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Author: Uiter, Edo van

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Redshift dependence of the mass-richness relation of clusters in the second Red-sequence Cluster Survey

We study the relation between the richness and mass of a sample of 1.4×10^4 clusters of galaxies in the redshift range $0.2 < z < 1.2$ and masses $M_{200} > 2 \times 10^{13} h_{70}^{-1} M_{\odot}$, discovered in the second Red-sequence Cluster Survey (RCS2). Cluster masses are determined from the weak gravitational lensing signal of the clusters; the depth and image quality of the RCS2 enable the detection of the cluster-mass cross-correlation signal even at redshifts $z \sim 1$. We fit the mass-richness relation with $M_{200} = A(N_{200}/20)^{\alpha}$, and find $A = (15.09 \pm 0.66) \times 10^{13} h_{70}^{-1} M_{\odot}$ and $\alpha = 0.86 \pm 0.05$ for the full sample. To explore any redshift dependence of the scaling relation, we split the cluster sample in four redshift slices. We find that the mass-richness relation depends on redshift. The change with redshift is strongest for galaxy groups and poor clusters; we find that a $N_{200} = 5$ cluster at $z = 0.25$ is $1.6^{+0.6}_{-0.4}$ times more massive than a $N_{200} = 5$ cluster at $z = 0.7$. For the clusters with $N_{200} > 15$, the data are consistent with no change. With this calibration between richness and mass, the RCS2 cluster sample can be exploited to constrain cosmological parameters. We discuss a few potential observational biases and physical processes that may contribute to the observed redshift dependence.

E. van Uitert, H. Hoekstra, E. Semboloni, D.G. Gilbank, M.D. Gladders, H.K.C. Yee, in preparation;

6.1 Introduction

Galaxy clusters correspond to the largest gravitational potentials in the universe. Their abundance as a function of mass sensitively depends on various cosmological parameters, such as the normalization of the matter power spectrum, σ_8 , and the cosmological matter density, Ω_M (e.g. Evrard 1989; White et al. 1993). The evolution of the abundance depends on the dark energy equation of state (e.g. Voit 2005; Allen et al. 2011). These cosmological parameters can therefore be constrained by accurately determining the cluster mass function, and its dependence on redshift.

The first step of determining the cluster mass function is the detection of the clusters. Clusters can be found in various ways, such as by detecting X-ray peaks in the sky background (e.g. Böhringer et al. 2000; Lloyd-Davies et al. 2011), by measuring the spectral distortions of the cosmic microwave background radiation from inverse Compton scattering, known as the Sunyaev-Zeldovich effect (SZE; Sunyaev & Zeldovich 1972) which has recently been applied to various dedicated surveys (e.g. Williamson et al. 2011; Marriage et al. 2011), or by detecting galaxy density enhancements in optical surveys (e.g. Gladders & Yee 2005; Koester et al. 2007). These observations provide various cluster properties which can be related to the mass, including the X-ray flux and temperature, SZE properties of the clusters such as the detection significance, the number of cluster members within a certain aperture (the richness), but not the mass itself.

The total mass of a cluster can only be determined indirectly. Various methods have been employed for this purpose. The kinematics of satellite galaxies in clusters have been used (e.g. van der Marel et al. 2000; Lokas et al. 2006), but these observations are generally expensive as they require spectroscopic observations of many cluster members. Additionally, assumptions on the satellite orbits are needed to convert the velocity dispersions into a mass estimate. X-ray luminosities emitted by hot gas in clusters can also be used to estimate the mass (e.g. Reiprich & Böhringer 2002), under the assumption that the gas is in hydrostatical equilibrium. The results of Mahdavi et al. (2008) suggest, however, that clusters are generally not in hydrostatical equilibrium, which could bias the X-ray based mass estimates. The Sunyaev-Zeldovich effect has also been used (e.g. Williamson et al. 2011), and appears particularly useful to estimate the masses of massive clusters at high redshifts. Another popular method, the one employed in this work, is weak gravitational lensing.

In weak lensing the distortion of the images of faint background galaxies (sources) due to the gravitational potentials of intervening structures (lenses) is measured. From this distortion, the differential surface mass density of the lenses can be deduced, which can be modeled to obtain the total mass. A major advantage of gravitational lensing over other methods is that it does not rely on optical tracers; the distortion can be measured for any lens, out to large radii where no optical tracers can be used. Additionally, the weak lensing signal does not depend on the physical state of the matter in the clusters, and no assumptions have to be made (e.g. virial equilibrium) to measure the total mass.

Weak gravitational lensing has been used to determine the mass of individual massive low-redshift clusters (e.g. Hoekstra 2007; Okabe et al. 2010). The signal-to-noise of low-mass clusters or galaxy groups is generally not high enough

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to obtain a reliable mass estimate. However, by stacking the signal of a certain set of these clusters, the average mass of these systems can be determined (e.g. Mandelbaum et al. 2006; Sheldon et al. 2009b).

A number of complications limit a simple interpretation of the weak lensing mass estimates of clusters. The two complications that are thought to dominate are the triaxiality of dark matter haloes (e.g. Clowe et al. 2004; Corless & King 2007), and the presence of correlated and uncorrelated structure along the line-of-sight (e.g. Metzler et al. 2001; Hoekstra 2001; Hoekstra et al. 2011b). These complications are mainly thought to increase the scatter of the mass estimates, but may even lead to small ($\sim 5\text{--}10\%$) biases if model fitting techniques are used (Becker & Kravtsov 2011; Rasia et al. 2012). The lensing signal can be modeled in various ways, and particular choices can reduce this bias (Mandelbaum et al. 2010). More detailed numerical simulations are required to quantify this bias more precisely, e.g. as a function of mass and redshift, to interpret the results correctly. This is important for the exploitation of clusters as a percent-level precision tool for cosmology.

To accurately determine the cluster mass function and its redshift dependence, we need mass estimates of large numbers of clusters covering a broad range of masses and redshifts. Since the lensing signal of individual clusters that are not massive, or located at high redshifts, is generally too weak to extract a reliable mass estimate, we cannot measure the cluster mass function directly from the data. A common solution is to determine how a cluster property that can be directly estimated from the data is related to the total mass as determined from lensing. A convenient cluster property that can be used for this purpose is the richness, because it is a quantity that can be obtained from readily available multi-colour imaging data, the same data that is used for the lensing analysis. To constrain the cosmological parameters with the cluster richness function rather than the mass function requires a careful calibration of the relation between the mass and richness of clusters.

To determine the richness of a cluster it is necessary to distinguish the cluster galaxies from the fore- and background galaxies. Cluster members can be identified if their redshift or velocity dispersions are available, which either requires spectroscopy or observations in many bands for reliable photometric redshifts. Alternatively, cluster members can be identified using their colours as the majority of early-type galaxies in a cluster populate a narrow range in colour-magnitude space, i.e. the E/S0 ridge-line or the red sequence (Gladders & Yee 2000). The advantage of the latter is that observations in only two bands suffice, which makes it cheap and particularly suited for the automated detection of clusters in large imaging surveys (e.g. Gladders & Yee 2005). This richness does not include the blue star-forming galaxies, but since we are mainly interested in calibrating a cluster observable to the total mass, this is of no importance.

Note that the mass-richness relation is not only interesting for the exploitation of clusters as cosmological probes, but also to improve our understanding of cluster evolution processes. Once formed, clusters continue to evolve through the accretion of galaxies and dark matter, internal processes in the cluster members, tidal interactions and mergers with other clusters. These processes change both the appearance of clusters as well as other intrinsic properties, such as their mass, shape and angular momentum. To learn more about these processes, we can study the evolution of the relation between various cluster properties, such as the relation between mass and richness.

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This study is performed using the imaging data from the second Red-sequence Cluster Survey (RCS2; Gilbank et al. 2011). The study of cluster evolution is one of the main science goals of the RCS2. The survey design was chosen such to optimize the detection of a large number of clusters using the red sequence method (Gladders & Yee 2000). A preliminary cluster catalogue has been made available containing 27 793 clusters spread over a large range in optical richness, and redshifts in the range $0.2 < z < 1.2$ (Gladders et al., in prep.). In contrast, the redshift range of the maxBCG cluster sample (Koester et al. 2007), a catalogue of 13 823 clusters that has been detected in the Sloan Digital Sky Survey (SDSS; York et al. 2000), only covers a redshift range $0.1 < z < 0.3$, which limits their use for evolutionary studies. The redshift range of clusters in the RCS2, however, combined with the excellent lensing quality of the data, makes the RCS2 exceptionally suited for this purpose. This is demonstrated in this work, where we analyse the redshift dependence of the mass-richness relation.

The outline is as follows. In Section 6.2, we discuss the various steps of the lensing analysis: we detail the creation of the shape measurement catalogues, provide a short summary on the detection of clusters, and discuss the modeling of the lensing signal. The mass-richness relation for the RCS2 clusters is presented in Section 6.3, and its redshift dependence is discussed in Section 6.4. We conclude in Section 6.5. Throughout the paper we assume a WMAP7 cosmology (Komatsu et al. 2011) with $\sigma_8 = 0.8$, $\Omega_\Lambda = 0.73$, $\Omega_M = 0.27$, $\Omega_b = 0.046$ and $h = 0.7$ the dimensionless Hubble parameter. All distances quoted are in physical (rather than comoving) units unless explicitly stated otherwise.

6.2 Lensing analysis

The Red-sequence Cluster Survey 2 (RCS2) (Gilbank et al. 2011) is a nearly 900 square degree imaging survey in three bands (g' , r' and z') carried out with the Canada-France-Hawaii Telescope (CFHT) using the 1 square degree field of view camera MegaCam. In this work, we use the 740 square degree of the primary imaging data. The remainder constitutes the ‘Wide’ component of the CFHT Legacy Survey (CFHTLS). The lensing analysis is performed on the 8 minute exposures of the r' -band ($r'_{\text{lim}} \sim 24.3$), which is best suited for lensing with a median seeing of $0.71''$.

6.2.1 Data reduction

The photometric calibration of the RCS2 is described in detail in Gilbank et al. (2011). The magnitudes are calibrated using the colours of the stellar locus and the overlapping Two-Micron All-Sky Survey (2MASS), and have an accuracy smaller than 0.03 mag in each band compared to the SDSS. For more details, we refer the reader to Gilbank et al. (2011).

The lensing analysis is described in van Uitert et al. (2011). Here, we present a summary of the essential steps. In order to create the shape catalogues, we retrieve the Elixir¹ processed images from the Canadian Astronomy Data Centre (CADC) archive². We use the THELI pipeline (Erben et al. 2005, 2009) to subtract the image backgrounds, create weight maps that we use in the

¹<http://www.cfht.hawaii.edu/Instruments/Elixir/>

²<http://www1.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/cadc/>

object detection phase, and to identify satellite and asteroid trails. To detect the objects in the images, we use **SExtractor** (Bertin & Arnouts 1996). The stars that are used to model the PSF variation across the image are selected using size-magnitude diagrams. All objects larger than 1.2 times the local size of the PSF are identified as galaxies. We measure the shapes of the galaxies with the KSB method (Kaiser et al. 1995; Luppino & Kaiser 1997; Hoekstra et al. 1998), using the implementation described by Hoekstra et al. (1998, 2000). This implementation has been tested on simulated images as part of the Shear Testing Programmes (STEP) (the ‘HH’ method in Heymans et al. (2006) and Massey et al. (2007), respectively), and these tests have shown that it reliably measures the unconvolved shapes of galaxies for a variety of PSFs. Finally, the source ellipticities are corrected for camera shear, which originates from slight non-linearities in the camera optics. The resulting shape catalogue of the RCS2 contains the ellipticities of 2.2×10^7 galaxies. A more detailed discussion of the analysis can be found in van Uitert et al. (2011).

6.2.2 Cluster detection

The clusters are identified with the Cluster-Red-Sequence method (CRS; Gladders & Yee 2000) using the deep optical imaging data of the RCS2. This technique makes use of the property that the majority of early-type galaxies of a cluster at a given redshift populate a narrow volume in colour-magnitude space, i.e. the red sequence, with a small scatter (e.g. Bower et al. 1992). The intrinsic colour scatter does not significantly evolve up to a redshift of 1.5 (for a compilation of low- and high-redshift results, see Jaffé et al. 2011), and has a low variance between clusters (e.g. López-Cruz et al. 2004). In the CRS method, the colours, magnitudes and the locations of the galaxies are used to span a space in which the overdensities correspond to clusters. These overdensities are detected to identify and characterize the clusters following the methodology of Gladders & Yee (2000), the method that has been successfully applied to detect clusters in the first Red-sequence Cluster Survey (Gladders & Yee 2005). The location of the overdensity in colour space provides an accurate estimate of the redshift of the cluster. The significance of the detected overdensity is related to the richness. Details of the implementation of the CRS method for the RCS2 is presented in Gladders et al. (in prep.).

To identify the centre of the cluster, we use the location of the overdensity in the colour-magnitude-position space. The position of the brightest cluster galaxy is another commonly used estimator of the centre (e.g. Koester et al. 2007), and has been measured as well for the RCS2 clusters (Gralla et al., in prep.). By comparing the lensing signals around both estimates of the cluster centre, we can determine which one is closer to the actual centre of the projected total mass distribution. This will be done in a future work.

The richness of a cluster can be characterized in various ways (e.g. Rykoff et al. 2011; Rozo et al. 2009; Hansen et al. 2005; Yee & López-Cruz 1999). In this work we use N_{200} , the richness estimator that was used in the weak lensing analysis of the maxBCG clusters (Johnston et al. 2007; Sheldon et al. 2009b,a), as it eases a comparison of the results. N_{200} is defined as the number of E/S0 (red sequence) galaxies brighter than M^*+2 within r_{200}^{gal} , the radius where the

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density is 200 times the critical density ρ_c . This radius is determined from the empirical relationship between N_{gal} , the number of red sequence cluster members within a fixed $1 h^{-1}$ Mpc aperture, and r_{200}^{gal} , the radius where the mean number density of galaxies is 200 times larger than the mean space density of galaxies, as measured for the maxBCG clusters (Hansen et al. 2005). This relation implicitly assumes that galaxies are unbiased with respect to the dark matter. The relation is given by

$$r_{200}^{\text{gal}} = 0.156 N_{\text{gal}}^{0.6} h^{-1} \text{Mpc}. \quad (6.1)$$

This radius agrees within 5% to the r_{200} as determined with lensing (Johnston et al. 2007).

The definition of richness slightly differs between the maxBCG and the RCS2: the N_{200} of a maxBCG cluster includes all red galaxies (within $\pm 2\sigma$ of the red sequence) brighter than $0.4L^*$ in the i -band. We study how the richness estimates compare by matching the maxBCG cluster catalogue to the RCS2 cluster catalogue, using the ~ 300 square degrees overlap between the RCS2 and the SDSS. Approximately 150 clusters are matched. We find that the richness estimates agree well, albeit with large scatter. However, there is no evidence for a large systematic offset, and we conclude that we do not need to account for the different definitions of richness in order to compare the results of the maxBCG and the RCS2.

In this work, we use a preliminary version of the RCS2 cluster catalogue, which contains 14 279 clusters with $N_{200} > 5$. We show the distribution of redshift and richness of the cluster sample in Figure 6.1. The cluster sample covers a redshift range of $0.2 < z < 1.2$, which makes this sample very well suited for evolutionary studies (in particular compared to the maxBCG cluster sample of the SDSS, that only covers redshifts $0.1 < z < 0.3$). The richness estimates are not discrete values, as the average number of background galaxies is subtracted. Note that the abundance of clusters drops below $N_{200} < 4$ ($\log(N_{200}) < 0.6$). The lack of low-richness clusters at low redshift is not physical, and will be corrected in the final cluster catalogue. The richness estimates are therefore potentially biased in this richness range. We cannot assess this bias by comparing to the publicly available maxBCG catalogue, as this catalogue only covers $10 < N_{200} < 190$. Therefore, we only include clusters with $N_{200} > 5$ in our analysis. Since most of the lensing signal is produced by the rich clusters, this cut only causes a small increase of the errors of the best fit parameters of the mass-richness relation.

6.2.3 Lensing measurement

Imprinted on the ellipticities of the source galaxies are small distortions induced by the density profiles of the clusters. These distortions are measured by averaging the ellipticities of the source galaxies in radial bins centered at the lenses. The resulting tangential shear,

$$\langle \gamma_t \rangle(r) = \frac{\Delta \Sigma(r)}{\Sigma_{\text{crit}}}, \quad (6.2)$$

is related to the surface density contrast $\Delta \Sigma(r) = \bar{\Sigma}(< r) - \bar{\Sigma}(r)$, the difference between the mean projected surface density enclosed by r and the mean

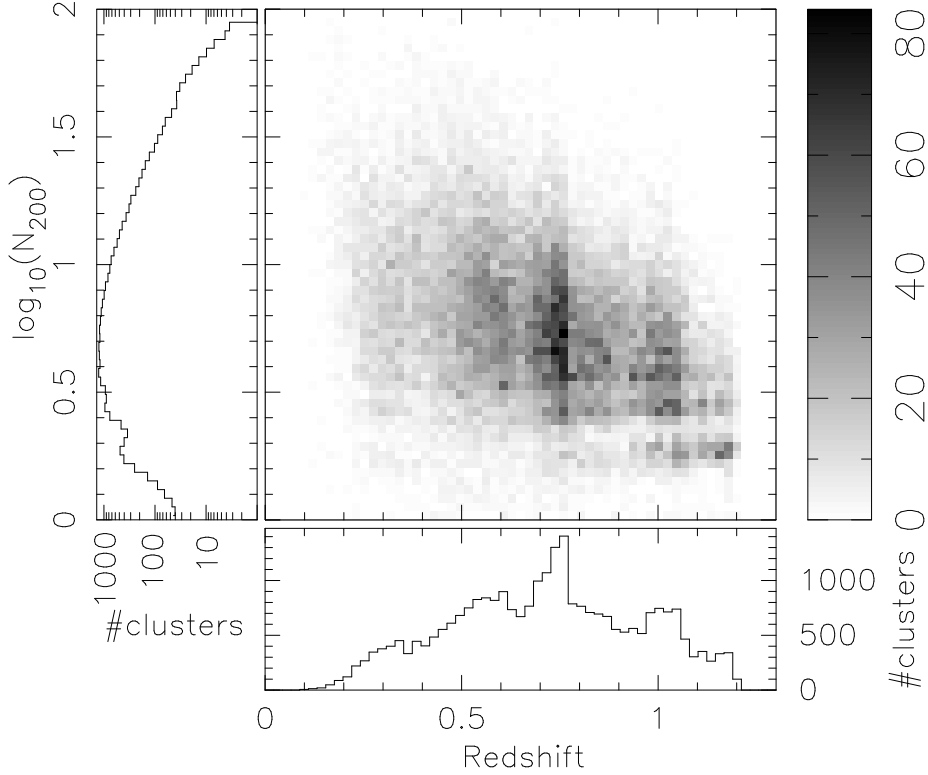


Figure 6.1: Redshift versus $\log(N_{200})$, the logarithm of the number of early-type cluster members brighter than M^*+2 inside r_{200} , of the cluster sample. The clusters cover a large range in richness and redshift, and are therefore very well suited to study the redshift dependence of the mass-richness relation.

projected surface density at a radius r . Σ_{crit} is the critical surface density:

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_s}{D_l D_{ls}}, \quad (6.3)$$

with D_l , D_s and D_{ls} the angular diameter distance to the lens, the source, and between the lens and the source, respectively. Since we lack redshifts, we select galaxies with $22 < m_{r'} < 24$ that have a reliable shape estimate (ellipticities smaller than one, no SExtractor flag raised) as sources. We obtain the approximate source redshift distribution by applying identical magnitude cuts to the photometric redshift catalogues of the Canada-France-Hawaii-Telescope Legacy Survey (CFHTLS) “Deep Survey” fields (Ilbert et al. 2006). To remove contributions of systematic shear (from, e.g., the image masks), we subtract the signal computed around random points from the signal computed around the real lenses (see van Uitert et al. 2011).

The distortions induced by weak lensing are much smaller than the intrinsic ellipticities of the sources. The lensing measurement of a single cluster is therefore generally very noisy. To improve the signal-to-noise, the lensing signal is therefore stacked for a sample of clusters that have similar properties (e.g. within a certain richness range). Stacking the lensing signal has the additional

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advantage that the contribution from uncorrelated structures, as well as from potential small-scale residual systematics, averages out.

6.2.4 Contamination

A fraction of our source galaxies is physically associated with the clusters. They are not lensed and therefore dilute the lensing signal. We cannot remove them from the source sample because we lack redshifts. We can remove the bright elliptical cluster members using their colours. The faint cluster members, however, cannot be efficiently removed using their colours, because their red sequence is not well defined, and many of them are blue (Hoekstra 2007). Fortunately, we can account for the dilution of the lensing signal by measuring the excess source galaxy density around the lenses, $f_{cg}(r)$, and boost the lensing signal with $1+f_{cg}(r)$. This correction implicitly assumes that the satellite galaxies are randomly oriented. If the satellites are preferentially radially aligned to the lens, however, the contamination correction may be too low. Attempts have been made to measure this type of intrinsic alignment around galaxies. Some intrinsic alignment was detected in the studies that used the isophotal position angles for the galaxies (e.g. Agustsson & Brainerd 2006; Faltenbacher et al. 2007), whilst studies that used the galaxy moments instead did not measure a significant detection (e.g. Hirata et al. 2004; Mandelbaum et al. 2005). This discrepancy was attributed by Siverd et al. (2009) and Hao et al. (2011) to the different definitions of the position angle of a galaxy; the favoured explanation is that light from the central galaxy contaminates the light from the satellites, which affects the isophotal position angle more than the galaxy moments one. In addition, Sheldon et al. (2009b) detects no intrinsic alignment for a sample of 4119 spectroscopically confirmed clusters from Berlind et al. (2006), using all galaxies from the SDSS main spectroscopic sample (Strauss et al. 2002) in the range $\pm 2000 \text{ km s}^{-1}$. Since we measure the shapes of source galaxies using galaxy moments, and considering the results from Sheldon et al. (2009b), we expect that intrinsic alignments have a minor impact at most and can be ignored.

6.2.5 Lensing analysis

Numerical simulations suggest that the density distribution of collapsed dark matter haloes over a wide range of masses are well described by a Navarro-Frenk-White profile (NFW; Navarro et al. 1996). Therefore, we use this profile to model the lensing signal. The NFW density profile is given by

$$\rho(r) = \frac{\delta_c \rho_c}{(r/r_s)(1 + r/r_s)^2}, \quad (6.4)$$

with δ_c the characteristic overdensity of the halo, ρ_c the critical density for closure of the universe, and $r_s = r_{200}/c_{200}$ the scale radius, with c_{200} the concentration parameter. The NFW profile is fully specified for a given set of (M_{200}, c_{200}) , with M_{200} the mass inside a sphere of radius r_{200} , the radius inside of which the density is 200 times the critical density ρ_c . Since numerical simulations have shown that the concentration depends on the mass and redshift of the halo, we can reduce the number of free parameters in the fit by

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adopting a mass-concentration relation. Although the concentration at a fixed cluster mass exhibits a large scatter (e.g. Bahé et al. 2012), this does not affect our analysis since we stack the lensing signals of a large number of clusters. We use the mass-concentration relation from Duffy et al. (2008), which is based on numerical simulations using the best fit parameters of the WMAP5 cosmology. It is given by

$$c_{\text{NFW}} = 5.71 \left(\frac{M_{200}}{2 \times 10^{12} h^{-1} M_{\odot}} \right)^{-0.084} (1+z)^{-0.47}. \quad (6.5)$$

Hence the only parameter we fit is M_{200} . We calculate the tangential shear profile using the analytical expressions provided by Bartelmann (1996) and Wright & Brainerd (2000).

To determine in which range the lensing signals of the clusters are accurately described by an NFW profile, we show the tangential shear of the full cluster sample in Figure 6.2. Since the assigned cluster centre used in the lensing measurements does not always correspond to the actual centre of the dark matter distribution, the lensing signal on small scales is biased low (e.g. Johnston et al. 2007; Hoekstra et al. 2011a). On large scales, the lensing signal is increased by the contribution of neighbouring structures. To prevent the effect of miscentering of clusters and the neighbouring structures from biasing the results, we fit the NFW profiles between 0.2 and $2 h_{70}^{-1}$ Mpc. We find that in this range, the NFW profile describes the lensing signal well, as is shown in Figure 6.2. Note that for this figure, we fit both M_{200} and c_{200} since the clusters cover a broad range of masses and concentrations.

In future work the measurements will be analysed using cluster halo models similar to those described in Johnston et al. (2007), and account for the miscentering of the clusters, for the additional lensing signal on large scales from neighbouring structures and for the scatter between halo mass and richness. This will enable us to include a broader range of scales in the fit, which improves the errors on the best fit parameters. Also, it will enable us to study the relation between the total mass and various other cluster properties, such as the concentration and the bias.

The results from Johnston et al. (2007) show that the distribution of projected radial offsets between the actual and the observed cluster centres is not well constrained by the lensing measurements. The lensing results are therefore sensitive to the assumed shape of this distribution that is used as a prior in the lensing models. To improve the prior from the data, we plan to use the galaxy overdensity measured around the cluster centres. Galaxies trace the dark matter potential, and the number density is therefore also affected by miscentering of clusters. We show the average galaxy overdensity around all clusters in Figure 6.2, and as a function of richness in Appendix 6.A. In short, the results we present here are preliminary, although we do not expect that the best fit values of M_{200} will change significantly.

6.3 Mass-richness relation

To determine the relation between richness and mass, we divide the clusters in bins of richness. Details for the cluster samples are given in Table 6.1. The

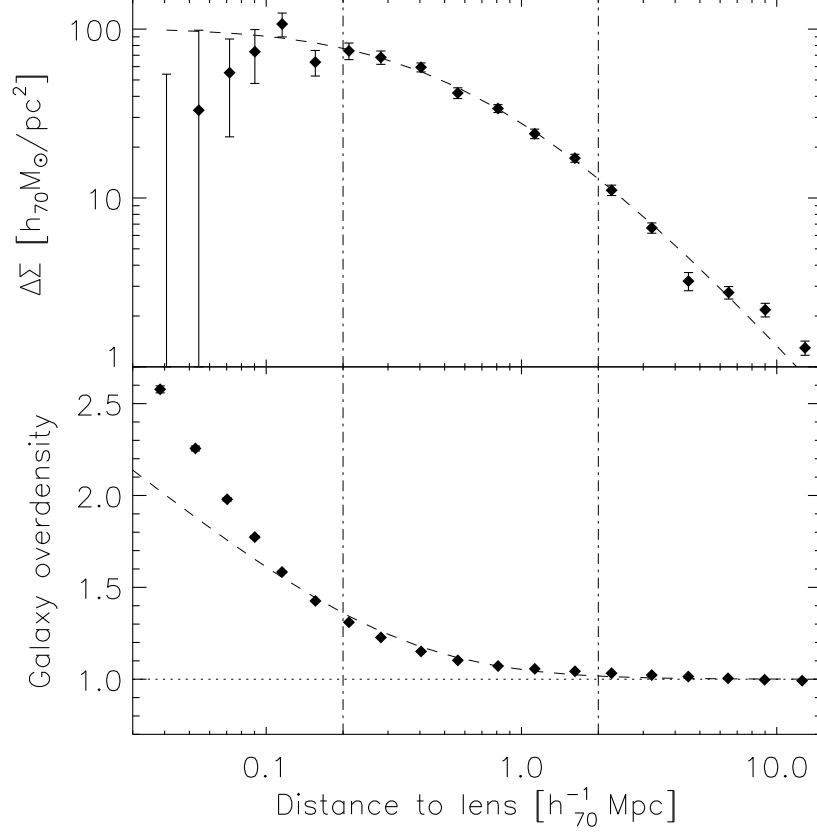


Figure 6.2: Stacked lensing signal and galaxy overdensity measured for all clusters with $N_{200} > 5$ in the RCS2. The dashed line in the top panel indicates the best fit NFW profile fitted to shear; the vertical dot-dashed lines indicate the fitting range. The surface density Σ that corresponds to the best fit lensing profile has been scaled to match the observed galaxy overdensity in the range $0.2 < r < 2 h_{70}^{-1} \text{Mpc}$ in the bottom panel. Both profiles are shown for illustration only.

richness ranges are chosen such to enable a straightforward comparison to Johnston et al. (2007). The lensing signals of all clusters in each bin are stacked, and boosted with the excess source galaxy density to correct for the contamination of physically associated galaxies in the source sample. The resulting lensing signals are shown in Figure 6.3, together with their best fit NFW profiles. We find that in the range between $200 h_{70}^{-1} \text{kpc}$ and $2 h_{70}^{-1} \text{Mpc}$, the lensing signal is described reasonably well by a single NFW profile, which is reflected by the χ^2 -values of the fit. The average χ^2 is 8.4, whilst the expected value is 6. The largest χ^2 is for the $18 < N_{200} < 25$ bin, and has a value of 15.0.

Before we can compare the mass-richness relation we need to correct N_{200} for Eddington bias: clusters scatter preferentially from richness ranges where

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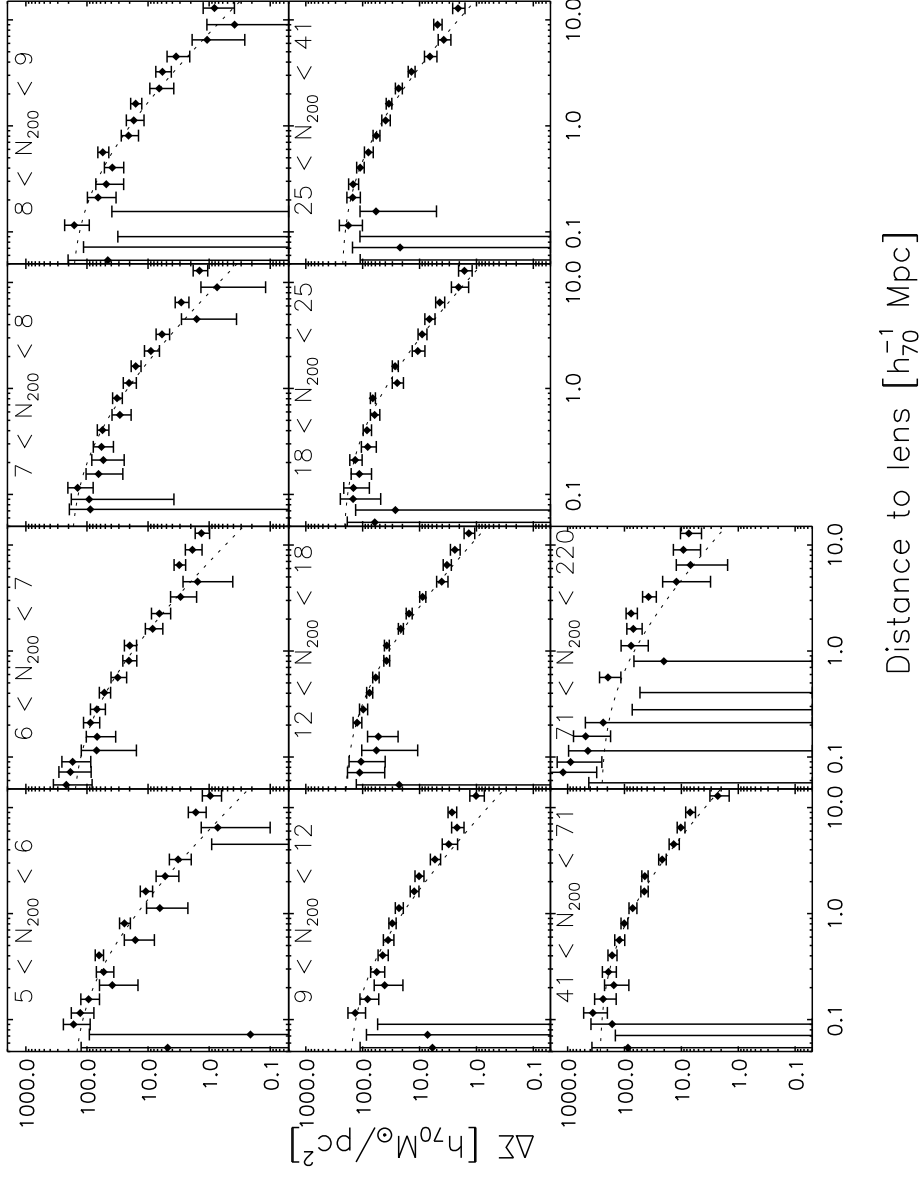


Figure 6.3: Lensing signal $\Delta\Sigma$ for each richness bin as a function of physical distance to the lens. The dashed lines indicate the best fit NFW profile, fitted to scales between 0.2 and $2 h_{70}^{-1}$ Mpc.

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Table 6.1: Cluster sample details

bin	N_{200} (1)	n_{clus} (2)	z_{med} (3)	$\langle N_{200} \rangle$ (4)	N_{200}^{corr} (5)	$M_{200}[10^{13}h_{70}^{-1}M_{\odot}]$ (6)
N1	5-6	2815	0.72	5.48	2.91	$3.40^{+0.51}_{-0.51}$
N2	6-7	2218	0.69	6.49	3.92	$4.22^{+0.63}_{-0.58}$
N3	7-8	1723	0.68	7.50	4.93	$5.46^{+0.79}_{-0.72}$
N4	8-9	1323	0.66	8.48	5.91	$4.90^{+0.84}_{-0.79}$
N5	9-12	2545	0.63	10.3	7.78	$5.06^{+0.56}_{-0.56}$
N6	12-18	2117	0.58	14.4	11.85	$10.86^{+0.80}_{-0.74}$
N7	18-25	851	0.55	20.9	18.22	$13.59^{+1.35}_{-1.23}$
N8	25-41	513	0.51	30.7	27.40	$19.10^{+1.84}_{-1.80}$
N9	41-71	160	0.47	50.4	47.37	$38.35^{+4.58}_{-4.21}$
N10	71-220	14	0.45	82.0	75.87	$30.65^{+15.21}_{-12.49}$

(1) richness range of the bin; (2) number of clusters; (3) median redshift; (4) mean richness; (5) mean richness corrected for Eddington bias; (6) best fit NFW mass.

the number of clusters is high to those where the abundance is low. Since there are generally more poor clusters than rich clusters, the average richness of clusters within a certain richness range is biased high. For broad richness bins the bias is small, but for small richness ranges as used in our analysis the bias is non-negligible.

To correct the values of N_{200} for Eddington bias, we follow Bayes theorem. The probability distribution of N_{200} given an observed value N_{200}^{obs} (the posterior) is proportional to the product of the chance of having a value of N_{200}^{obs} given a distribution of N_{200} (likelihood) and the probability distribution of N_{200} (prior):

$$p(N_{200}|N_{200}^{\text{obs}}) \propto p(N_{200}^{\text{obs}}|N_{200})p(N_{200}). \quad (6.6)$$

The adopted likelihood distribution is a Poisson distribution. In principle, the observed richness distribution can be used as an estimate of the prior. However, as shown in Figure 6.1, the cluster sample is incomplete at the low richness end by an uncertain amount, and using it as a prior would lead to an erroneous correction. Since we expect that the cluster sample is complete for approximately $N_{200} > 15$, we fit a powerlaw to the richness distribution at $N_{200} = 15$. For the prior, we replace the observed richness distribution with this powerlaw at $N_{200} < 15$, whilst at larger richnesses we use the observed richness distribution. The posterior is normalized and integrated up to the mean, N_{200}^{corr} . These values are tabulated in Table 6.1, as well as the uncorrected values.

We show both the original and the Eddington-corrected mass-richness relation in Figure 6.4. The Eddington correction mainly affects the low-richness bins. We fit the corrected mass-richness relation with $M_{200} = A(N_{200}^{\text{corr}}/20)^{\alpha}$, and find $A = (15.09 \pm 0.66) \times 10^{13}h_{70}^{-1}M_{\odot}$ and $\alpha = 0.86 \pm 0.05$. The errors on the amplitude are determined by marginalizing over the slope, and vice versa.

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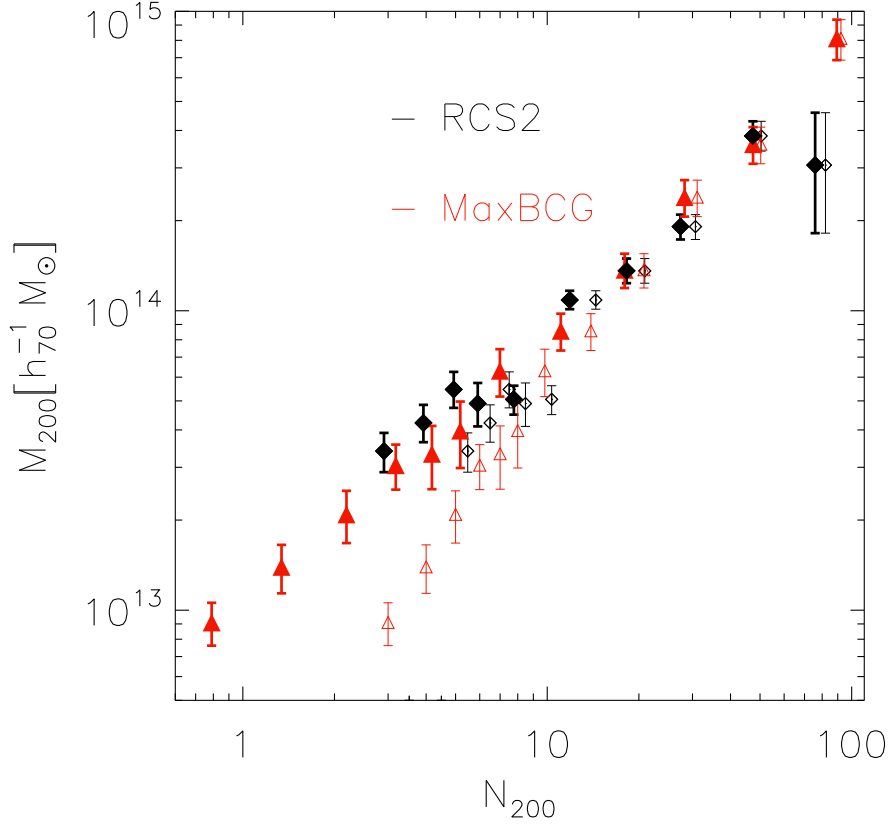


Figure 6.4: Best fit cluster mass versus the richness. The black diamonds denote the results from this work, the red triangles denote the results from the lensing analysis of the maxBCG clusters in Johnston et al. (2007). Open symbols indicate the original measurements, the filled symbols indicate the measurements corrected for Eddington bias.

The likelihood contour of this fit is shown in panel (a) of Figure 6.5. Without the correction for Eddington bias, we obtain $A = (12.84 \pm 0.50) \times 10^{13} h_{70}^{-1} M_{\odot}$ and $\alpha = 1.03 \pm 0.05$, which demonstrates that the correction is important.

Not all detections in the cluster catalogue are real clusters: a fraction of the clusters may actually correspond to a chance projection of galaxies rather than to a real cluster. These false detections have presumably a different lensing mass than the real clusters of that richness, and therefore potentially bias the average lensing signal. The fraction of real clusters is called the purity, which is generally a function of richness and redshift, but its particular shape depends on the cluster detection algorithm. Therefore, to determine the actual value of the purity for our cluster sample, we need to apply the detection algorithm to simulations that mimic the RCS2, which has currently not been done. The false positives do not add random noise, but a coherent (but likely lower) lensing

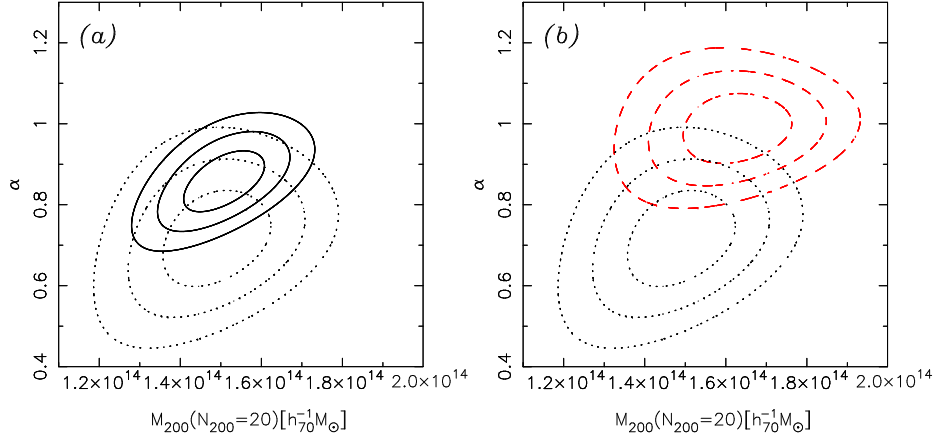


Figure 6.5: 67.8%, 95.4% and 99.7% confidence limits of the fits to the mass-richness relation. In panel (a), the solid black lines indicate the results for the full RCS2 sample, and the dotted black lines indicate the results for the RCS2 clusters in the redshift range $0.1 < z < 0.3$. The contours do not overlap, which suggests that the mass-richness relation depends on redshift. In panel (b) we compare the results for the RCS2 clusters in the redshift range $0.1 < z < 0.3$ to the results of the maxBCG sample covering the same richness range as the RCS2, i.e. $N_{200}^{\text{corr}} > 4$, which is indicated by the dashed red lines. The agreement between the results is fair.

signal. How large the impact is on the lensing mass needs to be addressed with simulations. Note, however, that the purity is only expected to be less than 100% for the low-richness bins. The high-richness bins should be very pure, and the bias on the masses negligible. The effect on the best-fit parameters of the mass-richness relation is therefore expected to be small.

6.3.1 Comparison to the maxBCG cluster sample

We compare our results to the weak lensing analysis of the maxBCG cluster sample (Koester et al. 2007), a catalogue of 13823 clusters that has been detected in the SDSS. The cluster detection algorithm employed in Koester et al. (2007) identifies the cluster red-sequence galaxies, and selects the brightest, the BCG, as centre of the cluster. The resulting cluster sample covers the richness range $10 < N_{200} < 190$ and a redshift range of $0.1 < z < 0.3$. In Sheldon et al. (2009b), the cluster sample is extended to $N_{200} = 3$, which leads to a sample of $\sim 130\,000$ galaxy groups and clusters. The lensing analysis of the sample is presented in Sheldon et al. (2009b); the mass-richness relation is derived in Johnston et al. (2007).

The richnesses of Johnston et al. (2007) have not been corrected for Edington bias. We perform the correction, using a probability distribution for the maxBCG sample of $p(N_{200}) \propto (N_{200})^{-3}$ over the entire richness range, following Andreon & Hurn (2010). We show both the original and the Edington bias corrected results in Figure 6.4. We fit the same powerlaw to the corrected results in the overlapping richness range, $N_{200}^{\text{corr}} > 3$, and find

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$A = (16.29 \pm 0.88) \times 10^{13} h_{70}^{-1} M_{\odot}$ and $\alpha = 0.99 \pm 0.06$, which does not agree well with our results. However, the average redshift of the clusters in the RCS2 sample is considerably higher than those in the maxBCG sample. To account for possible changes with redshift, and to enable a fairer comparison between the results, we only select RCS2 clusters that cover the same redshift range. Hence we select all clusters with $0.1 < z < 0.3$ from the RCS2 cluster sample, measure their lensing signals and fit the mass-richness relation. We find that $A = (14.91 \pm 0.88) \times 10^{13} h_{70}^{-1} M_{\odot}$ and $\alpha = 0.72 \pm 0.08$, and show the confidence limits in Figure 6.5b. The amplitude of the fit is about 2σ lower than the amplitude of the maxBCG results in the range $N_{200}^{\text{corr}} > 3$. Using the marginalized errors on the powerlaw slopes, we find that best fit slopes for the maxBCG and the RCS2 are more than $\sim 3\sigma$ apart. Figure 6.5 shows that this discrepancy is partly the result of the particular shapes of the contours, and that the actual tension is somewhat smaller.

There are several differences between the analyses that may contribute to the difference between the results. For example, the lensing models used in this work and in Johnston et al. (2007) are different. To estimate how much this impacts the results, we create a mock lensing signal that mimics a typical lensing model used in Johnston et al. (2007), and fit a single NFW profile to it. The difference between the input mass and the best fit NFW mass then provides an estimate of the sensitivity of the results on the adopted lensing model.

In the lensing models of Johnston et al. (2007), it is assumed that a fraction p_c of the clusters is correctly centered, and their lensing signal follows an NFW profile, $\Delta\Sigma_{\text{NFW}}^{\text{cent}}$. The other $(1 - p_c)$ is miscentered with a Gaussian radial offset distribution that has a width $\sigma_s = 0.42 [h^{-1} \text{ Mpc}]$. We refer readers to Johnston et al. (2007) for details on the calculation of the average shear of these miscentered clusters, $\Delta\Sigma_{\text{NFW}}^{\text{miscent}}$. Neighbouring clusters add to the lensing signal at large projected separations. To calculate their contribution to the shear, $\Delta\Sigma^{2h}$, we use the 2-halo term from the halo model described in van Uitert et al. (2011), and use the best fit mass-bias relation from Johnston et al. (2007) to calculate the bias for a given halo mass, $b(M_{200})$. Hence the lensing signal is modeled with

$$\Delta\Sigma_{\text{mod}} = p_c \Delta\Sigma_{\text{NFW}}^{\text{cent}} + (1 - p_c) \Delta\Sigma_{\text{NFW}}^{\text{miscent}} + b(M_{200}) \Delta\Sigma^{2h}. \quad (6.7)$$

To account for the scatter between mass and richness, we integrate this model over a halo mass probability distribution $P(M_{200})$ that is log-normal and has a variance that depends on richness following Equation (25) in Johnston et al. (2007). We fit a single NFW profile to the resulting signal on scales between $200 h_{70}^{-1} \text{ kpc}$ and $2 h_{70}^{-1} \text{ Mpc}$, and use a weight that is proportional to the projected separation squared to account for the increase of background galaxies at larger projected separations. The redshift we adopt for the model clusters is $z = 0.3$. We find that the best fit NFW mass overestimates the input mass with 9% for an input cluster of mass $M_{200} = 3 \times 10^{13} h_{70}^{-1} M_{\odot}$ and richness $N_{200} = 5$, which reduces to 5% for a $M_{200} = 3 \times 10^{14} h_{70}^{-1} M_{\odot}$ cluster with richness $N_{200} = 50$. Note that we use different values for the fraction of correctly centered clusters for the low and high mass model, i.e. $p_c = 0.6$ and $p_c = 0.75$, respectively, based on Figure 5 from Johnston et al. (2007). Also note that we adopt a concentration of $c = 3.5$ for both clusters, but the results do not sensitively depend on this choice. Therefore, if the RCS2 clusters have a similar miscentering distribution as the maxBCG clusters, we find that the differences between the modeling of

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the lensing signal only has a minor effect on the best fit masses. The reason is that various effects cancel each other: the miscentering lowers the model lensing signal on small scales, whilst the 2-halo term increases the model signal on large scales. Additionally, by integrating the models over a log-normal halo mass probability distribution, we increase the model signal on all scales. Note, however, that the actual miscentering distribution for the RCS2 clusters might be different from what we assumed, as the cluster centres have been found with a different algorithm. The actual bias could therefore differ somewhat from the values presented here.

A second potential source of difference between the results from the RCS2 and the maxBCG is that we used the observed richness distribution as the prior in the calculation of the Eddington bias correction. The real richness distribution, which should have been used, is different from the observed one as clusters have already scattered. Therefore, the Eddington bias correction is potentially biased, and this bias could differ between the RCS2 and the maxBCG results. To estimate the size of the bias for the SDSS, we create a mock catalogue of 10^6 clusters by random drawing clusters from a richness distribution that scales as $N_{200}^{\text{clus}} \propto N_{200}^\beta$. These richnesses are assumed to be the real values. Next, we assume that the probability distribution of the richness of each mock cluster is Poisson, and we reassign the richness of each cluster by random drawing from their Poisson distribution, mimicking the scatter that affects the richness estimates in real data. The resulting values are assumed to be the observed richnesses. We try different values of β , and find that the value that, after applying the scatter, results in an observed richness distribution with slope -3 in the range $3 < N_{200} < 200$ is given by $\beta = -2.55$. Hence the real richness distribution of the maxBCG sample is shallower than the observed one. The reason is that the scatter is dominated by the $N_{200} = 1$ and $N_{200} = 2$ clusters, as their abundance is largest. These clusters mainly scatter to other low richnesses, and less and less to increasing richnesses, causing a steepening of the slope.

To obtain the correct Eddington bias correction, we use as a prior $p(N_{200}) \propto N_{200}^{-2.55}$, and recalculate the average values of the richness. We find that at low richnesses, the values we obtain are $\sim 25\%$ larger than the values tabulated in Table 6.1, but the difference decreases to less than a percent for the highest richness bins. We use these new values to fit the mass-richness distribution for the maxBCG clusters in the range $N_{200}^{\text{corr}} > 4$, and find $A = (15.74 \pm 0.85) \times 10^{13} h_{70}^{-1} M_\odot$ and $\alpha = 1.03 \pm 0.06$, which is consistent with the previous best fit values. Hence the bias from assuming an incorrect prior is small, and does not significantly affect the results. For the RCS2, we cannot perform a similar test due to the fact that the current catalogue cannot be parameterized by a single powerlaw. Nevertheless, for the final RCS2 cluster sample a similar approach might work.

A third potential difference between the results could arise if the purity of the two cluster samples differ, and the lensing signals are not corrected for it. The purity is likely to differ somewhat between the catalogues as different cluster detection algorithms have been used. Koester et al. (2007) show how the purity of the sample depends on particular settings of the maxBCG algorithm using mock catalogues. The purity is typically of the order 90% or higher at richnesses $N_{200} > 10$; how the purity varies at lower richnesses is not shown. In the lensing analysis of the maxBCG clusters, no correction for the purity of the sample is mentioned. Since we do not correct for it either, the impact on

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the two lensing analyses may actually be comparable. This can be tested by applying both cluster finding algorithms to simulated data. To compare the results with simulations, it is important to account for the false positives in the cluster sample.

6.4 Redshift dependence of the mass-richness relation

The clusters in the RCS2 survey cover a large redshift range, which makes them particularly suited for evolutionary studies of cluster properties. Here, we study the redshift dependence of the mass-richness relation. We split each richness bin in four redshift slices, and stack the lensing signal of all clusters in each slice. We fit NFW profiles to the shear, and show the best fit NFW masses as a function of richness in Figure 6.6.

We find that the mass-richness relation evolves with redshift. At a fixed richness below $N_{200}^{\text{corr}} < 15$, the mass increases with decreasing redshift, whilst at $N_{200}^{\text{corr}} \geq 15$ the best fit masses do not increase by much. We fit the mass-richness relation in each redshift slice, and show the best fit models in Figure 6.6. The best fit powerlaw parameters are given in Table 6.2, and shown as a function of redshift in Figure 6.7. To quantify the redshift dependence, we fit a linear relation to the powerlaw parameters of the form $A = a_{A,z} \times (z - 0.4) + b_{A,z}$, and similarly for α . We show the best fit parameters in Table 6.3, and the confidence contours of the fits in Figure 6.8. We find a clear indication that the slope of the mass-richness relation increases with increasing redshift.

We quantify the redshift dependence of the rich and poor clusters separately by performing the fit to the clusters with a richness that is respectively larger and smaller than $N_{200}^{\text{corr}} = 15$. The best fit powerlaw parameters are shown in Figure 6.7, and the redshift dependence of these parameters is shown in Table 6.3. We find that the redshift dependence of the amplitude and slope for the poor and rich clusters are similar, although the errors are rather large and potential differences may be buried in the noise.

The redshift dependence of the mass-richness relation is also measured in Sheldon et al. (2009b) for the maxBCG clusters, but due to the limited redshift range of that sample no change with redshift was found. However, in a study of the relation between X-ray luminosity and richness for the maxBCG clusters, Rykoff et al. (2008) find that the X-ray luminosity at $z = 0.28$ is twice as high as the X-ray luminosity at $z = 0.14$. Becker et al. (2007) study the relation between velocity dispersion and richness for the same clusters, and find that the clusters at high redshifts systematically have higher velocity dispersions. Both Becker et al. (2007) and Rykoff et al. (2008) expect the main cause to be the evolution of the N_{200} richness measure, implying a fractional decrease in N_{200} of 30%-40% from $z = 0.14$ to $z = 0.28$ (i.e. N_{200} is underestimated at higher redshifts). No evidence is presented that supports such a strong decrease of N_{200} , and it does not explain why no redshift dependence of the mass-richness relation was detected in Johnston et al. (2007). Note that no correction for the Eddington bias was applied in each of these works, and a redshift dependent bias could contribute to the apparent evolution. To test this assumption, we compare

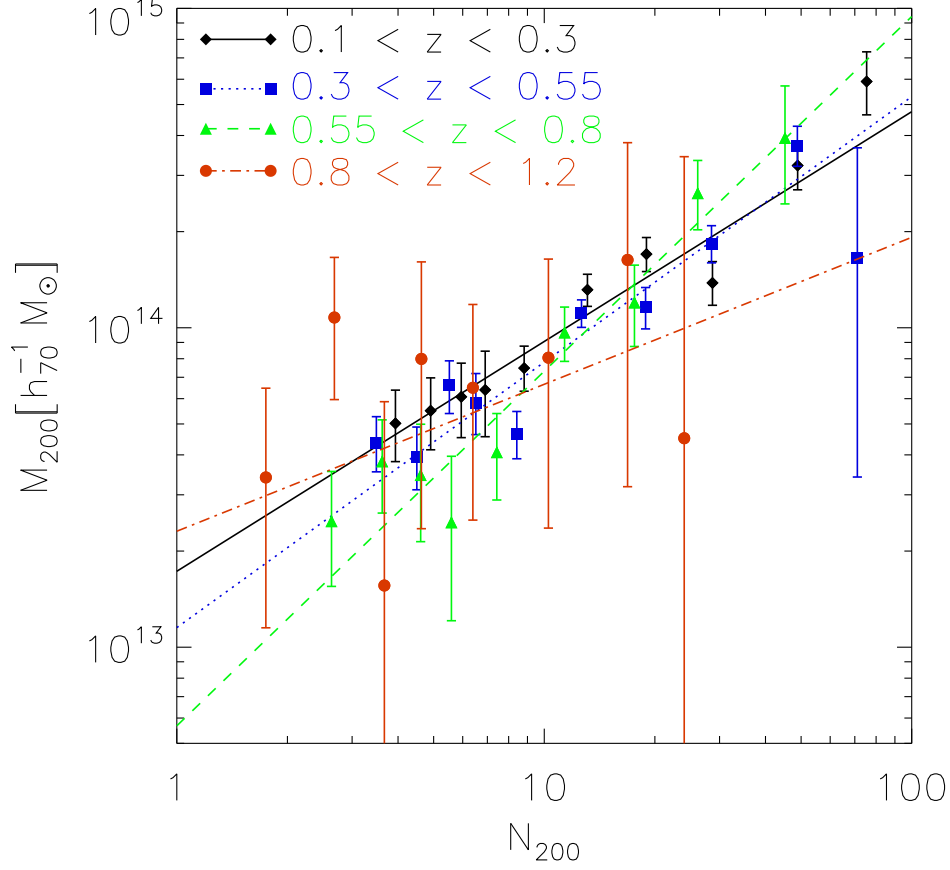


Figure 6.6: Redshift dependence of the mass-richness relation. Different colours correspond to different redshift bins, as indicated in the figure. The dashed lines indicate the powerlaw fits to the mass-richness relation in each redshift slice.

the slope of the cluster number counts for the maxBCG clusters with $z \geq 0.25$ and $z \leq 0.20$, respectively. We find that the slope of the high redshift-sample is ~ -3.5 , only slightly steeper than the slope of ~ -3 for the low-redshift sample. The Eddington bias correction for the high-redshift sample is therefore slightly larger, which actually increases the difference between the high- and low-redshift results. The discrepancy remains therefore unexplained.

Our results suggest that the mass-richness relation is steeper at higher redshifts. The strongest change occurs at the lowest richness range: we find that a $N_{200}^{\text{corr}} = 5$ cluster at $z = 0.25$ is $1.6^{+0.6}_{-0.4}$ times more massive than a $N_{200}^{\text{corr}} = 5$ cluster at $z = 0.7$. This ratio and its errors are determined using the best fit parameters of the fit to the mass-richness relation in the redshift range $0.1 < z < 0.3$ and $0.55 < z < 0.80$, respectively. Clusters with $N_{200}^{\text{corr}} > 15$ do not appear to change much in mass over the same redshift interval. In the following sections, we discuss various observational biases and physical processes that may contribute to the observed redshift dependence.

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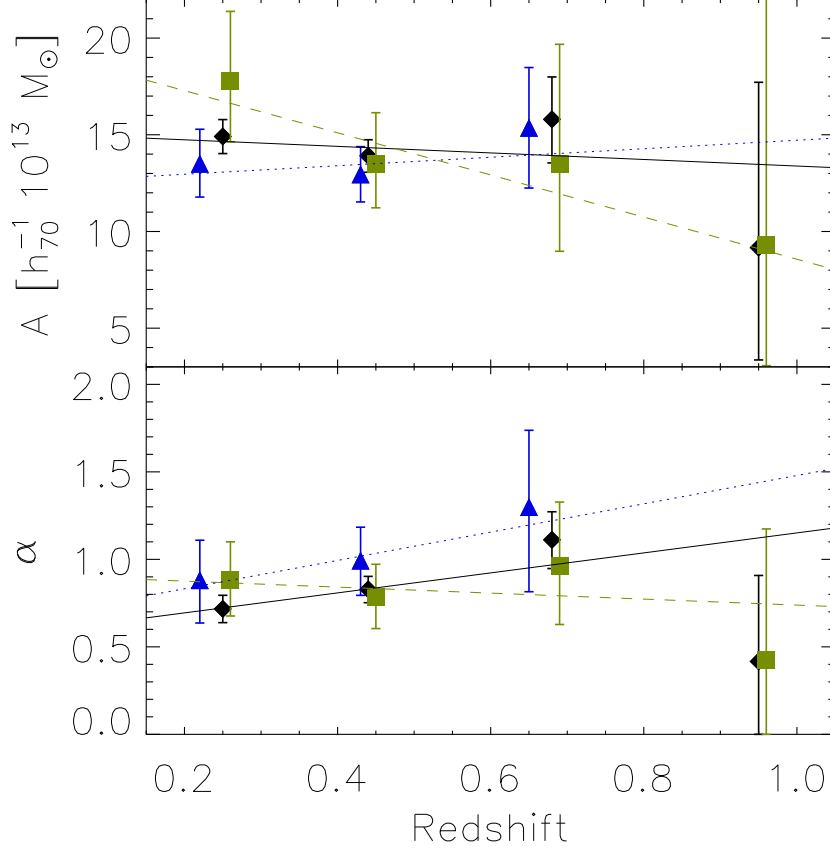


Figure 6.7: Redshift dependence of the powerlaw parameters of the mass-richness relation. The black diamonds indicate the results for all clusters, the green triangles (blue squares) for the clusters in the range $N_{200}^{\text{corr}} > 15$ ($N_{200}^{\text{corr}} < 15$). The black solid lines indicate the best fit linear relation between these parameters and redshift, and the green dashed (blue dotted) lines are for the clusters in the range $N_{200}^{\text{corr}} > 15$ ($N_{200}^{\text{corr}} < 15$).

6.4.1 Non-evolutionary causes of redshift dependence $M_{200} - N_{200}$

The observed change in the mass-richness relation with redshift may be caused by cluster evolution processes, but potentially also partly by the way the richness is defined. Additionally, there may be observational effects that cause a change in the mass-richness relation with redshift. Hence to study the cluster evolution processes, we first need to address if the redshift evolution of the mass-richness relation has different causes. We mention various effects below, and discuss how to estimate their impact.

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Table 6.2: best fit parameters of the powerlaw fits to the mass-richness relation at different redshifts

z	A [$10^{13} h_{70}^{-1} M_{\odot}$]	α
0.10-1.20	15.09 ± 0.66	0.86 ± 0.05
0.10-0.30	14.91 ± 0.88	0.72 ± 0.08
0.30-0.55	$13.91^{+0.83}_{-0.85}$	0.83 ± 0.07
0.55-0.80	$15.80^{+2.19}_{-2.25}$	1.11 ± 0.16
0.80-1.20	$9.17^{+8.55}_{-5.81}$	$0.46^{+0.49}_{-0.46}$

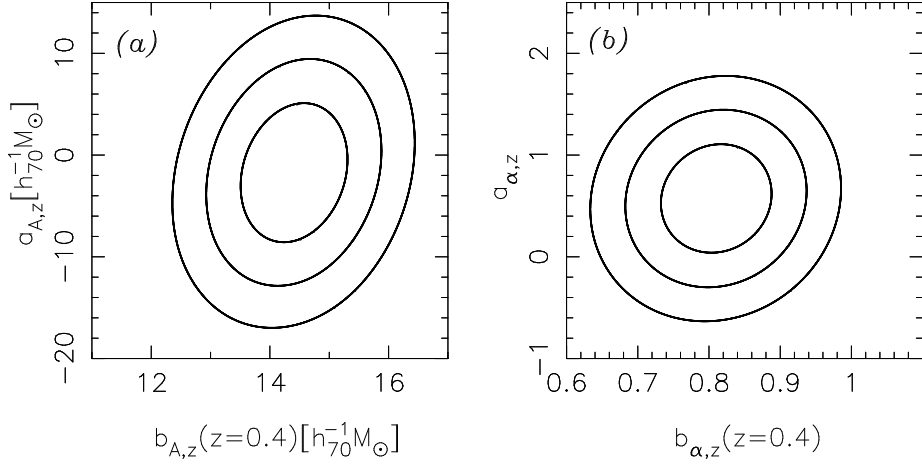


Figure 6.8: 67.8%, 95.4% and 99.7% confidence limits of the fits that describe the linear redshift dependence of the best fit parameters of the mass-richness relation, as detailed in the text. In panel (a) we show the results for the redshift dependence of the amplitude of the mass-richness relation, and in panel (b) for the slope.

The richness measure N_{200} is by definition a redshift dependent quantity: it includes all galaxies brighter than M^*+2 , which is a lower magnitude limit that evolves with redshift. Also, as the critical density changes with redshift, so does r_{200} , the radius within which we count the number of cluster members. Furthermore, at the high redshift end, the richness estimates are somewhat incomplete, which has not been corrected for. Hence, two identical clusters located at different redshifts are potentially assigned with different values of N_{200} . Note that already for the maxBCG cluster sample, which extends to $z = 0.3$, it has been suggested that N_{200} evolves (Becker et al. 2007; Rykoff et al. 2008). Our cluster sample extends to $z \sim 1$, making an evolution of N_{200} even more relevant. To understand how the richness of a given cluster changes with redshift, we can apply the detection method on simulations that mimic the RCS2 survey.

The purity of the cluster sample may depend not only on richness, but also on redshift. If the fraction of false detections increases with redshift for a fixed richness, this would lower the lensing mass and could cause the trend we ob-

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Table 6.3: best fit parameters that describe the linear redshift dependence of the normalization and slope of the mass-richness relation, as detailed in the text.

N_{200}^{corr}	$a_{A,z}$ [$10^{13} h_{70}^{-1} M_{\odot}$]	$b_{A,z}$ [$10^{13} h_{70}^{-1} M_{\odot}$]	$a_{\alpha,z}$	$b_{\alpha,z}$
all	-1.7 ± 4.5	14.4 ± 0.6	0.57 ± 0.35	0.81 ± 0.05
$N_{200}^{\text{corr}} < 15$	$-10.9^{+11.7}_{-8.8}$	15.1 ± 1.8	-0.17 ± 0.75	0.84 ± 0.13
$N_{200}^{\text{corr}} > 15$	2.2 ± 7.6	13.4 ± 1.0	0.81 ± 1.09	0.99 ± 0.14

serve. The purity of the sample, and its dependence on richness and redshift, needs to be estimated using simulations as well.

The miscentering distribution of clusters may also depend on redshift. Miscentering causes a drop in the lensing signal on small scales, which biases the lensing mass low if not accounted for (see Figure 4 in Hoekstra et al. (2011a) for estimates of the amplitude of this bias). In our final analysis, we include the miscentering distribution in the cluster halo model fits, and the lensing mass should be unaffected. However, the richness estimates of clusters are also affected by miscentering. Hilbert & White (2010) estimated the impact using the Millennium Simulation, and found that the cluster abundances are reduced by $\sim 20\%$. The miscentering of clusters may be dependent on the richness and the redshift of the clusters, and so is the size of the bias. We can in principle estimate the impact for each lensing bin once we have fitted the cluster halo model to the shear, using the constraints this has provided on the miscentering distribution.

6.4.2 Impact of cluster evolutionary processes

Next to these observational effects, there are several cluster evolution processes that affect the redshift evolution of the mass-richness relation. Below, we describe some of the processes that may be important in shaping this relation. We cannot disentangle these processes using the mass-richness relation alone. The goal of this section is to describe how each of these processes might impact the evolution of the mass-richness relation, and indicate which of them could contribute to the observed redshift dependence. It is important to realize that the richness estimates only include the red-sequence galaxies. The blue, star-forming galaxies, which are an important component of clusters, are not included.

Galaxy clusters evolve through the accretion of matter. Large clusters accrete matter faster than small clusters, because their potential wells are deeper and more extended (e.g. Fakhouri et al. 2010). Clusters accrete galaxies, gas and dark matter; how this affects the mass-richness relation depends on the relative amount of accreted total mass and galaxies. If the amount of accreted galaxies and total mass would not depend on the richness of a cluster nor on its redshift, clusters would only move up on the mass-richness relation, and no redshift dependence would be observed. A possible explanation for the increase of the mass of poor clusters with decreasing redshift is that poor clusters accrete relatively more dark matter than galaxies, compared to the rich clusters. This

could mean that either the accreted galaxies in poor clusters have more massive dark matter haloes, or lower luminosities such that they do not increase the richness of the clusters. Alternatively, poor clusters could accrete a larger additional amount of dark matter compared to rich clusters. This could be assessed using numerical simulations.

The galaxies that reside in a cluster evolve as well. Galaxies are stripped of their gas through tidal interactions and ram pressure stripping, which quenches their star formation (e.g. Boselli & Gavazzi 2006). Consequently, the late-type spiral galaxies that are accreted turn into early-type S0 galaxies, and subsequently appear on the E/S0 ridgeline. Hence even without accreting new galaxies, the richness of early-type galaxies in clusters may increase as more galaxies turn red. The fraction of satellites whose star formation is quenched strongly increases with halo mass (Wetzel et al. 2011), which could indicate that satellites in rich clusters are more efficiently quenched than those in small clusters. Hence, in the absence of accretion events, the richness of rich clusters may grow faster than the richness of poor clusters. The richness of poor clusters may therefore be lagging behind, which could also be partly responsible for the flattening of the mass-richness relation over time.

The richness of a galaxy cluster decreases if early-type cluster members merge, but the mass remains constant. When we determine the masses of clusters at a fixed richness, this leads to an increase of mass with decreasing redshift. The dependence of galaxy mergers on environment has been studied in Perez et al. (2009). In this work, it is found that the majority of merging galaxies are found in intermediate density environments. If such environments mainly correspond to galaxy groups, hence if mainly the galaxies in poor groups merge, it could explain why the mass of low-richness clusters increase more rapidly than those of high-richness clusters.

There are various other processes that may also have an effect on the redshift dependence of the mass-richness relation. For example, the properties of field galaxies that are accreted by clusters may evolve over time as well; the fraction of late-type galaxies that is accreted is likely larger at high redshift than at low redshift. Additionally, the pre-processing of accreted galaxies may be different for rich and poor clusters. The environment of the cluster is also expected to play a role, as it provides the material that accretes onto the cluster. In short, numerous processes are potentially involved in the evolution of the mass-richness relation, which makes any trend particularly hard to interpret. To start unraveling the various physical processes, we can compare our measurements to predictions from numerical simulations such as those described in Hilbert & White (2010). In this work, the mass-richness relation is predicted using semi-analytic galaxy formation models in the Millennium simulation. The predictions from this work are found to agree well with the maxBCG results from Johnston et al. (2007). It would be very interesting to see if a similar study, but now as a function of redshift, correctly predicts the redshift dependence we find.

6.5 Conclusion

We present the first results of the weak lensing analysis of the RCS2 cluster sample. The preliminary RCS2 cluster catalogue contains 1.4×10^4 galaxy clusters with $N_{200} > 5$, with masses $M_{200} > 2 \times 10^{13} h_{70}^{-1} M_{\odot}$ and redshifts in

the range $0.2 < z < 1.2$. The redshift coverage makes this cluster sample particularly suited for cluster evolution studies. In this work, we study the relation between the mass and richness of clusters, and how this relation depends on redshift. The calibration between richness and mass enables the exploitation of the RCS2 cluster sample to constrain cosmological parameters. Furthermore, the redshift dependence of the mass-richness relation can be used to study cluster evolution processes.

We split the cluster sample in richness bins, stack the lensing signal in each bin and fit an NFW profile between 0.2 and $2 h_{70}^{-1}$ Mpc. We fit the mass-richness relation with $M_{200} = A(N_{200}^{\text{corr}}/20)^\alpha$, and find $A = (15.09 \pm 0.66) \times 10^{13} h_{70}^{-1} M_\odot$ and $\alpha = 0.86 \pm 0.05$. To study the redshift dependence of the mass-richness relation, we split the cluster sample in four redshift slices. We find that the mass-richness relation depends on redshift. The change with redshift is strongest for galaxy groups and poor clusters: we find that a $N_{200}^{\text{corr}} = 5$ cluster at $z = 0.25$ is $1.6_{-0.4}^{+0.6}$ times more massive than a $N_{200}^{\text{corr}} = 5$ cluster at $z = 0.7$. The high-richness clusters at different redshifts have comparable masses. Fitting a linear relation to the slope of the mass-richness relation of the form $\alpha = a_{\alpha,z} \times (z - 0.4) + b_{\alpha,z}$, we find $a_{\alpha,z} = 0.57 \pm 0.35$ and $b_{\alpha,z} = 0.81 \pm 0.05$.

Finally, we measure the excess galaxy number density around the cluster samples. We find that the number density profiles of the $N_{200}^{\text{corr}} < 7$ -bins are steeper than the dark matter profiles on small scales, whilst for the $N_{200}^{\text{corr}} > 7$ -bins the overdensities are generally less steep. The overdensities can be used to improve the modeling of the lensing signal, as they provide additional constraints on the miscentering distribution of the clusters.

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6.A. DISTRIBUTION OF SATELLITES

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6.A Distribution of satellites

The galaxies in a cluster trace the dark matter distribution, although there are indications that the slope of the radial distribution of satellite galaxies differs from the slope of the projected total mass distribution (e.g. Watson et al.

CHAPTER 6. REDSHIFT DEPENDENCE OF $M_{200} - N_{200}$ IN THE RCS2

2010, 2011; Budzynski et al. 2012; Tal et al. 2012). The radial distribution of satellite galaxies can be determined by measuring the galaxy overdensity around clusters. If a fraction of the clusters is not correctly centered, this also affects the observed distribution of satellites. Hence the overdensity measurement provides additional constraints on the miscentering distribution of the clusters. When we implement a more sophisticated lensing model, in which we account for the miscentering of clusters, the galaxy overdensity can serve as a prior for the miscentering distribution. Including this information is beneficial, as it reduces the errors on the best fit parameters from the lensing model.

To illustrate this, we measure the total galaxy overdensity in a similar way as for the sources, as discussed in Section 6.2.4. We use all galaxies in the magnitude range $16 < m_{r'} < 24$, and show the results for all clusters in Figure 6.2, and for the clusters divided in richness bins in Figure 6.9. Overplotted in each panel is the surface mass density, Σ , that corresponds to the best fit NFW model of the lensing measurements in the same richness bin, scaled with an arbitrary amplitude to match the data between 0.2 and $2 h_{70}^{-1}$ Mpc. This model is shown for illustration only, and no attempts have been made to improve the fit. It shows, however, that simply rescaling Σ does not describe the excess galaxy density well. In particular, for the $N_{200}^{\text{corr}} < 7$ -bins we find that the overdensities follow steeper profiles on small scales, whilst for the $N_{200}^{\text{corr}} > 7$ -bins the overdensities are generally flatter.

Closing in to the lens ($r < 100 h_{70}^{-1}$ kpc), we find that the overdensities do not increase as rapidly, and even decrease for the innermost radial bin. This is partly due to the miscentering of galaxies, which flattens the Σ profile on small scales (Johnston et al. 2007). Note that miscentering has a significantly smaller effect on Σ than on $\Delta\Sigma$, which is clearly illustrated in Figure 4 in Johnston et al. (2007). However, the signal-to-noise of the overdensity measurements is five to ten times larger than the one from shear, and the overdensity may therefore still provide useful constraints.

There are several other effects that cause a reduction of the galaxy number density near clusters. For example, the presence of large cluster galaxies in the centre of a cluster blocks or swamps the light of small satellites that are close to the line of sight. Additionally, the sky background subtraction near bright clusters could be inaccurate due to the high abundance of galaxies, and due to the diffuse intercluster light. This could affect the detection of faint cluster members, which would bias the excess galaxy number density measurements. Next to that, magnification leads to a reduction in number density of background sources close to the clusters, which also reduces the excess galaxy density. If not accounted for, these effects could be misinterpreted as being the result of miscentering. The impact of these complications have to be estimated before we can use the galaxy overdensity to improve the cluster halo model fits of the lensing signal.

6.A. DISTRIBUTION OF SATELLITES

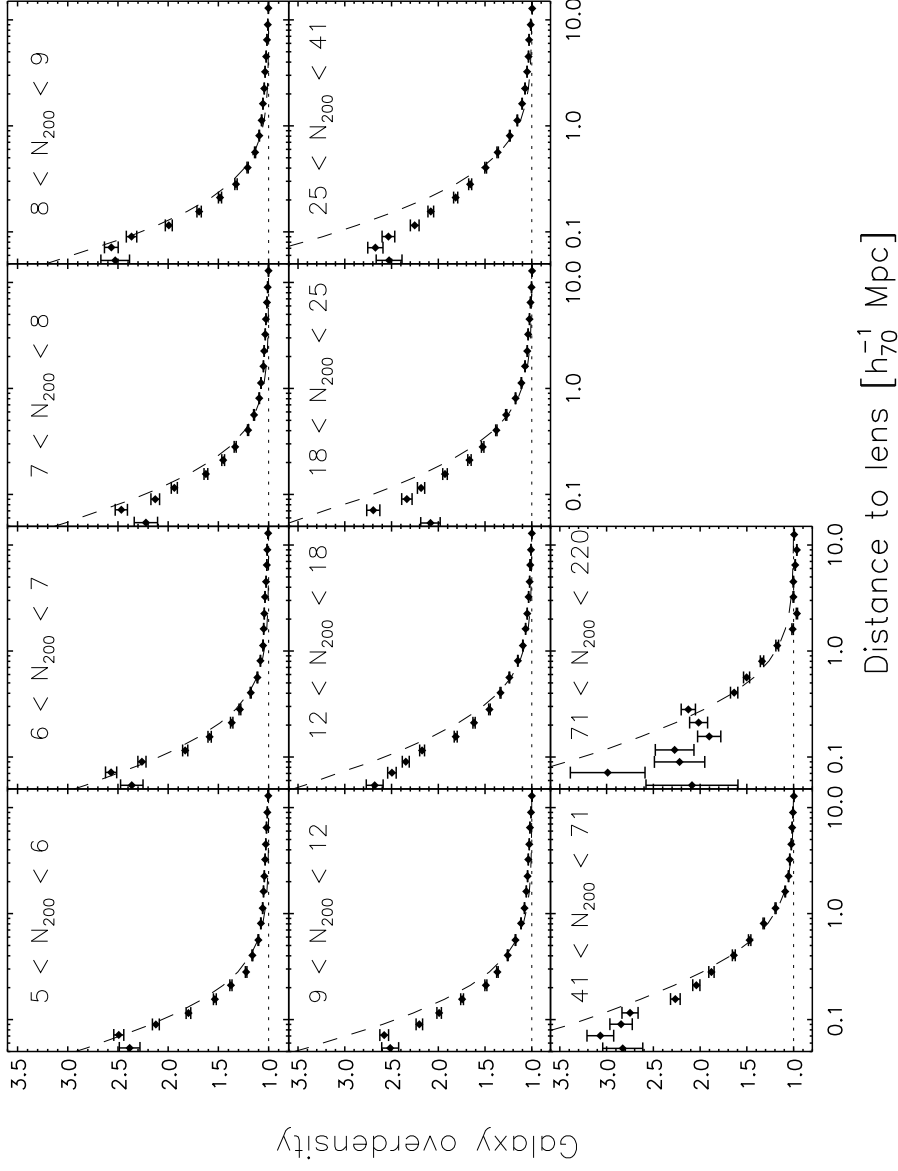


Figure 6.9: The overdensity of galaxies in the magnitude range $16 < m_r < 24$ with shape measurements around the clusters as a function of projected separation. The dashed lines indicate the surface density Σ that correspond to the best fit model to the lensing measurements, scaled with an arbitrary amplitude to match the data between 0.2 and $2 h_{70}^{-1}$ Mpc.

