The XMM Cluster Survey: the halo occupation number of BOSS galaxies in X-ray clusters

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ABSTRACT

We present a direct measurement of the mean halo occupation distribution (HOD) of galaxies taken from the eleventh data release (DR11) of the Sloan Digital Sky Survey-III Baryon Oscillation Spectroscopic Survey (BOSS). The HOD of BOSS low-redshift (LOWZ: 0.2 < z < 0.4) and Constant-Mass (CMASS: 0.43 < z < 0.7) galaxies is inferred via their association with the dark matter haloes of 174 X-ray-selected galaxy clusters drawn from the XMM Cluster Survey (XCS). Halo masses are determined for each galaxy cluster based on X-ray temperature measurements, and range between log_{10}(M_{180}/M_☉) = 13 and 15. Our directly measured HODs are consistent with the HOD-model fits inferred via the galaxy-clustering analyses of Parejko et al. for the BOSS LOWZ sample and White et al. for the BOSS CMASS sample. Under the simplifying assumption that the other parameters that describe the HOD hold the values measured by these authors, we have determined a best-fitting alpha-index of 0.91 ± 0.08 and 1.27 ± 0.03 for the CMASS and LOWZ HOD, respectively. These alpha-index values are consistent with those measured by White et al. and Parejko et al. In summary, our study provides independent support for the HOD models assumed during the development of the BOSS mock-galaxy catalogues that have subsequently been used to derive BOSS cosmological constraints.

Key words: galaxies: haloes – X-rays: galaxies: clusters.

1 INTRODUCTION

In the hierarchical formation scenario, large-scale structures in the Universe arise through the successive mergers of increasingly large dark matter haloes. These haloes cannot be observed directly, but their presence can be inferred from the galaxies they contain, assuming light traces mass. Galaxy surveys therefore can be applied to studies of both cosmology (e.g. Cole et al. 2005; Eisenstein et al. 2005; Percival et al. 2007; Blake et al. 2011; Sánchez et al. 2012; Tinker et al. 2012a; Parkinson et al. 2012; Anderson et al. 2014) and galaxy evolution (e.g. Abbas et al. 2010; Tinker & Wetzel 2011; Zehavi et al. 2011; Leauthaud et al. 2012; Tojeiro et al. 2012; Wetzel, Tinker & Conroy 2012).

An essential component of many galaxy survey based cosmology and galaxy evolution studies is the halo occupation distribution (HOD) model (e.g. Peacock & Smith 2000; Seljak 2000; Berlind & Weinberg 2002; Cooray & Sheth 2002; Kravtsov et al. 2004). This model encapsulates the complicated physics of galaxy formation and evolution within a relatively simple framework. HOD describes the mean number of galaxies above a luminosity threshold within a virialized halo of given mass. Under the HOD framework, the number of galaxies populating a halo increases, on average, as a function of halo mass. Galaxies populating a halo are divided into either ‘central’ or ‘satellite’ galaxies (e.g. Berlind et al. 2003; Zheng et al. 2005a,b). Depending on its mass and evolution history, a halo
can host, or be devoid of, either or both types of galaxies (above the chosen luminosity threshold).

Dark matter haloes can accrete satellite galaxies and grow in mass through halo–halo mergers. The central (and satellite) galaxies of the newly acquired sub-haloes become the satellite galaxies of the dominant halo. In HOD nomenclature, the ‘two-halo’ term refers to the region of the HOD where the physical separation between galaxies is sufficiently large that the clustering statistic counts pairs of galaxies hosted by separate dark matter haloes; whereas the ‘one-halo’ term refers to the non-linear regime where the clustering statistic counts pairs of galaxies hosted by the same dark matter halo.

Several methods have been implemented to measure the form of the HOD for a given galaxy type. These include fitting a model to the HOD predicted by galaxy-clustering analyses (e.g. Abazajian et al. 2005; Zheng, Coil & Zehavi 2007; Zheng et al. 2009; White et al. 2011, hereafter W11; Parejko et al. 2013, hereafter P13; Reid et al. 2014; Nuza et al. 2014; Guo et al. 2015; Miyatake et al. 2015; More et al. 2015; Rodríguez-Torres et al. 2016), measurements of the galaxy conditional luminosity function (e.g. Yang, Mo & van den Bosch 2003; Cooray 2006; van den Bosch et al. 2007; Yang, Mo & van den Bosch 2008; Rodríguez-Puebla, Avila-Reese & Drory 2013; Guo et al. 2016), satellite kinematics, (e.g. More, van den Bosch & Cacciato 2009; More et al. 2011); galaxy–galaxy lensing (e.g. Leauthaud et al. 2012; Zu & Mandelbaum 2015; Park et al. 2015) or by directly counting the number of galaxies within predetermined dark matter haloes e.g. as those identified by galaxy-cluster/group surveys (e.g. Lin, Mohr & Stanford 2004; Collister & Lahav 2005; Ho et al. 2009; Reid & Spergel 2009; Capozzi et al. 2012a,b; Tinker et al. 2012b; Hoshino et al. 2015).

The Sloan Digital Sky Survey (SDSS-III) Baryon Oscillation Spectroscopic Survey (or BOSS; Eisenstein et al. 2011) is a spectroscopic survey that has measured redshifts for ≃1.5 million galaxies over an area of ≃10 000 deg². The primary scientific goal of BOSS is to place constraints on cosmological models by measuring the Baryon Acoustic Oscillation (BAO) feature (Peebles & Yu 1970; Sunyaev & Zeldovich 1970; Doroshkevich, Zeldovich & Sunyaev 1978). BOSS also enables other science, for example studies of galaxy evolution and galaxy bias. Using the galaxy-clustering approach, measurements of the HOD of BOSS galaxies have been presented in both W11 and P13. Using the first year of BOSS spectroscopic data, W11 performed a measurement of the real and redshift-space clustering of BOSS CMASS-galaxies at z ≃ 0.5, and simultaneously fit an HOD model to these data to predict the mean number of CMASS-galaxies contained within a halo of given mass. A similar analysis, using low-redshift BOSS galaxies, was performed by P13, in which they predict the HOD of BOSS LOWZ-galaxies at z ≃ 0.3.

In this paper, we test the HOD models of W11 and P13 by directly counting the number of BOSS galaxies in the vicinity of X-ray clusters taken from the XMM Cluster Survey (XCS; Romer et al. 2001) in the SDSS DR11 BOSS spectroscopic footprint (Alam et al. 2015). Our motivation for this project is that the W11 and P13 HOD models have been adopted by many of the subsequent BOSS science analyses, and it is important to check them using an independent technique.

Clusters selected using optical/near-IR galaxy over density methods suffer from mis-centring issues, e.g. Rykoff et al. 2016, that could impact HOD measurements. Therefore, we have chosen X-ray-selected clusters for this study. In principle, we would like to have weak lensing mass measurements for all the clusters in our sample. However, in practice, it is not yet possible to gather the required data for large numbers of clusters: the largest recent studies are limited to ≲50 clusters (see e.g. Applegate et al. 2016; Smith et al. 2016). Therefore, for this study, we have used cluster-averaged X-ray temperatures. The ‘one-halo’ term refers to the region of the HOD where the physical separation between galaxies is sufficiently large that the clustering statistic counts pairs of galaxies hosted by separate dark matter haloes; whereas the ‘two-halo’ term refers to the non-linear regime where the clustering statistic counts pairs of galaxies hosted by the same dark matter halo. In this paper, we test the HOD models of W11 and P13 by direct counting the number of BOSS galaxies in the vicinity of X-ray clusters taken from the SDSS DR11 BOSS spectroscopic footprint (Alam et al. 2015). Our motivation for this project is that the W11 and P13 HOD models, combined with an externally calibrated T_X–M relation, preclude the measured core-excised T_X values at the redshift of most of our clusters. [It is only after core excision that T_X can be used as a reliable mass proxy (see e.g. Stanek et al. 2006; Maughan 2007)].

The structure of the paper is as follows: Section 2 describes the BOSS-galaxy redshift catalogue, and X-ray cluster samples used in the analysis, as well as the methods used to estimate virial masses, virial radii, velocity dispersions, redshifts and X-ray temperatures for the clusters. Section 3 presents the HOD measurements. Section 4 compares those measurements to the W11 and P13 HOD models. Section 5 discusses the implications of our findings, and possible sources of systematic error. Throughout, we assume a flat ΛCDM cosmology with values Ω_m = 0.274, Ω_L = 0.726 and h = 0.7 (as used in W11 and P13). Comoving separations are measured in h⁻¹ Mpc, with h₀ = 100 km s⁻¹ Mpc⁻¹. In the following, when we refer to dark matter haloes in the ‘one-halo’ regime, we mean those of sufficient mass that they could contain satellite galaxies. For the redshifts considered in our analysis, the ‘one-halo’ regime typically applies to haloes of mass log_{10}M(180) ≃ 13−15 M⊙ (where M(180) is the mass contained in a spherical overdensity Δ(180) with radius R(180)).

2 THE DATA

The data used in this paper are taken from two main sources: the BOSS (Dawson et al. 2013, Section 2.1) and the XCS (Romer et al. 2001, Section 2.2).

2.1 BOSS data

The third phase of the SDSS (York et al. 2000), termed SDSS-III (Eisenstein et al. 2011), included four projects: BOSS (Eisenstein et al. 2011), SEGUE-2 (Kollmeier et al. 2010), MARVELS (Lee et al. 2011), APOGEE (Deshpande et al. 2013). Data were obtained using the 2.5-m Sloan telescope (Gunn et al. 2006) at Apache Point Observatory, New Mexico, and the SDSS spectrographs (Sme et al. 2013). The study presented here only makes use of BOSS data products (Bolton et al. 2012; Dawson et al. 2013).

BOSS was designed to measure the BAO feature at z ≤ 0.7 to sub 2 per cent accuracy using luminous galaxies with an approximately constant comoving number density (n ≃ 3 × 10⁻²² h³ Mpc⁻³). Galaxies were selected for BOSS spectroscopic observation from u, g, r, i, z imaging data (Fukugita et al. 1996; Gunn et al. 1998) taken from the Eight and Ninth SDSS Data Releases (SDSS DR8, Aihara et al. 2011; SDSS DR9, Eisenstein et al. 2011). The galaxy targets were selected using colour and magnitude cuts that track the expected evolution of passively evolving luminous red galaxies (LRGs) with redshift. These evolutionary tracks are based on the population synthesis models of Maraston et al. (2009).

Due to the transition of the 4000 Å break of LRGs between the g and r filters at z ≃ 0.4, two sets of cuts were necessary. This divided the targets into two broad redshift bins: a low-redshift sample...
(LOWZ; equation 1) spanning the redshift range $0.2 \leq z \leq 0.4$, and a high-redshift sample (CMASS – for ‘Constant-Mass’; equation 2) spanning the redshift range $0.43 \leq z \leq 0.7$. The CMASS sample is defined by:

$$r < 13.6 + c_i/0.3, \quad |c_{\perp}| < 0.2, \quad 16 < r < 19.5,$$

where the colours $c_i$, $c_{\perp}$ and $d_i$ are given by equations (3), (4) and (5), respectively.

$$c_i = 0.7 \times (g - r) + 1.2 \times (r - i - 0.18),$$

$$c_{\perp} = (r - i) - (g - r)/4 - 0.18,$$

$$d_i = (r - i) - (g - r)/8.$$

Because DR11 did not include a complete spectroscopic census of all of the galaxies selected to be BOSS targets, we use the terms ‘BOSS-target’, ‘BOSS-galaxy’, ‘CMASS-galaxy’, and ‘LOWZ-galaxy’ in this paper. The BOSS-target sample is the superset; the BOSS-galaxy sample is the subset of these with redshift information (spectroscopic or close-pair corrected) in DR11. The BOSS-galaxy sample is the union of the distinct CMASS-galaxy and LOWZ-galaxy samples.

### 2.2 XCS data

XCS uses all available data in the XMM–Newton (XMM) public archive to search for galaxy clusters that were detected serendipitously in XMM images. X-ray sources are detected in XMM images using an algorithm based on wavelet transforms (see Lloyd-Davies et al. 2011, henceforth LD11, for details). Sources are then compared to a model of the instrument point spread function to determine if they are extended: XCS uses the signature of X-ray extent to distinguish clusters from more common X-ray sources, such as active galactic nuclei. Optical imaging is used to confirm the identity of the extended sources (most are clusters, but low-redshift galaxies and supernova remnants are also extended in XMM images). Where possible, either a photometric or spectroscopic redshift is determined for the confirmed cluster. For each confirmed cluster with an associated redshift, cluster-averaged X-ray luminosities ($L_X$) and cluster-averaged X-ray temperatures ($T_X$) are measured using an automated pipeline (LD11).

The majority of the X-ray clusters used in the HOD study described herein were drawn from the first XCS data release (XCS-DR1; Mehtens et al. 2012, henceforth M12), with the remainder from the ‘XCS-Ancillary’ sample (see below). The optical imaging and spectroscopic campaign described in M12 resulted in 503 optically confirmed clusters, including 464 with redshifts, and 401 with $T_X$ estimates. The XCS-DR1 clusters are distributed across the sky and span the redshift and temperature ranges $0.06 < z < 1.46$ and $0.04 \text{keV} < T_X < 14.7 \text{keV}$, respectively. This temperature range corresponds to halo masses of $\log_{10}(M_{180}/M_\odot) = 13–15$ (see Section 2.3). For our HOD study, we used 121 XCS-DR1 clusters that are located within the spectroscopic BOSS footprint. The footprint has a complex shape, so the MANGLE software (Swanson et al. 2008) was used to track its angular completeness, using a completeness threshold of 0.8 for a cluster to be included in the spectroscopic footprints. These 121 XCS-DR1 clusters have redshifts and temperatures in the range $0.203 < z < 0.686$ and $0.35 < T_X < 9.41 \text{keV}$.

The XCS-Ancillary sample includes extended XMM sources that were not included in XCS-DR1 (M12) for one of three reasons: they were associated with the target of the respective XMM image (and hence were not serendipitous detections); they were not included in any of the three XCS-Zoo exercises (used to optically confirm the XCS-DR1 clusters; see Section 4 of M12); or they were detected in XMM images processed in the time elapsed since the publication of M12. Initial redshifts were assigned to these clusters using NED$^2$ identifications using the method described in Section 4.1 of LD11. These redshifts were refined using the method described in Section 2.4. For our HOD study, we used 53 XCS-Ancillary clusters that are located within the spectroscopic BOSS footprint. These 53 clusters have redshifts and temperatures in the range $0.207 < z < 0.699$ and $1.13 < T_X < 10.37 \text{keV}$.

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1. http://hubblesite.org

2. http://ned.ipac.caltech.edu
2.3 Cluster velocity dispersions, masses, and radii

In order to validate cluster redshifts (see Section 2.4), and to measure halo occupation numbers (HON; see Section 3), we need to estimate cluster velocity dispersions, masses and radii. For the velocity dispersions, we use the empirical $\sigma_v - T_X$ relation of Xue & Wu (2000). This relation is based on a sample of 145 X-ray groups and clusters with temperatures ranging from 0.1 < $T_X$ < 10 keV, and is therefore similar to the X-ray temperature range of the clusters in XCS-DR1. Several fits are presented in Xue & Wu (2000); we have chosen to adopt the relation measured via an orthogonal distance regression fit to the whole sample, because this method accounts for uncertainties in both the $\sigma_v$ and $T_X$ values. The relation is given by

$$\sigma_v = 10^{2.51 \pm 0.01} T_X^{0.61 \pm 0.01},$$

where $\sigma_v$ and $T_X$ are in units of km s$^{-1}$ and keV, respectively.

For the cluster masses, we adopt the prescription in Sahlén et al. (2009), which involves fitting the following model to each cluster:

$$T_X = T_{X,\text{mean}}(M_{\text{180}}) + \Delta \log T_X,$$

where $T_{X,\text{mean}}(M_{\text{180}})$ is the mean $M$--$T_X$ relation and $\Delta \log T_X$ represents the scatter of individual clusters about the mean relation.

We parametrize the $M$--$T_X$ relation according to the self-similar prediction (e.g. Kaiser 1986; Bryan & Norman 1998; Voit 2005),

$$T_{X,\text{mean}} = A M_{\text{vir}}^{2/3} \left[ \Omega_m(z) T_X^2(z) \right]^{1/3},$$

where $M_{\text{vir}}$ is the virial mass of the cluster, $\Omega_m(z)$ is the spherical overdensity within the virial radius of the cluster, and $T_X^2(z)$ is the reduced Hubble parameter for our cosmological model,

$$T_X^2(z) = \Omega_m(1+z)^2 + \Omega_k(1+z)^2 + \Omega_\Lambda,$$

with $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$. In our analysis, we restrict ourselves to a flat universe with $\Omega_k = 0$. $A$ is a normalization constant set by requiring

$$M_{\text{180}} = 3 \times 10^{14} h^{-1} M_\odot,$$

at $z = 0.05$ for $T_X = 5$ keV. Our fiducial cosmological model reproduces the local abundance of galaxy clusters as given by the HIFLUGCS catalogue (Pierpaoli, Scott & White 2001; Reiprich & Böhringer 2002; Viana et al. 2003).

Conversions between $M_{\text{180}}$, $M_{\text{500}}$, and $M_{\text{vir}}$ are performed using the standard Navarro, Frenk & White (1996) profile prescription by Hu & Kravtsov (2003) with a halo concentration parameter of $c = 5$. We have tested the impact of changing the concentration parameter on the mass and radius estimates, and find that the change, compared to $c = 5$, to the mean value is much less than the one sigma errors, when using either $c = 2.5$ or $c = 10$.

We model the scatter $\Delta \log T_X$ as log-normal about the mean $M$--$T_X$ relation, with a standard deviation $\sigma_{\log T_X} = 0.1$. This model is motivated by observational estimates of the intrinsic scatter (e.g. Arnaud, Pointecouteau & Pratt 2005; Kravtsov, Vikhlinin & Nagai 2006b; Zhang et al. 2006b) and results from N-body hydrodynamic simulations (e.g. Viana et al. 2003; Borgani et al. 2004; Balogh et al. 2006; Kravtsov et al. 2006b). The likelihood is constructed from the $T_X$ measurement probability distributions, modelled by a split normal distribution:

$$L(T_X) = A \exp\left(-2(T_X - T_X^*)^2/2\sigma^2\right),$$

where

$$\sigma = \begin{cases} \sigma_v & \text{if } T_X \geq T_X^* \\ \sigma_\Delta & \text{if } T_X < T_X^* \end{cases},$$

with $A = \sqrt{2\pi} (\sigma_v + \sigma_\Delta)^{-1}$. Here, $T_X^*$ is the measured central value of $T_X$, $\sigma_v$ and $\sigma_\Delta$ the upper and lower 1-$\sigma$ uncertainties. The likelihood is explored using Monte Carlo Markov Chain (MCMC; e.g. Gelman & Rubin 1992; Lewis & Bridle 2002; Tegmark et al. 2004; Dunkley et al. 2005) sampling, using $M_{\text{180}}$ and the temperature scatter $\Delta \log T_X$ as free parameters. An uninformative flat prior is placed on $M_{\text{180}}$, and a prior $N(0, \sigma_{\log T_X})$ on $\Delta \log T_X$. Approximately 10 000 Markov chain elements are generated for each cluster, for which the distributions have converged. In addition to visual inspection of chain statistics, we assess this using the Gelman–Rubin test. We require the Gelman–Rubin ratio $R < 1.05$.

The cluster radii ($R_{180}$) are derived parameters in the MCMC procedure, computed by assuming that the cluster mass $M_{\text{180}}$ is contained in a spherical overdensity $\Delta \log T_X$ with radius $R_{180}$. The MCMC procedure thereby produces chain samples of the distributions of $R_{180}$ values. From these samples, the mean $R_{180}$ values and their uncertainties are derived.

2.4 Cluster redshifts and temperatures

For many clusters in our study we have updated the M12 (XCS-DR1) or NED (XCS-Ancilliary) redshift estimates using BOSS spectroscopy. For this, galaxy redshifts were extracted from the appropriate BOSS spectroscopic redshift catalogue (see e.g. Fig. 1).

For clusters with spectroscopic redshifts in M12 or NED, we defined a cylinder centred on the XCS centroid. This cylinder had a radius, on the sky, of $R_{180}$. The cylinder had a depth, along the line of sight, of $\pm 3 \sigma_v$. $(R_{180}$ and $\sigma_v$ values were estimated from the $T_X$ values using the method described in Section 2.3.) Spectroscopic redshifts for the galaxies enclosed by the cylinder were then extracted from the BOSS catalogues. For clusters with only a photometric redshift in M12 or NED, we again defined a cylinder centred on the XCS centroid with a radius of $R_{180}$, but this time set no bounds along the line of sight.

If more than one BOSS redshift was extracted for a given cylinder, we followed the redshift-gapper method (Halliday et al. 2004), i.e. we identify the location of the most likely peak in redshift space and determine the mean cluster redshift using all galaxies with redshifts within $\Delta z = 0.015$ of that peak.

If no galaxies were extracted for a given cylinder, then the respective cluster was still included in the HOD analysis (Section 3) if it had a spectroscopic redshift in M12 or NED. After all, BOSS targets represent only a subset of galaxies, i.e. there will be other cluster members that do not meet the colour and magnitude thresholds described in Section 2.1. However, if the cluster only had a photometric redshift in M12 or NED, it was excluded from the HOD analysis. We discuss possible implications of this approach in Section 5.1.

After the CMASS- or LOWZ-galaxies were extracted for the respective cluster, the SDSS image was inspected to check the location of the galaxies with respect to the X-ray emission (see Fig. 1). This highlighted the fact that the XCS-DR1 spectroscopic redshift of XMMXCS J023346.0--085048.5 was inaccurate: in M12 it had been based on the observation of a single galaxy that yielded a redshift of $z = 0.25$. The same galaxy was measured to have a redshift of $z = 0.265$ by BOSS (the BOSS value was adopted for the cluster).

In this case, defining a cylinder based on the M12 redshift did not automatically extract the BOSS redshift for that galaxy.

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Footnote 3: Xue & Wu (2000) note that the cluster and group relations when fitted separately are consistent with the combined fit.
The HOD of BOSS galaxies in X-ray clusters

The clusters XMMXCS J133453.1+405654.5 (top; \(z = 0.233\)) and XMMXCS J112259.3+465916.8 (bottom; \(z = 0.480\)) as imaged by SDSS DR8. False colour-composite images show the central 2 × 2 arcmin region of each cluster. Highlighted by pink triangles are SDSS DR11 BOSS galaxies falling within a projected \(R_{500}\) radius. These were adopted as member galaxies and used to assign a spectroscopic cluster redshift based on BOSS spectroscopy.

The resulting changes were small (\(\Delta z < 0.02\)) when spectroscopically determined cluster redshifts were used as the input (see Fig. 2, top). However, as expected, they were larger when photometric redshifts were used as inputs; the changes ranged up to \(\Delta z = 0.25\), although 90 per cent were less than \(|\Delta z = 0.1|\); see Fig. 2 (bottom). From Fig. 2 (bottom), it is clear that above \(z_{\text{BOSS}} \simeq 0.3\), the photometric redshift estimates in M12 are systematically low. The same effect was highlighted in M12 (see discussion in section 5.3 of M12).

Figure 2. Comparison between XCS-DR1 cluster redshifts published in M12, \(z_{\text{XCS}}\), and the updated values based on BOSS spectroscopy, \(z_{\text{BOSS}}\). Top: clusters with spectroscopic redshifts in M12. The 1-\(\sigma\) dispersion is \(\Delta z = 0.003\). Bottom: clusters with photometric redshifts in M12. The 1-\(\sigma\) dispersion is \(\Delta z = 0.05\).

There is a known degeneracy between \(z\) and \(T_X\) in X-ray spectral fitting (e.g. see Liddle et al. 2001), so we remeasured the \(T_X\) values once the BOSS determined clusters redshifts were in hand. The method used is as described in LD11, but using updated XMM calibration and XSPEC (12.8.1g) versions. Specifically, we have fitted the XMM spectra to a WABS×MEKAL model (Mewe & Schrijver 1986), fixing the hydrogen column density to the Dickey & Lockman (1990) value and the metal abundance to 0.3 times the solar value. For consistency, \(T_X\) values were also re-measured using the updated XMM calibration and XSPEC versions even if the redshifts had not changed compared to M12.

Using these updated \(z\) and \(T_X\) values, we recalculated cluster masses and radii following the method in Section 2.3. The resulting distribution of cluster mass with redshift for our full cluster sample is shown in Fig. 3.
3 MEASUREMENT OF THE HALO OCCUPATION NUMBER

We have measured the HON for 174 clusters. This includes 74 clusters in the CMASS redshift range (0.43 ≤ z < 0.7) and 100 in the LOWZ redshift range (0.2 ≤ z ≤ 0.4). Of these, 56 and 18 came from the XCS-DR1 and XCS-Ancillary sample, respectively, for the CMASS sample (65 and 35 respectively, for the LOWZ sample). All of these clusters have spectroscopic redshifts, with almost all determined from BOSS DR11 data (only 2 per cent came from M12 or NED).

We determine the HON values by counting the number of CMASS- or LOWZ-galaxies in the vicinity of the respective cluster centroid. The method is similar to that described above (Section 2.4) with regard to measuring cluster redshifts using BOSS data, i.e. we extract galaxies from a cylinder, of radius $R_{180}$, centred on the cluster location and with a depth, along the line of sight, of ±3σv. The HON values so derived are provided in Column 5 of Table 1.

The HON values for our cluster sample are small (from 0 to 21); therefore it was appropriate to use Poisson uncertainties (taken from Gehrels 1986) to estimate the associated counting error. Errors on individual BOSS-galaxy redshifts will not impact the HON measurements, being $\Delta z < 0.001$, i.e. they are much smaller than the estimated $\sigma_v$ values. We have made the simplifying assumption that the uncertainty on the mean cluster redshift is much smaller than $\sigma_v$. We have checked the sensitivity of the HON to the accuracy of the $R_{180}$ estimate, by recalculating the HON using both $R_{180} + \sigma_R$ and $R_{180} - \sigma_R$ (where the 1-$\sigma$ uncertainties in $R_{180}$ were calculated using the method described in Section 2.3). For all the clusters, the HON either did not change at all, or changed less than the Poisson uncertainty, so we chose to only quote the latter in Table 1 (Column 5).

We present the results of our HON analysis in Table 1. The column descriptions are as follows:

1. The XCS cluster ID. Encoded within each ID is the RA and Dec (J2000.0) position of the X-ray centroid.
2. The mean spectroscopic redshift of each cluster. The 2 per cent of clusters that came from XCS-DR1 or NED are indicated using footnotes.
3. An estimate of the cluster halo mass, $M_{180}$, and its 1-$\sigma$ uncertainty (see Section 2.3). The best-fitting mean halo mass is given in parentheses. We adopt the best-fitting value throughout.
4. An estimate of the cluster virial radius, $R_{180}$, and its 1-$\sigma$ uncertainty (see Section 2.3). The best-fitting mean virial radius is given in parentheses. We adopt the best-fitting value throughout.
5. The HON, and its 1-$\sigma$ uncertainty, of BOSS galaxies (LOWZ or CMASS).

4 COMPARISON TO HOD-MODEL PREDICTIONS

Here we compare the HON of CMASS- and LOWZ-galaxies measured within XCS cluster haloes (Section 3) to the HOD-model fits of W11 and P13.

4.1 CMASS HOD-model comparison

The left panel of Fig. 4 displays the HON of CMASS-galaxies measured within XCS cluster haloes (Section 3) to the HOD-model fits of W11 and P13.

![Figure 3. Distribution of halo mass with spectroscopic redshift for the 174 X-ray clusters used in this study. Blue symbols represent clusters in the XCS-DR1 sample, and red symbols represent additional, or 'Ancillary' clusters. The XCS-DR1 sample includes lower-mass clusters than the Ancillary sample at $z < 0.5$ because high-mass clusters at $z < 0.5$ are typically the intended target of their respective XMM pointing (XCS-DR1 does not include target clusters).](http://www.mnras.org/)
The HOD of BOSS galaxies in X-ray clusters

Figure 4. Left: The HOD of CMASS-galaxies (0.43 < z < 0.7) as a function of halo mass within 74 X-ray-selected clusters (XCS-DR1: blue circles; XCS-Ancillary: red circles). Uncertainties (including those for clusters HON value of 0) are Poisson (Gehrels 1986). For presentation purposes, points with a HON value of 0 are shown as upper limits due to the log-scale of the y-axis. Right: the mean HOD of CMASS-galaxies for 74 clusters in mass bins containing approximately equal numbers of clusters (XCS-DR1: blue squares; XCS-DR1 plus XCS-Ancillary: red squares). Uncertainties on the binned points are given by the error on the mean. Both: the mean HOD prediction (and the 1-σ uncertainty range) for the combined central and satellite population of W11 is indicated by the solid red line (and the yellow shaded region). The mean HOD predictions for the separate central galaxy and satellite galaxy populations are shown by the black dashed and dotted lines, respectively. Note that the W11 results did not extend beyond 10^{15} M_{\odot}. While the HONs of CMASS-galaxies measured for individual clusters show a broad distribution of values, the binned values are consistent with the CMASS HOD-model fit of W11.

4 Error on the mean=σ/\sqrt{N).
Figure 5. Left: the HOD of LOWZ-galaxies (0.2 < z < 0.4) as a function of halo mass within 100 X-ray-selected clusters (XCS-DR1: blue circles; XCS-Ancillary: red circles). Uncertainties (including those for clusters HON value of 0) are Poissonian for presentation purposes, points with a HON value of 0 are shown as upper limits due to the log-scale of the y-axis. Right: the mean HOD of LOWZ-galaxies for 100 clusters in mass bins chosen to contain the same number of clusters per bin. The blue squares represent the XCS-DR1 sample only, whereas the red squares represent the XCS-DR1 sample combined with XCS-Ancillary clusters (XCS-DR1+Anc). There are 13 (20) XCS-DR1 (XCS-DR1+Anc) clusters per bin, including in the last bin. Uncertainties on the binned points are equated to the error on the mean. Both: the mean HOD prediction (and the 1-sigma uncertainty range) for the combined central and satellite population of P13, derived from the Northern Galactic Hemisphere, is indicated by the solid green line (and the blue shaded region). The mean HOD predictions for the separate central galaxy and satellite galaxy populations are shown by the black dashed and dotted lines, respectively. Note that the P13 results did not extend beyond 10^{15} M⊙. While the HONs of LOWZ-galaxies measured for individual clusters show a broad distribution of values, the binned values are consistent with the LOWZ HOD-model fit of P13.

Table 2. The mean and standard deviation of the HOD parameters as measured in W11 and P13 for the CMASS and LOWZ samples, respectively. Values in parenthesis are those derived for the best-fitting model (best-fitting values were not reported for the LOWZ Full sample in P13).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CMASS Full</th>
<th>LOWZ NGC</th>
<th>LOWZ SGC</th>
<th>LOWZ Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>log_{10}M_{cut}</td>
<td>13.08 ± 0.12 (13.04)</td>
<td>13.17 ± 0.14 (13.16)</td>
<td>13.09 ± 0.09 (13.11)</td>
<td>13.25 ± 0.26</td>
</tr>
<tr>
<td>log_{10}M_{1}</td>
<td>14.06 ± 0.10 (14.05)</td>
<td>14.06 ± 0.07 (14.11)</td>
<td>14.05 ± 0.09 (14.07)</td>
<td>14.18 ± 0.39</td>
</tr>
<tr>
<td>σ</td>
<td>0.98 ± 0.24 (0.94)</td>
<td>0.65 ± 0.27 (0.741)</td>
<td>0.53 ± 0.28 (0.692)</td>
<td>0.70 ± 0.40</td>
</tr>
<tr>
<td>κ</td>
<td>1.13 ± 0.38 (0.93)</td>
<td>1.46 ± 0.44 (0.921)</td>
<td>1.74 ± 0.74 (1.26)</td>
<td>1.04 ± 0.71</td>
</tr>
<tr>
<td>α</td>
<td>0.90 ± 0.19 (0.97)</td>
<td>1.18 ± 0.18 (1.38)</td>
<td>1.31 ± 0.19 (1.31)</td>
<td>0.94 ± 0.49</td>
</tr>
</tbody>
</table>

4.3 A new HOD-model fit

The HOD model implemented by W11 and P13 comprises five parameters that describe the HOD of central (equation 13) and satellite (equation 14) galaxies within dark matter haloes. The sum of these two components produces the mean HOD of all galaxies within a halo of given mass (equation 15).

\[ N_{\text{cen}}(M) = \frac{1}{2} \text{erfc} \left( \frac{\ln(M_{\text{cut}}/M)}{\sqrt{2} \sigma} \right), \]  

\[ N_{\text{sat}}(M) = N_{\text{cen}} \left( \frac{M - \kappa M_{\text{cut}}}{M_{1}} \right)^{\alpha}, \]  

\[ N(M) = N_{\text{cen}}(M) + N_{\text{sat}}(M), \]  

where \( M_{\text{cut}} \) is the minimum mass for a halo to host a galaxy, \( M_{1} \) is the typical mass for haloes to host one satellite, \( \sigma \) is the fractional scatter in \( M_{\text{halo}} \), \( \kappa \) is the threshold mass for satellites and centrals to differ, and \( \alpha \) is the mass dependence of the efficiency of galaxy formation.

We have explored the appropriateness of the HOD-model fits in W11 and P13 (summarized in Table 2) by estimating the \( \alpha \)-index from our measured cluster HON values. Ideally, we would have estimated all five free parameters in the HOD model, but our data only span the mass regime pertaining to the ‘one-halo’ term (Section 1), and so are primarily sensitive to the satellite galaxy component (i.e. to the \( \alpha \) parameter). Therefore, we fixed the other four parameters to best-fitting values of W11 and P13 (see Table 2). To determine the best-fitting \( \alpha \)-index value, we performed a chi-squared fit, corrected for a Poisson distribution (equation 16),

\[ \chi^{2}_{p-1} = \sum_{i} \frac{(N_{o} - N_{e})^{2}}{N_{e}}, \]  

where \( N_{o} \) is the observed HON, \( N_{e} \) is the expected HON estimated from the HOD model, \( x \) is the number of data points considered, and \( p \) is the number of degrees of freedom.

We have examined values for \( \alpha \) ranging between 0.1 and 2.0 (in 0.01 steps), deemed to be a realistic representation of the data. Similar to P13, when performing our fit to the LOWZ HOD, we exclude haloes that have a HON of zero. The results are shown in Table 3, where the best-fitting \( \alpha \)-index values presented correspond...
to the minimum chi-squared value over the $\alpha$-index range tested. The 1-$\sigma$ uncertainty range of the $\alpha$-index value is also given in Table 3. The $\alpha$ values presented in Table 3 are fully consistent with those from W11 and P13 quoted in Table 2 (see Figs A1 and A2). That said, the measured best-fitting $\alpha$-index values vary depending on the input sample (XCS-DR1 versus XCS-DR1+Anc), and we discuss possible reasons for this result in Section 5.

## 5 DISCUSSION

Our aim in this paper was to examine the HOD models for BOSS galaxies that have been published by W11 and P13, and used in several subsequent BOSS analyses. Evidence in support of the models is provided in Figs 4 and 5, which show our directly measured HON values to be in agreement with the model predictions, and from the slope of our CMASS HON distribution, which is consistent with the value in W11. We discuss potential sources of bias in our analysis below (Section 5.2), often drawing on the results of a comparison, photometric redshift based, CMASS HON measurement (Section 5.1). We end this section with a preliminary study of HON evolution, with comparison to the predictions of Saito et al. (2016) (Section 5.3).

### 5.1 Measurement of the halo occupation number using photometric redshifts

We have performed an additional HOD analysis using photometric redshifts for two reasons: (1) to investigate the robustness of the results in Section 4, and (2) to determine whether future HON analyses based on photometric data, for example using the Dark Energy Survey, will be analyses based on photometric data, for example using the Dark Energy Survey, will be.

Our HON analysis has demonstrated that there are a number of genuine (i.e. confirmed by their X-ray emission) dark matter haloes that have been published by W11 and P13, and used in several subsequent BOSS analyses. Evidence in support of the models is provided in Figs 4 and 5, which show our directly measured HON values to be in agreement with the model predictions, and from the slope of our CMASS HON distribution, which is consistent with the value in W11. We discuss potential sources of bias in our analysis below (Section 5.2), often drawing on the results of a comparison, photometric redshift based, CMASS HON measurement (Section 5.1). We end this section with a preliminary study of HON evolution, with comparison to the predictions of Saito et al. (2016) (Section 5.3).

Our best-fitting values are close to the mean values over the parameter range tested.

5 Given by the minimum and maximum alpha-index values corresponding to one plus the minimum $\chi^2$-squared value, $1 + \chi_{\text{min}}^2$.  

## 5.2 Potential sources of error in our analysis

### 5.2.1 Incomplete redshift information

Our HON analysis has demonstrated that there are a number of genuine (i.e. confirmed by their X-ray emission) dark matter haloes that have been published by W11 and P13, and used in several subsequent BOSS analyses. Evidence in support of the models is provided in Figs 4 and 5, which show our directly measured HON values to be in agreement with the model predictions, and from the slope of our CMASS HON distribution, which is consistent with the value in W11. We discuss potential sources of bias in our analysis below (Section 5.2), often drawing on the results of a comparison, photometric redshift based, CMASS HON measurement (Section 5.1). We end this section with a preliminary study of HON evolution, with comparison to the predictions of Saito et al. (2016) (Section 5.3).
met al. (2012) redshift range, and so would not be expected to be fossil system sample (the others fall outside of the Harrison
the fact that one of these clusters is included in the Harrison et al.
accumulate its former satellites. This hypothesis is strengthened by systems in which the central galaxy has had time to attract and
shown that there are also haloes without any BOSS targets, or with
investigation using the photometric redshift data (Section 5.1) has
those had yet to be confirmed as CMASS- or LOWZ-galaxies in
= 1 in our CMASS analysis, and 31 in our LOWZ analysis (4 and 1 per cent of the samples, respectively). There are 21 cases of HON=0 in our CMASS analysis, and 31 in our LOWZ analysis (28 and 31 per cent of the samples, respectively). This could be a reflection of the fact that the BOSS programme was incomplete in DR11, i.e. there are BOSS targets in those HON=0,1 haloes, but those had yet to be confirmed as CMASS- or LOWZ-galaxies in DR11. However, this is unlikely to be the major reason, because our investigation using the photometric redshift data (Section 5.1) has shown that there are also haloes without any BOSS targets, or with only one.

The HON=0,1 haloes possibly represent ‘Fossil systems’, i.e. systems in which the central galaxy has had time to attract and accumulate its former satellites. This hypothesis is strengthened by the fact that one of these clusters is included in the Harrison et al. (2012) fossil system sample (the others fall outside of the Harrison et al. (2012) redshift range, and so would not be expected to be included.). It is widely accepted that fossil systems have a different evolution history, both in terms of the galaxies and the dark matter.

in the DR11 region that contain zero or one CMASS- or LOWZ-galaxies, even at masses approaching $10^{15}h^{-1} M_\odot$. There are three cases of HON=0 in our CMASS analysis, and one in our LOWZ analysis (4 and 1 per cent of the samples, respectively). There are 21 cases of HON=0 in our CMASS analysis, and 31 in our LOWZ analysis (28 and 31 per cent of the samples, respectively). This could be a reflection of the fact that the BOSS programme was incomplete in DR11, i.e. there are BOSS targets in those HON=0,1 haloes, but those had yet to be confirmed as CMASS- or LOWZ-galaxies in DR11. However, this is unlikely to be the major reason, because our investigation using the photometric redshift data (Section 5.1) has shown that there are also haloes without any BOSS targets, or with only one.

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of a sample resulted in unconstrained fits. This, in turn, dragged the value all five HOD parameters, the shortage of low-mass haloes in our when we tried to make a multi-parameter MCMC fit to constrain more clusters in the HOD study, especially at the low-mass end: order to include more free parameters in our fit, we would require parameter in the model is varied separately) certain HOD parameters

5.2.3 Freezing model parameters

In our study, we have only allowed one parameter in the HOD model to vary, the slope $\alpha$. However, as shown in Fig. A1 of P13 (where each parameter in the model is varied separately) certain HOD parameters are degenerate to the overall shape of the correlation function. In order to include more free parameters in our fit, we would require more clusters in the HOD study, especially at the low-mass end: when we tried to make a multi-parameter MCMC fit to constrain all five HOD parameters, the shortage of low-mass haloes in our sample resulted in unconstrained fits. This, in turn, dragged the value of $\alpha$ to lower values (due to its degeneracy with $M_\nu$). Consequently, due to our inability to constrain additional HOD parameters at this stage, we report our constraints on $\alpha$ from the one-parameter fit described in Section 4.3. It is hoped that a forthcoming extension of XCS will provide a sufficient number of low-mass haloes to allow for more free parameters, including $M_\nu$ (i.e. the minimum halo mass required to host a satellite galaxy). We note that for the multi-parameter MCMC fit, we used the EMCEE (Foreman-Mackey et al. 2013) python package, imposing uniform priors (0.01 to 2.0 on $\alpha$, and $\pm 3\sigma$ around the W11 and P13 values for the remaining HOD parameters). We also performed MCMC fits with different combinations of three- and four-parameters with similar outcomes.

5.2.4 Use of cluster redshifts from the literature

Not all the XCS-DR1 clusters in the DR11 footprint contain one or more BOSS galaxies within a cluster’s search volume (see Section 3). As a consequence, it is not possible to assign these types of cluster a spectroscopic redshift using BOSS data. However, sometimes it is possible to assign a spectroscopic redshift using information in the literature. As a result, clusters with an HON value of zero are included in our study. However, not all of the XCS clusters with an HON value of zero in the BOSS footprint are included. Those with photometric redshifts available in the literature are excluded. This is a potential source of bias, because the likelihood of a given X-ray cluster having a spectroscopic literature redshift goes up with its mass: higher mass clusters have higher X-ray fluxes (at a given redshift) and so are historically more likely to have been the target of an X-ray cluster spectroscopic follow-up campaign. Therefore, it would be worth measuring the spectroscopic redshifts of the excluded clusters to illustrate whether our current approach has impacted the HOD-model slope.

5.2.5 X-ray based mass determinations

Our analysis relies on an external normalization for the halo mass–temperature relation based on the low-redshift HIFLUGCS catalogue (Pierpaoli et al. 2001; Reiprich & B"ohringer 2002; Viana et al. 2003). Not only does this approach require the extrapolation of the normalization to higher redshifts, it also fails to take into account of the fact that measured X-ray temperature is dependent on the instrument used for the measurement (e.g. Donahue et al. 2014). Independent mass measurements of the clusters, either from weak lensing or from hydrostatic mass determinations, in our study would be needed to quantify the impact of these issues.

5.2.6 X-ray selection effects

It is possible that an XCS-specific selection bias is resulting in a depressed HON at the high-mass end. This is because the XCS-DR1 survey covers only a few hundred square degrees in total (albeit scattered across the BOSS footprint), meaning the volume covered at low redshifts is small compared to that of BOSS. Within this volume, many of the high-mass clusters will have been the intended target of an XMM observation. As a result they will have been excluded from XCS-DR1 because target clusters are, by construct, not included in our serendipitous sample. There is some qualitative evidence for this effect in our analysis: when ancillary clusters, which are predominantly XMM targets, are included, the averaged HONs more closely match the model predictions for the LOWZ-galaxies. In order to quantify these effects, a larger sample of XCS clusters in the BOSS footprint is needed, as is a full parametrization of the XCS selection function.

5.2.7 Optical selection bias

Another selection bias that might impact our current study arises from the optical confirmation process used in XCS-DR1. This process involved visual checks by collaboration members (at least five members per cluster) to ensure that each XCS extended source coincided with an overdensity of galaxies in optical images. The subjective nature of this process could bias the XCS-DR1 samples towards low-mass clusters with higher than average HONs, hence artificially increasing the average HON in that mass range.

5.3 Redshift evolution in the HON

The recent study of Saito et al. (2016) used sub-halo abundance matching to model the stellar mass function and redshift-dependent clustering of CMASS-galaxies. Their model predicts a positive evolution in the mean-halo mass of CMASS-galaxies, which they
attribute to stellar-mass incompleteness at $z > 0.6$. At higher redshifts, this effect leads to a decreasing fraction of satellite galaxies within a halo of given mass; and therefore a non-trivial variation in the HOD of CMASS-galaxies with redshift.

We investigate their prediction for a redshift-dependence of the CMASS HOD by dividing the clusters in the CMASS sample into two redshift bins at $z = 0.55$. For both redshift bins, we calculate the $\alpha$-term of the CMASS HOD following the method described in Section 4.3. Our best-fitting $\alpha$-terms are listed in Table 6 and provide some evidence for a shallower slope on the CMASS HOD at higher redshifts, albeit with large uncertainties. This result would be expected for a decreasing fraction of satellite galaxies with redshift and lends preliminary support for the claims made in Saito et al. (2016).

### Table 6. Best-fitting index $\alpha$ values and 1-$\sigma$ uncertainties as inferred from the HOD of CMASS at split into two redshift bins at $z = 0.55$.  

<table>
<thead>
<tr>
<th>Cluster sample</th>
<th>CMASS (0.43 &lt; $z$ &lt; 0.55) $\alpha$-term</th>
<th>CMASS (0.55 &lt; $z$ &lt; 0.7) $\alpha$-term</th>
</tr>
</thead>
<tbody>
<tr>
<td>XCS-DR1</td>
<td>0.96 $\pm$ 0.13 ($\chi^2$: 49; d.o.f.: 32)</td>
<td>0.80 $^{+0.18}_{-0.19}$ ($\chi^2$: 17; d.o.f.: 20)</td>
</tr>
<tr>
<td>XCS-DR1 + Anc</td>
<td>0.96$^{+0.08}_{-0.09}$ ($\chi^2$: 58; d.o.f.: 40)</td>
<td>0.77$^{+0.10}_{-0.17}$ ($\chi^2$: 40; d.o.f.: 30)</td>
</tr>
</tbody>
</table>

(6) In both the spectroscopic and the photometric analyses, there are examples of massive haloes (where the masses are determined from their X-ray properties) that contain either one or zero BOSS galaxies.

(7) Conclusions 5 and 6 suggest that redshift incompleteness in the SDSS-DR11 sample is not the reason why some massive (including $> 10^{14} h^{-1} M_\odot$) haloes contain either one or zero BOSS galaxies.

(8) Conclusion 5 demonstrates that it will be possible to obtain new understanding of the HOD model using photometric galaxy surveys, such as The Dark Energy Survey.

(9) When the redshift range of the CMASS analysis is changed from $0.43 < z < 0.7$ to $0.4 < z < 0.7$, in direct accordance with the W11 analysis, the slope ($\alpha$ value) does not change significantly. A more recent, to W11, derivation of the CMASS HOD model (Reid et al. 2014) was based on the $0.43 < z < 0.7$ redshift range and is similar to both our directly measured HOD and the W11 model.

(10) When the CMASS sample was divided into two redshift bins, the best-fitting slope ($\alpha$ value) is shallower at $z > 0.55$ compared to $z < 0.55$. This result provides preliminary support to the Saito et al. (2016) prediction that there should be a decreasing fraction of satellite galaxies within a halo of given mass.

There are several ways that our study could be improved in future. These include: including X-ray and optical selection functions to account for biases in the XCS-DR2 sample; expanding the number of free parameters in the HOD-fit; undertaking spectroscopy on a sample of XCS clusters in the BOSS footprint; and testing the normalization of the mass estimation technique used for the XCS clusters by measuring masses for a sample of clusters through independent techniques, e.g. weak lensing shear or resolved X-ray spectroscopy.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:
Table 1. The HOD of BOSS-galaxies in XCS clusters (0.2 < z < 0.7).

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APPENDIX A

Figure A1. As Fig. 4, but with the XCS best-fitting HOD (red solid line) replacing the HOD fit from W11.

Figure A2. As Fig. 5, but with the XCS best-fitting HOD (green solid line) replacing the HOD fit from P13.