al. 2004), but while the properties of the galaxy hosts are the same, including their environment. The result by von der Linden et al. (2009), who obtained a reddening of the hosts of AGNs towards the cluster centres, could be detecting the variation in the properties of typical AGN hosts as measured by our control samples.

We remind the reader that these latter results correspond to an environment characterized by a fixed median local density of $\sigma_5 = 1/h^{-2} \text{Mpc}^2$. When analysing higher densities, $\sigma_3 > 10/h^{-2} \text{Mpc}^2$, we find consistent results, but with AGN colours bluer than galaxies in the control sample out to greater distances from the cluster centres (probably due to the effect of higher local densities); in this case, the group luminosities that produce similar fractions of red galaxies to this higher local density cut are $-24 < M^r_{\text{vir}} < -22$. Our data set does not allow us to draw conclusions for low densities, $\sigma_5 < 0.5/h^{-2} \text{Mpc}^2$, since the resulting samples contain too few galaxies.

## 4 Discussion

The objectives of this paper consisted in studying the variations in the properties of galaxies with their environment and comparing it to what is expected from galaxy formation models. We have analysed separately these variations for normal galaxies and for galaxies with AGNs. We will now compare our results to previous studies for these two types of galaxies in the following subsections.

### 4.1 Results for the full galaxy population

There have been numerous studies on the environmental dependence of galaxy properties, where the environment has been given, for example, by projected galaxy densities on different scales (e.g. Balogh et al. 2004; Kauffmann et al. 2004; Baldry et al. 2005; O’Mill, Padilla & Lambas 2008), the host halo mass (Weinmann et al. 2006) or the distance to cluster centres (e.g. Wang et al. 2009a; Smriti & Raychaudhury 2009). As these three quantities are correlated, the results obtained by different authors consistently show that galaxies located in lower density environments or farther away from clusters or in host haloes with lower masses are characterized by bluer colours.

Given that it is expected that the local density in the very high redshift Universe affects the final local DM halo mass (e.g. Weinmann et al. 2006; González & Padilla 2009) and, in turn, the history of mergers, it could be expected that the properties of galaxies at equal $z = 0$ local densities, but different large-scale environments tracing different initial conditions, could show different properties. Note that this would also be the case for galaxies with equal host-halo masses, as the different merger histories could also imprint different galaxy properties in haloes of equal mass, but different large-scale environments and therefore different assembly histories. This is clearly expected in view of the assembly bias effect, now detected in simulations (starting with Gao, Springel & White 2005) and observations (Wang et al. 2008; Zapata et al. 2009), where equal-mass haloes with different assembly histories show different clustering properties as well as different galaxy populations.

Therefore, we studied the variation of red galaxy fractions as the distance to clusters increases, but at fixed values of local densities or host-halo masses, and found an increasing fraction of blue galaxies with a high statistical significance (9 and 5σ for fixed local densities and host-halo masses, respectively). With this result, we confirmed those found for semianalytic galaxies by González & Padilla (2009). Previously, Ceccarelli et al. (2008) had been able to find an indication of this effect, but with much lower statistical significance, comparing galaxies in equal local density environments, but in void walls, and outside voids.

González & Padilla (2009) also found that even when the local densities and DM halo masses are constrained to fixed values, different large-scale environments can still induce changes on the modelled galaxy properties, an effect that could be attributed to coherent motions or further assembly effects. We repeated this analysis with our full galaxy sample, but were not able to find any significant remaining variations of colours. Given the large error bars involved, larger galaxy samples are needed in order to confirm this effect in observations.
4.2 Results on AGN hosts

Our analysis of the AGN hosts used projected local densities, host halo masses and their distance to clusters of galaxies (and combinations of these) as proxies for their environment. We also defined a control sample of non-AGNs, such that their stellar masses, r-band luminosities, colours, local densities, concentrations, fractions of central and satellite galaxies, and host halo masses show the same distributions as the AGN hosts. By applying all these restrictions independently on each parameter of non-AGN galaxies, any correlations between these quantities introduced by, or allowing, the AGN activity will produce differences with the control sample, particularly when analysing different environments. In the literature, several works make comparisons between the properties of AGN hosts and of non-AGN galaxies characterized by similar properties, but still allowing for differences on several parameters. For instance, most studies on the fractions of AGNs essentially make a comparison to the full galaxy population divided according to the local density, host morphology, stellar mass and nuclear OIII luminosity (Cappi et al. 2001; Martini et al. 2002; Molnar et al. 2002; Miller et al. 2003; Kauffmann et al. 2004; Popesso & Biviano 2006; Pasquali et al. 2007; Martini et al. 2009). In other cases, the studies served to identify the environments of AGN hosts (Martini et al. 2004; Waskett et al. 2005; Koulouridis et al. 2006; Gilmore et al. 2007; Martel et al. 2007; Choi et al. 2009; Montero-Dorta et al. 2009; Silverman et al. 2009; von der Linden et al. 2009) using a single parameter, such as the local density, distance to cluster centres or cluster membership, or the typical AGN host properties (Kauffmann et al. 2003a; Kewley et al. 2006; Hao et al. 2009), as in Pasquali et al. (2009), who studied the hosts of AGNs as a function of the host halo mass. In the process of constructing our control samples, we compared the distributions of several parameters of AGN hosts and the full galaxy population, and we were able to confirm several of these results (e.g., constant fraction of AGNs as a function of the local density, a larger occurrence of AGNs in higher mass host haloes).

Our approach is complementary to these previous works and is designed to find the effect of changing only one parameter, the detection of AGN activity. In our study, we found that as the local density or the host halo mass increases, AGN hosts become slightly redder (while occupying the green valley) and of higher luminosity, consistent with studies of the hosts of AGNs. However, even though the control galaxies also show this qualitative behaviour, they are always slightly bluer and fainter than AGN hosts, a clear difference coming from a condition related to the AGN detection, either an effect of the BH on the galaxy or a condition that allows the BH activity. In this sense, this could indicate that AGNs in clusters are hosted by larger galaxies (a correlation in the AGN hosts not present in the control samples) in order to be able to retain gas in the intracluster conditions. Note that this result is seemingly contrary to what was found by Pasquali et al. (2007, although this paper deals only with early-type galaxies) and Hao et al. (2009), since they connected the AGN activity with SF events (discy and barred galaxies, respectively). However, part of this signal is due to the typical hosts of AGNs and not due to the detection of AGN activity in these galaxies.

Consistent with the interpretation that our control samples contain dormant BHs, where the SF has regained its strength, we find that when the local density is held fixed at intermediate (or high) values and the distance to clusters varies, the hosts of AGNs show constant colours. Thus, close to the clusters, AGNs are significantly bluer than the control galaxies (however, it could also be possible that AGNs near cluster centres need more available gas to remain active).

In this case, most of the galaxies (AGN hosts and control) are satellites of the clusters and therefore the AGN hosts under analysis would only conform to a subsample of the AGNs studied by Pasquali et al. (2009), who did not divide their sample according to the local density.

At low local densities, the low OIII luminosity AGNs are found to extend their range of colours and concentration to lower values as the host luminosity increases. Only part of this behaviour comes from the morphologies and characteristics of the AGN hosts, as the control sample shows a less clear trend, in slightly better agreement with the behaviour of normal galaxies (higher concentrations and colours). This could favour the view that the AGNs are not the most important factor in transforming galaxies into red and dead objects as suggested by Schawinski et al. (2007), in comparison with cluster environmental processes (Kewley et al. 2006), since at low densities, low OIII luminosity AGNs can even show blue colours.

4.3 Perspectives

Even though we were able to detect signatures of assembly on the properties of galaxies for our full sample, in the form of different colours for galaxies at fixed local densities and different distances from clusters, there still remain many questions regarding the effect from particular details of the development of structures in the Universe, for instance, the apparent correlation between coherent motions and the remnant variations in galaxy properties at a fixed local density and host halo mass (González & Padilla 2009) or the contamination of the areas surrounding clusters by ejected satellite galaxies Wang et al. (2009a). This will require considerably larger galaxy samples, which could also be useful in detecting the evolution of this phenomenon with redshift. These effects will be small but they are an expected outcome of the development of galaxies within a ΛCDM scenario.

The same applies to the study of AGN hosts, where the comparison to a strict control sample has allowed us to find the correlations between the detection of an AGN and the local density, the distance to clusters (with respect to a control sample) and the host halo mass. More systematic studies on the effect of each parameter included in the selection of the control sample are possible and would allow a more detailed understanding of the processes behind the detection of an AGN and its relation to the different phenomena associated with the origin and development of structure.

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REFERENCES

Abazajian K. et al., 2003, AJ, 126, 2081
Abazajian K. et al., 2009, ApJS, 182, 543
