THE SLOAN BRIGHT ARCS SURVEY: TEN STRONG GRAVITATIONAL LENSING CLUSTERS AND EVIDENCE OF OVERCONCENTRATION

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ABSTRACT

We describe 10 strong lensing galaxy clusters of redshift 0.26 < z < 0.56 that were found in the Sloan Digital Sky Survey. We present measurements of richness (N_{200}), mass (M_{200}), and velocity dispersion for the clusters. We find that in order to use the mass–richness relation from Johnston et al., which was established at mean redshift of 0.25, it is necessary to scale measured richness values up by 1.47. Using this scaling, we find richness values for these clusters to be in the range of 22 < N_{200} < 317 and mass values to be in the range of 1 \times 10^{14} h^{-1} M_{\odot} \lesssim M_{200} \lesssim 30 \times 10^{14} h^{-1} M_{\odot}. We also present measurements of Einstein radius, mass, and velocity dispersion for the lensing systems. The Einstein radii (\theta_E) are all relatively small, with 5.4' \lesssim \theta_E \lesssim 13''. Finally, we consider if there is evidence that our clusters are more concentrated than \Lambda CDM would predict. We find that six of our clusters do not show evidence of overconcentration, while four of our clusters do. We note a correlation between overconcentration and mass, as the four clusters showing evidence of overconcentration are all lower-mass clusters. For the four lowest mass clusters the average value of the concentration parameter c_{200} is 11.6, while for the six higher-mass clusters the average value of c_{200} is 4.4. \Lambda CDM would place c_{200} between 3.4 and 5.7.

Key words: galaxies: clusters: general – galaxies: high-redshift – gravitational lensing: strong

Online-only material: color figures

1. INTRODUCTION

Galaxy clusters are the largest gravitationally bound structures in the universe and as such can tell us many things about the origin and structure of the universe. Clusters indicate the locations of peaks in the matter density of the universe (Allen et al. 2011) and represent concentrations of dark matter. Galaxy clusters are also places where gravitational lensing is likely to be observed (e.g., Mollerach & Roulet 2002; Kochanek et al. 2003). Gravitational lensing in a cluster can provide even more information, giving us a window not only to the cluster itself but to far more distant source galaxies.

Gravitational lensing, both strong and weak, can be useful in the study of galaxy clusters. Strong lensing, the formation of multiple resolved images of background objects by a cluster or other massive object, can be useful as it provides a direct measure of the mass contained within the Einstein radius of a cluster (e.g., Narayan & Bartelmann 1997). Weak lensing, the systematic but subtle change in ellipticities and apparent sizes of background galaxies, can also provide a precise measure of the mass of a cluster (e.g., Mollerach & Roulet 2002; Kochanek et al. 2003).

Galaxy cluster finding in optical data is performed using an algorithm based on some known properties of galaxy clusters (e.g., Berlind et al. 2006; Koester et al. 2007a; Hao 2009; Soares-Santos et al. 2011). Koester et al. (2007a) describe the maxBCG method, a cluster-finding method used in the Sloan Digital Sky Survey (SDSS) data. We describe in Section 3 how we used this method for cluster galaxy identification.

The dark matter mass distribution of galaxy clusters is well fitted by a Navarro–Frenk–White (NFW) profile (Navarro et al. 1997; Wright & Brainerd 2000). One of the parameters in the NFW profile is the concentration parameter (here c_{200}), which is a measure of the halo density in the inner regions of the cluster. The concentration parameter can be measured directly through strong lensing. The standard cold dark matter cosmology (\Lambda CDM) describes the history of galaxy cluster formation and as such can make predictions (e.g., Duffy et al. 2008) about the value for c_{200} as a function of cluster mass and redshift. If measured values for c_{200} are higher than predictions, then the clusters are said to be overconcentrated.

There have been indications from several groups (Broadhurst et al. 2005; Broadhurst & Barkana 2008; Oguri et al. 2009, 2012; Gralla et al. 2011; Fedeli 2012) that galaxy clusters that exhibit strong lensing are overconcentrated. The overconcentration has been shown by disagreement between predicted and observed Einstein radii (Gralla et al. 2011) or by disagreement between predicted and observed concentration parameter (Fedeli 2012; Oguri et al. 2012). There are some indications that the overconcentration problem is most significant in clusters with mass less than 10^{14} h^{-1} M_{\odot} (Fedeli 2012; Oguri et al. 2012). This overconcentration problem might indicate that clusters are collapsing more than we expected (Broadhurst & Barkana 2008). This collapse may be related to baryon cooling, especially in the central galaxy of the cluster (Oguri et al. 2012).

In this paper, we describe a sample of 10 galaxy clusters showing evidence of strong gravitational lensing. These clusters were discovered in the SDSS during a search for strong lensing arcs. We took follow-up data on these 10 systems using the Wisconsin–Indiana–Yale–NOAO (WIYN) telescope at Kitt Peak National Observatory (KPNO). In this paper, we describe our analyses of these data, including both the properties of the clusters and the properties of the arcs. In Section 2, we address how these systems were found and how the data were taken. We provide details regarding the searches which led to the discovery of these systems and we discuss the observing conditions.
at KPNO during the data acquisition. In Section 3, we discuss identification of cluster members and measurements of cluster properties. We describe how we used the maxBCG method to identify cluster members, quantify cluster richness, and estimate cluster masses. We also describe how we found and used a scale factor to scale our richness measurements up to match those that would be measured in SDSS data. We applied this scaling relation in order to use a relation between cluster richness and cluster mass that was calibrated using SDSS data. Four of our ten systems are also included in Oguri et al. (2012) and so we compare our results for cluster mass using cluster richness and strong lensing to their mass values which were found from strong and weak lensing. In Section 4, we present measurements of the strong lenses. For the lenses, we present Einstein radii, lens masses, and lens velocity dispersions. In Section 5, we discuss evidence of overconcentration. We show that most of our clusters do not show evidence of overconcentration, but several of them do. As the clusters showing evidence of overconcentration are all low-mass clusters, they support recent results (Oguri et al. 2012; Fedeli 2012) suggesting that the overconcentration problem is most significant for lower-mass clusters.

Throughout this paper, we assume a flat ΛCDM cosmology with Ω_m = 0.3, Ω_Λ = 0.7, and H_0 = 100 h km s^{-1} Mpc^{-1}.

2. DATA ACQUISITION

2.1. Lens Searches

The SDSS (York et al. 2000) is an ambitious endeavor to map more than 25% of the sky and to obtain spectra for more than one million objects. The SDSS was begun in 2000, and has completed phases I and II; phase III began in 2008 and will continue until 2014. The SDSS uses a 2.5 m telescope located at Apache Point Observatory in New Mexico. The Sloan Bright Arcs Survey (SBAS) is a survey conducted by a collaboration of scientists at Fermilab and has focused on the discovery of strong gravitational lensing systems in the SDSS imaging data and on subsequent analysis of these systems (Allam et al. 2007; Kubik 2007; Lin et al. 2009; Diehl et al. 2009; Kubo et al. 2009; Kubo & Allam et al. 2010; West et al. 2012). To this point, the SBAS has discovered and spectroscopically verified 19 strong lensing systems with source galaxy redshift between z = 0.4–2.9.

2.2. Follow-up at WIYN: Observing Details

On 2009 February 26 and 27, we took follow-up data for 10 of these systems at the 3.5 m WIYN telescope at KPNO. The 10 systems for which we took data are listed in Table 1. We took follow-up data in order to obtain images with finer pixel scale, improved seeing, and fainter magnitude limits than were available in the SDSS data. The pixel scale in the SDSS data is 0.′′3, while the median seeing in the SDSS Data Release 7 is 0.′′74. Magnitude limits for DR7 are 22′′ in each filter for each field was then added to the SExtractor instrumental magnitudes measured by SExtractor (Bertin & Arnouts 1996). Finally, the instrumental magnitudes measured by SExtractor were converted to calibrated magnitudes. This was done by finding the model magnitudes of stars in the SDSS DR7 Catalog Archive Server that also appeared in the WIYN data and finding the offset in magnitudes in the g, r, and i bands. The median offset in each filter for each field was then added to the SExtractor magnitudes (using MAG_AUTO).

3. GALAXY CLUSTER PROPERTIES

3.1. Identifying Cluster Galaxies

We first sought to characterize richness of the clusters in terms of N_{gal}, the number of cluster members within 1 h^{-1} Mpc of the brightest cluster galaxy (BCG) (Hansen et al. 2005), by using the maxBCG method. The maxBCG method (Koester et al. 2007a) uses three primary features of galaxy clusters to facilitate the detection of clusters in survey data. First, galaxies in a cluster tend to be close together near the center and to become more separated from one another toward the outskirts of the cluster. Second, galaxies in a cluster tend to closely follow a sequence in a color–magnitude diagram; this is referred to as the E/S0 ridgeline, where E and S0 refer to galaxy types in the Hubble classification. Finally, galaxy clusters typically contain a central BCG, which is defined as the brightest galaxy in the cluster. In all of the clusters in our sample, one or two BCGs can be seen near the center of the cluster surrounded by lensing arcs. While the dark matter halo dominates the lensing potential, the BCG contributes to the lensing potential as well since it comprises a large fraction of the baryonic matter in the cluster. Typically, the BCG would be expected to have a color similar to that of the other cluster galaxies and to be almost at rest with respect to the halo of the cluster.

### Table 1

| System       | R.A. (deg) | Decl. (deg) | Lens z | Source z |
|--------------|------------|-------------|--------|----------|
| SDSS J0900+2234 | 135.01128  | 22.567767  | 0.4890 | 2.0325   |
| SDSS J0901+1814 | 135.34312  | 18.242326  | 0.3459 | 2.2558   |
| SDSS J0957+0509 | 149.41318  | 5.1589174  | 0.4469 | 1.8230   |
| SDSS J1038+4849 | 159.67874  | 48.821613  | 0.4256 | 0.966    |
| SDSS J1120+2640 | 182.34866  | 26.679633  | 0.5580 | 1.018    |
| SDSS J1318+3942 | 199.54798  | 39.707469  | 0.4751 | 2.9437   |
| SDSS J1343+4155 | 205.88702  | 41.917659  | 0.4135 | 2.0927   |
| SDSS J1439+3250 | 219.98532  | 32.840162  | 0.4176 | 1.0–2.5* |
| SDSS J1511+4713 | 227.82802  | 47.227049  | 0.4517 | 0.985    |
| SDSS J1537+6556 | 234.30478  | 65.939313  | 0.2595 | 0.6596   |

Note. * Source redshift has not yet been determined for this system; thus we present a range of possible values.
Considering these properties of cluster galaxies, we searched the SExtractor catalog files for objects that (1) were classified as galaxies, not stars, (2) were within 1 \( h^{-1} \) Mpc of the central BCG, (3) had the characteristic \( r - i \) and \( g - r \) color of the E/S0 ridgeline, and (4) met a particular magnitude limit.

In order to separate galaxies from stars, we compared two different SExtractor magnitudes, \( MAG_{AUTO} \) and \( MAG_{APER} \). \( MAG_{AUTO} \) is the flux measured above background in a variable-size elliptical aperture. \( MAG_{APER} \) uses a circular aperture of fixed size to determine magnitude; we used a diameter of 2\( '' \). The difference \( MAG_{APER} - MAG_{AUTO} \) (henceforth \( \Delta m \)) can be used to identify the galaxies: stars stand out from galaxies because stars typically have a nearly identical shape while galaxies generally do not. Thus, for stars the fixed aperture of \( MAG_{APER} \) will measure a fairly constant fraction of the light that the variable aperture of \( MAG_{AUTO} \) will measure. Therefore, the difference between the measurements (\( \Delta m \)) will be mostly constant for stars, but not for galaxies. We used this fact to find stars by plotting \( \Delta m \) versus \( MAG_{AUTO} \). In this plot, stars will be found on a mostly horizontal line of nearly constant \( \Delta m \) value; this line is referred to as the stellar locus (see Figure 2).

We also tried using the SExtractor parameter \( CLASS\_STAR \) for star–galaxy separation by requiring 0 \( \leq \) \( CLASS\_STAR \) \( \leq 0.9 \) (1 is highly star-like and 0 is highly galaxy-like in this parameter) and remeasuring \( N_{gals} \) with this requirement. We chose this cutoff because when we plotted \( CLASS\_STAR \) against \( i \)-band magnitude (\( MAG_{AUTO} \)), we found a tight stellar sequence within 0.1 of \( CLASS\_STAR = 1 \). We found that the mean difference in \( N_{gals} \) values was 0.3, which corresponds to a mean percentage difference of 1.7%. Thus, we conclude that the \( \Delta m \) cut method is equivalent to using \( CLASS\_STAR \).

In order to select galaxies that are members of the cluster, we used the red sequence method (Gladders & Yee 2000; Koester et al. 2007a). This approach involves plotting a color–magnitude diagram of the \( g - r \) and \( r - i \) colors of the galaxies versus their \( i \)-band magnitude, looking for a nearly horizontal line of galaxies of similar color. Galaxies in a cluster are at similar redshifts and will be largely coeval, leading them to have similar colors. Thus, the galaxies that populate the red sequence are likely to be cluster members. For each cluster, we identified the
g – r and r – i color of the red sequence on the plots. A sample color–magnitude diagram is shown in Figure 3.

We also used a second method to check our identification of the red sequence color. For both g – r and r – i colors, we made a histogram of the colors of the galaxies within 1 \( h^{-1} \) Mpc of the BCG and found the distribution near the red sequence color we had previously identified. We then fitted this section of the histogram with a Gaussian profile and found the mean color of the red sequence galaxies.

Ultimately we used the first method (color–magnitude diagrams) to obtain a reasonable range of values for the colors of the red sequence and we used the second method (histograms) to determine final values for the colors. When we made color cuts, we only allowed galaxies that were within 2\( \sigma \) of the \( r - i \) and \( g - r \) colors, where \( \sigma \) was defined as

\[
\sigma = \sqrt{(\sigma_{ intrinsic})^2 + (\sigma_{ color})^2} \, .
\]
Here, $\sigma_{\text{intrinsic}}$ is the intrinsic scatter in the red sequence color in the absence of measurement errors, which we took to be 0.06 for $r-i$ and 0.05 for $g-r$ (Koester et al. 2007a). $\sigma_{\text{color}}$ is the color measurement error found by adding the SExtractor aperture magnitude measurement errors in quadrature.

Finally, we cut any galaxies that had a magnitude dimmer than 0.4$L^*$, where $L^*$ is defined as the luminosity at which the luminosity function (Schechter 1976) changes from a power law to an exponential relation. In the maxBCG algorithm 0.4$L^*$ is used as a limiting magnitude (Koester et al. 2007b), and so we adopt this as our magnitude limit as well. We referred to a table of 0.4$L^*$ (J. Annis & J. Kubo 2010, private communication) as a function of $z$ to make cuts, allowing only galaxies brighter than 0.4$L^*$ in $i$ band. All values used for cluster galaxy cuts are provided in Table 2.

### 3.2. Cluster Properties

#### 3.2.1. Area Corrections

We applied the four cuts described in Section 3.1 to measure $N_{\text{gals}}$. However, we found that for several of the 10 systems, regions of the cluster were not in the image. The reason for this is that when we took the data, our primary focus was on the strong lensing arcs, which were near the center in all of our images. In order to address this problem and still obtain accurate values for $N_{\text{gals}}$, we extrapolated values for $N_{\text{gals}}$ in the area off the CCD. In order to do this, we divided the 1 $h^{-1}$ Mpc aperture into six annuli with constantly increasing radii, as shown in Figure 4. We assumed that the number of galaxies in each annulus should only be a function of radius; this would suggest that the number of galaxies per area should be a constant in each annulus. Mathematically,

$$N_{\text{total}} = N_{\text{on CCD}} \left( \frac{A_{\text{ann}}}{A_{\text{ann on CCD}}} \right), \quad (2)$$

where $N_{\text{total}}$ means the total number of galaxies in each annulus, $N_{\text{on CCD}}$ means the number of galaxies actually found in the image in each annulus, $A_{\text{ann}}$ means the area of the annulus, and $A_{\text{ann on CCD}}$ means the area of the annulus that was on the CCD.

**Figure 3.** $r-i$ color–magnitude diagram for SDSS J1209+2640. The black dots denote the galaxies, the red diamonds denote the cluster galaxies, the vertical green line shows the value of 0.4$L^*$, and the horizontal violet dotted line represents the red sequence $r-i$ color. The objects plotted are galaxies within 1 $h^{-1}$ Mpc of the BCG. (A color version of this figure is available in the online journal.)

**Table 2**

| System       | $\Delta m$ | $g-r$ color | $r-i$ color | 0.4$L^*$ Magnitude |
|--------------|------------|-------------|-------------|-------------------|
| SDSS J0900+2234 | 0.56       | 1.83        | 0.73        | 21.20             |
| SDSS J0901+1814 | 0.22       | 1.72        | 0.52        | 20.26             |
| SDSS J0957+0509 | 0.15       | 1.78        | 0.71        | 21.26             |
| SDSS J1038+4849 | 0.07       | 1.72        | 0.62        | 20.84             |
| SDSS J1209+2640 | 0.34       | 1.79        | 0.93        | 21.59             |
| SDSS J1318+3942 | 0.06       | 1.73        | 0.73        | 21.15             |
| SDSS J1343+4155 | 0.16       | 1.75        | 0.54        | 20.71             |
| SDSS J1439+3250 | 0.11       | 1.74        | 0.67        | 20.78             |
| SDSS J1511+4713 | 0.17       | 1.78        | 0.75        | 20.97             |
| SDSS J1537+6556 | 0.14       | 1.50        | 0.52        | 19.38             |

**Notes.** $\Delta m$ is the magnitude measured in $i$ band in 2″ MAG_APER minus the magnitude in the same band measured in MAG_AUTO. $\Delta m$ was used for star–galaxy separation. The $g-r$ and $r-i$ colors are based on measurements in the 2″ aperture. Finally, the magnitude at 0.4$L^*$ was found in the $i$ band.

We checked the accuracy of Equation (2) using the SDSS data. We measured $N_{\text{gals}}$ twice, once covering the full 1 $h^{-1}$ Mpc as was on the CCD in the WIYN data. We then used Equation (2) to predict the final values of $N_{\text{gals}}$ based on the measurements with the WIYN area cuts. Finally, we compared the predicted values for $N_{\text{gals}}$ to the measured (true) values and found them to be similar. We plot the two sets of $N_{\text{gals}}$ against each other in Figure 5. Note that the points follow the $y = x$ line very closely, indicating that the measured and extrapolated values are quite similar and suggesting that the richness extrapolation works well. The typical fractional error in the extrapolated values is 0.06.

#### 3.2.2. Richness Measurements

We next found the richness, $N_{200}$ (Hansen et al. 2005), the number of galaxies in a spherical region within which the density was $200\rho_{\text{crit}}$, where $\rho_{\text{crit}}$ is the critical density of the universe. The radius of this spherical region of space is termed $r_{200}$. Hansen et al. (2005) give $r_{200}$ as

$$r_{200} = 0.156(N_{\text{gals}})^{0.6} h^{-1} \text{Mpc}. \quad (3)$$

We used the area-corrected values for $N_{\text{gals}}$ when calculating $r_{200}$. In order to find $N_{200}$ we again applied the four cuts discussed in Section 3.1, this time using $r_{200}$ as the distance cut rather than 1 $h^{-1}$ Mpc. Finally, once we found $N_{200}$, we again applied the area corrections using Equation (2).

We used the variable elliptical aperture of MAG_AUTO and the circular 2″ and 3″ diameter apertures using MAG_APER in order to determine object magnitudes and thus colors. We used 2″ and 3″ because both were significantly larger than the seeing FWHM, for which the median value was about 0.75″. The differences in colors measured in different apertures were usually small, on the order of 0.05 mag, but could be up to 0.2 mag. Since identification of a cluster galaxy depends on color, there was a resulting variation in richness values for different apertures. We determined that the 2″ aperture had the highest signal to noise by comparing the measurement errors of the $g-r$ and $r-i$ colors to see in which aperture the errors were typically lowest. We found that the 2″ aperture typically had the lowest error value; therefore, we used the colors and thus richness values in the 2″ aperture for richness measurements. However,
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Figure 4. Image of SDSS J1038+4849, with a circular region of radius $1 \ h^{-1} \text{Mpc}$ centered on the BCGs. We have divided the aperture into six annuli in order to apply Equation (2) for area corrections. (A color version of this figure is available in the online journal.)

Figure 5. This plot is a test of the accuracy of the $N_{\text{gal}}$ extrapolation described in Equation (2). Here we plot $N_{\text{gal}}$ values measured in SDSS data, with the measured values on the x-axis and the predicted values on the y-axis. The red line is the $y = x$ line. Since the data closely follow the $y = x$ line, we conclude that the predictions from the extrapolation are quite accurate. (A color version of this figure is available in the online journal.)

3.2.3. Cluster Mass

We define $M_{200}$ to be the mass contained within a spherical region of radius $r_{200}$ (Johnston et al. 2007). An empirical relation between mass and richness is found in Johnston et al. (2007) using a large sample of maxBCG clusters from the SDSS:

$$M_{200}(N_{200}) = M_{200|20} \left( \frac{N_{200}}{20} \right)^{\alpha_N}. \quad (4)$$

In this equation $M_{200|20} = (8.8 \pm 0.4_{\text{stat}} \pm 1.1_{\text{sys}}) \times 10^{13} \ h^{-1} M_\odot$ and $\alpha_N = 1.28 \pm 0.04$. Equation (4) was found empirically using data from the SDSS, using mean redshift of $z = 0.25$.

The error in $M_{200}$ values was considered in Rozo et al. (2009). In that paper, the logarithmic scatter in mass at fixed richness is given as

$$\sigma_{\ln M|N} = 0.45^{+0.20}_{-0.18}. \quad (5)$$

We thus can approximate the uncertainty in the mass itself as

$$\Delta M = 0.45 M_{200}. \quad (6)$$

We also propagate error from the uncertainty in values of $N_{200}$ through Equation (4). Our final values for error on $M_{200}$ were found by adding the uncertainty in the mass and the propagated error in quadrature. The propagated fractional errors had a median value of 0.13 while the scatter described by Equation (6) had a value of 0.45. The combined fractional errors had a median value of 0.47, with the scatter in mass dominating the errors.

we considered the variation in richness values to determine the error in richness: we took the standard deviation of the three values for $N_{200}$ for each cluster and used these values for the uncertainty in $N_{200}$. 

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3.2.4. Velocity Dispersion

Becker et al. (2007) give an empirical relationship for velocity dispersion as a function of richness found from redshifts of cluster members in the maxBCG cluster sample:

$$\langle \ln \sigma_v \rangle = A + B \ln \frac{N_{200}}{25}$$

(7)

The constants $A$ and $B$ are referred to as mean normalization and mean slope, respectively. They are given as $A = 6.17 \pm 0.04$ and $B = 0.436 \pm 0.015$. Becker et al. (2007) also found a relation for the scatter, $S$, in the velocity dispersion. The scatter is defined to be the standard deviation in $\ln \sigma_v$:

$$S^2 = C + D \ln \frac{N_{200}}{25},$$

(8)

where $C = 0.096 \pm 0.014$ and $D = -0.0241 \pm 0.0050$. We used this relation to calculate the errors on the velocity dispersion values, defining the errors as one standard deviation. We also propagated the error on $N_{200}$ through Equation (7) and added these errors in quadrature to the errors found from Equation (8). Again the propagated errors are minimal: the median fractional error on the velocity dispersions from the propagated error on $N_{200}$ is 0.08, while the median fractional error from Equation (8) is 0.31, leading to an overall median fractional error of 0.33.

3.2.5. Errors on Richness and Mass

In order to better constrain the error on our richness measurements, we also measured colors and richnesses for the 10 systems using the SDSS data. We found that richness values from the SDSS are typically much higher than those found in this paper; the mean ratio of $N_{\text{gals(SDSS)}}$ to $N_{\text{gals(2'' MAG APER)}}$ is 1.75 (for WIYN $N_{\text{gals}}$ before area corrections, using only cluster area found both in WIYN and SDSS data; see Table 3). These differences apparently arise because there is a larger error in magnitudes measured in the SDSS than in the data used here. This allows some objects to be counted as cluster members in the SDSS that are not counted as cluster members in the WIYN data. Note that in Figure 6, a color–color diagram for SDSS J1318+3942, more cluster members are found in SDSS data, but those objects are much more scattered in color–color space and many are not true cluster members. On the other hand, fewer objects are found in the WIYN data, but these objects form a much tighter red sequence and are more likely to be genuine cluster members.

We also include Figure 7, in which we show the deviation of each cluster galaxy’s color from the measured color of the E/S0 ridgeline; we plot this versus SDSS i-band magnitude for all 10 clusters. We found $g-r$ and $r-i$ colors for objects considered to be cluster galaxies within 1 h$^{-1}$ Mpc of the BCG in WIYN data and in SDSS data and compared them to the characteristic red sequence colors of the respective clusters. We also found the errors in colors for both sets of data using Equation (1) to find $\sigma$. We used magnitude errors reported by SExtractor for WIYN data and errors on model magnitudes for SDSS data. The error bars shown represent 2$\sigma$. It can be seen in Figure 7 that the differences between the measured color and the cluster color are much larger in the SDSS data than in WIYN data but the errors are larger for SDSS data as well. Due to these larger errors in SDSS data, there is a higher likelihood that objects with larger color deviations will still be counted as cluster members.

The differences in richness values between WIYN and SDSS data persist even at bright magnitudes. We measured values for $N_{\text{gals}}$ at an $i$-band magnitude of 19.38, which is the value for 0.4$L^*$ corresponding to $z = 0.25$. We found that the mean ratio of $N_{\text{gals(SDSS)}}$ to $N_{\text{gals(2'' MAG APER)}}$ is 1.63, meaning that SDSS values are typically about 60% higher than WIYN values. Thus, we find that in general for these 10 clusters richness values measured in our data do not closely match values measured in the SDSS data.

However, since the mass–richness relation (Equation (4)) is calibrated from SDSS data, if we use WIYN richness values with this equation, we would expect the masses to be biased to be too low. Therefore, we determined it would be necessary to scale our measured richness values up to match SDSS values. To do that, we first found all objects that were counted as cluster galaxies ($N_{\text{gals}}$) only in WIYN (not in SDSS) and then found the opposite, objects counted as cluster galaxies only in SDSS but not in WIYN. We then also found the galaxies counted as cluster galaxies in both WIYN and SDSS. Our goal was to constrain the amount that SDSS was overcounting galaxies. To do that we found the ratio

$$C = \frac{N_1 + N_2}{N_1} = 1 + \frac{N_2}{N_1}.$$

(9)

where $N_1$ represents the number of cluster members found in both WIYN data and SDSS data and $N_2$ represents the number of cluster members found only in SDSS data. Since we expect the numbers of galaxies in each magnitude bin to be a Poisson distribution, the standard deviation on $N_1$ and $N_2$ would be simply the square root of each. Then the fractional error on Equation (9) would be

$$\sigma_C = \frac{N_2}{N_1} \sqrt{\frac{1}{N_2} + \frac{1}{N_1}}.$$

(10)
Figure 7. Plot of color difference vs. SDSS $i$-band magnitude for all cluster members in both SDSS and WIYN data. Color difference is defined as the difference between the actual $r - i$ or $g - r$ color of each cluster galaxy and the measured red sequence color for that cluster. Cluster galaxies in each of the 10 clusters are plotted together here. The red diamonds denote WIYN data points and the black circles denote SDSS data points. The error bars represent $2\sigma$, where $\sigma$ is defined by Equation (1). For SDSS measurements, color is found from SDSS model magnitudes and the red sequence colors were measured in SDSS data. For WIYN measurements, color is found from $2''$ MAG_APER magnitudes and red sequence colors were measured in WIYN data. Note that WIYN data points are found much closer to the central line that represents color difference of 0, while SDSS points can be found further away. To be counted as cluster members, points must be within $2\sigma$ of the cluster red sequence colors, but $2\sigma$ is larger for the SDSS points.

(A color version of this figure is available in the online journal.)

Table 3

| System       | $N_{\text{gals}}$ (MAG.AUTO) | $N_{\text{gals}}$ (2'' MAG_APER) | $N_{\text{gals}}$ (3'' MAG_APER) | $N_{\text{gals}}$ (Sloan) |
|--------------|-------------------------------|----------------------------------|----------------------------------|---------------------------|
| SDSS J0900+2234 | 23                            | 28                               | 29                               | 56                        |
| SDSS J0901+1814 | 8                             | 14                               | 8                                | 11                        |
| SDSS J0957+0509 | 15                            | 28                               | 26                               | 63                        |
| SDSS J1038+4849 | 16                            | 15                               | 17                               | 32                        |
| SDSS J1120+2640 | 85                            | 101                              | 98                               | 190                       |
| SDSS J1318+3942 | 21                            | 23                               | 23                               | 39                        |
| SDSS J1343+4155 | 26                            | 25                               | 32                               | 46                        |
| SDSS J1439+3250 | 48                            | 55                               | 51                               | 82                        |
| SDSS J1511+4713 | 22                            | 29                               | 29                               | 54                        |
| SDSS J1537+6556 | 14                            | 20                               | 18                               | 8                         |

Notes. These values for $N_{\text{gals}}$ have not been area-corrected with Equation (2). For the SDSS values, any area which is not on the CCD in the WIYN data is excluded from consideration. Note that for SDSS J1537+6556 much of the WIYN area is outside the SDSS footprint, so the SDSS value is biased low.

We then plotted $C$ against binned WIYN $i$-band (MAG.AUTO) model magnitude. The result is shown in Figure 8. We fit the data with a linear relation using IDL routine FITEXY, which applies a linear fit including error bars. The final relation found was

$$C = (0.222 \pm 0.116)m_{i,\text{WIYN}} + (-2.84 \pm 2.29).$$

The magnitude $m_{i,\text{WIYN}}$ is WIYN $i$-band magnitude from MAG.AUTO. When this equation is evaluated at $i$-band $m = 19.38$, the value for $0.4L^*$ at the mean SDSS redshift of 0.25, then $C = 1.47$. We took this as the correction factor for our richness values.

We measured $N_{\text{gals}}$ and corrected these values for missing area in WIYN using Equation (2). Then we included the above correction factor when calculating $r_{200}$, letting

$$r_{200} = 0.156(N_{\text{gals,SDSS}})^{0.6} = 0.156(1.47N_{\text{gals,WIYN}})^{0.6}.$$

We remeasured $N_{200}$ using the new value for $r_{200}$ and corrected for missing area. Finally, we scaled these new $N_{200}$ values by multiplying them by the same scale factor of 1.47. We used these scaled values of $N_{200}$ to find $M_{200}$, velocity dispersion, and concentration parameter. We give values for all quantities found without the scale factor in Table 4 and we give the values found with the scale factor in Table 5.

We find the scaled values for $N_{200}$ are on average 1.7 times bigger than the unscaled values. This leads the new values for $M_{200}$ (those found from the scaled richness values) to be 2.0 times larger than the previous values. Also new values for velocity dispersion are 1.3 times larger than previous values, while new values for concentration parameter are all smaller, on average 0.63 times the previous values (see Section 5.2).

3.2.6. Comparison of Results

Several other groups have measured cluster masses or related quantities for some of our clusters. Oguri et al. (2012) present combined strong and weak lensing analyses for 28 clusters, including four of the clusters discussed in this paper. This allowed us to compare our results for $M_{200}$ to their results for these four systems. As Oguri et al. (2012) present values for $M_{\text{vir}}$, we...
A Summary of the Quantities Measured without Scaling for the 10 Galaxy Clusters

| System         | $N_{\text{gal}}$ | $r_{200}$ (h$^{-1}$ Mpc) | $N_{200}$ | $M_{200}$ (10$^{14} M_\odot$) | $\sigma_v$ (km s$^{-1}$) | $c_{200}$ |
|----------------|------------------|---------------------------|-----------|-----------------------------|--------------------------|-----------|
| SDSS J0900+2234 | 28               | 1.15                      | 30 ± 4.1  | 1.48 ± 0.715               | 518 ± 135                | 8.27 ± 3.32 |
| SDSS J0901+1814 | 15               | 0.792                     | 11 ± 0.58 | 0.409 ± 0.186              | 334 ± 137               | 19.0 ± 9.19 |
| SDSS J0957+0509 | 29               | 1.18                      | 36 ± 3.4  | 1.87 ± 0.870               | 561 ± 120                | 7.49 ± 3.81 |
| SDSS J1038+4849 | 16               | 0.823                     | 15 ± 0.62 | 0.609 ± 0.276              | 383 ± 150                | 34.9 ± 18.0 |
| SDSS J1209+2640 | 101              | 2.49                      | 214 ± 11.5 | 18.3 ± 8.32             | 1219 ± 293               | 3.64 ± 2.81 |
| SDSS J1318+3942 | 24               | 1.050                     | 25 ± 4.2  | 1.17 ± 0.583              | 478 ± 191                | 9.9 ± 3.49  |
| SDSS J1343+4155 | 28               | 1.15                      | 29 ± 1.1  | 1.42 ± 0.641              | 510 ± 135                | 14.3 ± 7.26 |
| SDSS J1439+3250 | 59               | 1.80                      | 105 ± 18  | 7.35 ± 3.69               | 894 ± 296                | 3.20 ± 1.03 |
| SDSS J1511+4713 | 31               | 1.22                      | 40 ± 2.9  | 2.14 ± 0.981              | 587 ± 203                | 7.69 ± 5.51 |
| SDSS J1537+6556 | 22               | 0.997                     | 22 ± 2.9  | 0.994 ± 0.477             | 452 ± 177                | 18.8 ± 9.42 |

Notes. These are all based on colors measured in the 2'' aperture. The $N_{\text{gal}}$ and $N_{200}$ values are area-corrected using Equation (2) and are scaled up using Equation (9).

### Figure 8

Plot comparing objects counted as cluster galaxies only in SDSS data and in both WYNN and SDSS data. Here, $N_1$ is the number of cluster members found in both SDSS and WYNN in that magnitude bin and $N_2$ is the number of cluster members found only in SDSS. We plot the ratio $1 + N_2/N_1$ (which we refer to in the text as C) on the y-axis and the magnitude bin on the x-axis, where magnitude bins are 0.5 mag in size. The red line is a linear best fit, found using IDL routine FITEXY. The equation of that line is $C = (0.222 ± 0.116)m_{\text{WYNN}} + (-2.84 ± 2.29)$, where $m_{\text{WYNN}}$ represents magnitude in i-band MAG_AUTO.

(A color version of this figure is available in the online journal.)

we converted these to $M_{200}$ values using the method described in Appendix A of Johnston et al. (2007) (see Section 5.1).

Bayliss et al. (2011) provided velocity dispersions for four of our clusters. We used the relation between cluster mass and galaxy velocity dispersion given in Evrard et al. (2008) to find $M_{200}$:

$$b_v M_{200} = 10^{15} M_\odot \left(\frac{\sigma_{\text{gal}}}{\sigma_{15}}\right)^{1.5} h(z)$$

(13)

Here, $h(z)$ is the Hubble parameter, $b_v = \sigma_{\text{gal}}/\sigma_{\text{DM}}$ is the velocity bias (we assume $b_v = 1$), $\sigma_{\text{gal}}$ is the galaxy velocity dispersion, $\sigma_{\text{DM}}$ is the dark matter velocity dispersion, $\sigma_{15} = 1084 ± 13$ km s$^{-1}$, and $\alpha = 0.3539 ± 0.0045$. E. Drabek et al. (in preparation) present masses for two clusters, SDSS J1343+4155 and SDSS J1439+3250, based on spectroscopy of a sample of galaxies in these clusters. We summarize all the values of $M_{200}$ found by these groups in Table 6. In Figure 9, we plot the $M_{200}$ values from the three other papers against our $M_{200}$ values; the dotted line in the plot is the $y = x$ line. We find that our values are reasonable in light of the findings of other groups as when we plot our values against those from other groups, the points are all scattered around the $y = x$ line.

### 4. STRONG LENSING PROPERTIES

In a strong lensing system, if the source galaxy and the galaxy cluster are perfectly aligned, then the image formed will be a
In order to try to quantify the uncertainty in our measurements, we measured the Einstein radii for all the objects again several months after the first measurement without referencing previous data. In all cases the differences between the original and new measurements were between 0.03 and 0.6. Since this represents up to 10% of the value of $\theta_E$, we estimated the uncertainty in $\theta_E$ as 10%.

We note however that this method of estimating Einstein radius can lead to large systematic errors, so we also compared our values for Einstein radii to values from other groups. West et al. (2012) present strong lensing models for three of our systems and Oguri et al. (2012) present models for four of our systems. Both groups have measurements for SDSS J1343+4155, so we compared values for a total of six systems. We provide measured Einstein radii from these papers in Table 7. For SDSS J0900+2234 and SDSS J0901+1814, our estimates are almost exactly the same as the values in West et al. (2012). However, for the other four systems, the scatter (standard deviation) in values is larger, between 2′′.1 and 4′′.0. We account for this error by calculating the fractional error in the values for $\theta_E$ and then finding the median value of the fractional errors for each of the six systems. The median value of the fractional errors is 0.32, or 32%, which we added in quadrature to the 10% errors to find final error values.

Solving Equation (14) for the mass, we obtain

$$M = \theta_E^2 \frac{c^2}{4G} \frac{D_dD_s}{D_{ds}}, \quad (15)$$

Using the redshifts listed in Table 1 for the galaxy clusters and the source galaxies, we calculated the angular diameter distances. We then used the Einstein radii we had measured to calculate the masses of the lenses.

Finally, we calculated the velocity dispersions of the regions of the clusters inside $\theta_E$ assuming the mass distribution was well fitted by a singular isothermal sphere (SIS). We used the following equation, from Narayan & Bartelmann (1997):

$$\sigma_v = \sqrt{\frac{\theta_E c^2 D_s}{4\pi D_{ds}}}. \quad (16)$$

All values measured for the strong lenses are presented in Table 8.

In Figure 10, we compare the velocity dispersions found from lensing to those found from richness measurements. Note that these velocity dispersions measure different things: the velocity.
Figure 10. Comparison of velocity dispersions found from θ_E and found from Einstein radii. The line shown has the equation y = x. The clusters on or above the y = x line are all higher-mass clusters.

(A color version of this figure is available in the online journal.)

dispersion from lensing describes the velocity dispersion inside θ_E and the velocity dispersion from r_200 describes the velocity dispersion within the much larger distance r_200. We see in Figure 10 that many of the clusters are found along the y = x line, several are found above it and several are found below it. For the clusters found along the y = x line, we see that the velocity dispersions are similar within the two different radii, θ_E and r_200, which suggests that these systems are largely isothermal. For the systems found above the y = x line, the velocity dispersion at large radii is much larger than at small radii, indicating that much of the mass is found at larger distance from the BCG, suggesting a low value for c_{200}. However, for several of the clusters, the velocity dispersion within θ_E is larger than that found within r_200, indicating that for several clusters there is more mass within the smaller radius and suggesting that the concentration parameter is large. Our highest mass clusters are found above the y = x line (suggesting lower concentration parameter), while our lower-mass clusters are found below the y = x line (suggesting higher concentration parameter). This would agree with what we discuss in the next section that our highest mass clusters are not overconcentrated but our lowest mass clusters seem to be.

5. APPLICATIONS TO COSMOLOGY

5.1. An Overconcentration Problem?

Several recent papers (Oguri & Blandford 2009; Gralla et al. 2011; Fedeli 2012; Oguri et al. 2012) have presented evidence that galaxy clusters that exhibit strong lensing have higher concentration parameters than ΛCDM would predict. The most recent considerations (Fedeli 2012; Oguri et al. 2012) suggest that this overconcentration is most significant at cluster masses less than 10^{14} h^{-1} M_\odot. Overconcentration can be illustrated by comparing Einstein radii to M_200 (Gralla et al. 2011). Since Einstein radii are dependent on both cluster mass and cluster concentration parameter, such a comparison will yield larger Einstein radii than would be expected for particular M_200 values if the clusters are overconcentrated.

Considering this, we have compared Einstein radius to M_200 for our 10 systems. One complication in making this comparison is that Einstein radius is a function of redshift. Since all of our systems have different redshifts for both lens and source, in order
to compare them, we needed to scale them to a single, constant redshift for lens and source. We chose both the lens and source redshifts (we refer to them henceforth as fiducial redshifts) by taking the mean of the 10 lens redshifts and the mean of the 10 source redshifts. Our fiducial redshifts are $z_d = 0.433$ for the lens and $z_s = 1.65$ for the source.

To scale Einstein radii to the fiducial redshifts, we needed to find a scale factor $k$ that would satisfy

$$\theta_{E, \text{scaled}}(z_d, z_s) = k \times \theta_{E, \text{measured}}(z_d, z_s).$$  \hspace{1cm} (17)

We note that Equation (16) can be rearranged as

$$\theta_E = \frac{4\pi\sigma^2}{c^2} \frac{D_{ds}}{D_s}. $$  \hspace{1cm} (18)

Since $\sigma$ is proportional to the mass and does not depend on redshift, $\theta_E$ scales with redshift according to the ratio $D_{ds}/D_s$. Thus, solving Equation (17) for $k$ we obtain

$$k = \frac{\theta_{E, \text{scaled}}}{\theta_{E, \text{measured}}} = \left( \frac{4\pi\sigma^2}{c^2} \frac{D_{ds, \text{fiducial}}}{D_{ds, \text{measured}}} \right),$$  \hspace{1cm} (19)

and since $\sigma$ does not scale with redshift, it cancels. Then

$$k = \frac{D_{ds, \text{fiducial}}}{D_{ds, \text{measured}}}. $$  \hspace{1cm} (20)

We applied Equation (20) to find the scale factor $k$ for each cluster and then scaled each Einstein radius to the fiducial values.

In order to compare the relation between Einstein radius and $M_{200}$ for our data to the relation that ΛCDM would predict, we refer to the models presented in Oguri et al. (2009, 2012) which predict concentration as a function of cluster mass. Concentration parameter, $c_\Delta$, is defined as

$$c_\Delta = \frac{r_\Delta}{r_s}. $$  \hspace{1cm} (21)

The $r_s$ term is the scale radius, a term in the NFW model of dark matter halo density (Navarro et al. 1997), described below. The quantity $\Delta$ is the virial overdensity. In this paper, we use $\Delta = 200$, but Oguri et al. (2009) use $\Delta = \nu \nu$, where the virial overdensity is the local overdensity that would cause halo collapse; it is a function of redshift. Oguri et al. (2009) suggest that lensing-selected clusters (those discovered based on lensing, like those in this paper) will have a value for the concentration that is 50% higher than for general clusters.

Oguri et al. (2009) present a relation for $c_{\nu \nu}$ in general clusters, citing results obtained from $N$-body simulations conducted using WMAP5 cosmology (Duffy et al. 2008):

$$\tilde{c}_{\nu \nu}(\text{sim}) = \frac{7.85}{(1 + z)^{0.71}} \left( \frac{M_{\nu \nu}}{2.78 \times 10^{12} M_\odot} \right)^{-0.081}. $$  \hspace{1cm} (22)

We consider this relation at $z = 0.45$, for consistency with the lensing-selected relation below. Oguri et al. (2012) present a relation for $c_{\nu \nu}$ in lensing-selected clusters, using ray tracing to estimate the effect of lensing bias:

$$\tilde{c}_{\nu \nu}(z = 0.45) \approx 6.3 \left( \frac{M_{\nu \nu}}{5 \times 10^{14} h^{-1} M_\odot} \right)^{-0.2}. $$  \hspace{1cm} (23)

In order to compare our data to these predictions, we chose a range of values of $M_{\nu \nu}$ and used Equations (22) and (23) to find the corresponding values for $c_{\nu \nu}$. We then used the relations in Johnston et al. (2007) and Hu & Kravtsov (2003) to convert from $c_{\nu \nu}$ and $M_{\nu \nu}$ to $c_{200}$ and $M_{200}$. Finally, we used the range of values for $M_{200}$ and the predicted values for $c_{\nu \nu}$ to find predicted values for Einstein radius ($\theta_E$) by using the NFW profile (see Equation (24) below). We plotted the relations between $M_{200}$ and $\theta_E$ as the general and lensing-selected predictions in Figures 11 and 12.

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Figure 11. Plot of Einstein radius vs. $M_{200}$ for unscaled $M_{200}$ values, with Einstein radii scaled to fiducial redshifts. The theoretical lines come from a prediction of Einstein radii for given $M_{200}$ and $c_{200}$ values found by using an NFW (Navarro et al. 1997) fit to the mass and concentration. The general clusters line was found using predicted $c_{200}$ values found from Equation (22) and the lensing-selected clusters line was found using predicted $c_{200}$ values found from Equation (23). The average $c_{200}$ for general clusters is 3.6 and for lensing-selected clusters it is 6.4. Both equations took $z = 0.45$. The approximate fit line was found by multiplying the values of $c_{\nu \nu}$ resulting from Equation (23) by 1.9. We tried different factors to multiply $c_{\nu \nu}$ until the resultant line went approximately through the low-mass data points. (A color version of this figure is available in the online journal.)
To find a predicted Einstein radius we used the NFW density profile, expressed as
\[
\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2},
\]
where \(r\) is the distance from the center of the cluster, \(\rho_s\) is a characteristic density, and \(r_s\) is the scale radius, given by \(r_s = r_{200}/c_{200}\). We implemented Equation 13 in Wright & Brainerd (2000), an equation that describes surface mass density \(\Sigma_{\text{NFW}}\) in the NFW model. The Einstein radius \(\theta_E\) is given implicitly by the solution of Narayan & Bartelmann (1997):
\[
\Sigma_{\text{NFW}} \left(\frac{\theta_E}{r_s}\right) = \Sigma_{\text{crit}},
\]
where the critical surface mass density \(\Sigma_{\text{crit}}\) is
\[
\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}}.
\]
Thus, we found the Einstein radius by solving for \(\Sigma_{\text{NFW}}\) and using that to find \(\theta_E\).

5.2. Consideration of the Overconcentration Problem

The final result of our analysis is shown in Figures 11 and 12. Figure 11 shows the relation between \(M_{200}\) and \(\theta_E\) for our measured values of \(M_{200}\) while Figure 12 shows the relation for the new \(M_{200}\) values that come from the scaled-up richness values. We consider Figure 12 to be more reliable as it uses richness values scaled to correspond with values from SDSS data, which were used to calibrate the mass–richness relation. In Figure 11, there is a noticeable disagreement between our data and the predicted relations. It can also be seen that the lower-mass clusters disagree more while the higher-mass clusters fit the predictions better, as found by other authors. However, in Figure 12, we see that all clusters are shifted to higher masses by an average factor of 2.0. In the plot of the scaled values, we see that many of the clusters now closely follow the lensing-selected prediction. There are still four clusters that do not fit the predicted relations. These clusters are SDSS J0901+1814, SDSS J1038+4849, SDSS J1343+4155, and SDSS J1537+6556, which are the lowest mass clusters in our sample. SDSS J1318+3942, which is also among the lowest mass clusters, is found close to the predicted line, but still slightly above it.

We determined values for \(c_{200}\) for our clusters by using our measured values for \(M_{200}\) and \(\theta_E\) in Equations (24) and (25); values are listed in Table 4. We estimated errors on \(c_{200}\) by varying \(M_{200}\) and \(\theta_E\) to the maximum and minimum values allowed by their respective error bars. Maximum values for \(c_{200}\) were found with minimum \(M_{200}\) and maximum \(\theta_E\) while minimum values for \(c_{200}\) were found with the opposite. For smaller values of \(M_{200}\), this led to very large upper error bars on \(c_{200}\) as a very high concentration parameter would then be required to achieve the large Einstein radius.

Our measurements of \(c_{200}\) follow the trends noted earlier: for many of the clusters, our measured values of \(c_{200}\) are within the range of predictions, but for the lowest mass clusters measured values of \(c_{200}\) are higher than predictions. The average value for \(c_{200}\) predicted for our scaled values of \(M_{200}\) by Equation (22) (for general clusters) is 3.4 while the average value predicted by Equation (23) (for lensing-selected clusters) is 5.7. The average of our 10 measured values of \(c_{200}\) is 7.3, which is slightly larger than the lensing-selected prediction. However, for our four lowest mass clusters the average \(c_{200}\) value is 11.6, much larger than the lensing-selected prediction. The four clusters we identify as overconcentrated above have the following values for \(c_{200}\): for SDSS J0901+1814, \(c_{200} = 9.6^{+13}_{-3.5}\); for SDSS J1038+4840, \(c_{200} = 17^{+73}_{-7.8}\); for SDSS J1343+4155, \(c_{200} = 9.1^{+32}_{-3.9}\); and for SDSS J1537+6556, \(c_{200} = 11^{+39}_{-15}\). These clusters have respective \(M_{200}\) of 0.99, 1.2, 2.3, and \(2.2 \times 10^{14} \, h^{-1} M_\odot\), which are the lowest masses in our sample.

Concentration parameters \((c_{vir})\) based on strong and weak lensing measurements are provided in Oguri et al. (2012) for two of these four clusters. We convert these to \(c_{200}\) using
the method discussed in Section 5.1. For SDSS J1038+4840, 
$c_{200} = 33.8^{+0.0}_{-0.3} \times 10^{13}$ and for SDSS J1343+4155, $c_{200} = 4.25^{+1.39}_{-0.79} \times 10^{13}$. 
Thus, for SDSS J1038+4840, the second lowest mass cluster in our sample, both sets of measurements find this cluster to be significantly overconcentrated. For SDSS J1343+4155 the evidence for overconcentration is not as strong. 

In Figures 13 and 14 we consider the mass–concentration relation, comparing log($c_{200}$) to log($M_{200}$). Figure 13 is the mass–concentration relation for our measured values of $c_{200}$ and $M_{200}$ found without scaling and Figure 14 is this relation for values found with scaling. We also include three lines in Figures 13 and 14; the blue solid line is the prediction from Oguri et al. (2012) for lensing-selected clusters, the green solid line is the best fit to the data in the Oguri paper (Equation (23)). The large vertical error bars on the mass–concentration relation for our measured values of $M_{200}$ and $c_{200}$ are significantly overconcentrated. For SDSS J1343+4155 the best-fit line is $c_{200} = 4.25^{+1.39}_{-0.79} \times 10^{13}$, our lowest value of $c_{200}$ is required to achieve the large value for Einstein radius. (A color version of this figure is available in the online journal.)

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![Figure 13. Plot of the logarithm of the concentration parameter $c_{200}$ vs. logarithm of $M_{200}$. This is modeled on Figure 1 in Fedeli (2012). The dotted red line is the best fit to the data and has a slope $\alpha = 0.45 \pm 0.30$. The solid green line (with the higher slope) is the fit to the data in Oguri et al. (2012) (their Equation (26)). The solid blue line (with the lower slope) is the Oguri prediction for lensing-selected clusters (Equation (23)). The large vertical error bars on the mass–concentration relation, comparing log($c_{200}$) to log($M_{200}$)) to log($M_{200}$) above 1.0 which suggest that these clusters are overconcentrated.

We find in Figure 13 that our data points are mostly above the predicted line, suggesting many of our clusters are overconcentrated. However, when we use the more reliable scaled values in Figure 14 we find that most of the clusters are found near the predicted line, but the lowest mass clusters (the four identified above) remain above the prediction. This again confirms our previous statement that most of our clusters do not appear to be overconcentrated, but there is evidence for overconcentration at lower cluster masses.

Thus, for most of our clusters, $\Lambda$CDM seems to match their observed properties. But for our several clusters showing evidence of overconcentration, what does the overconcentration problem suggest is happening in galaxy clusters? It seems to suggest that clusters are collapsing more than $\Lambda$CDM would predict (Broadhurst & Barkana 2008; Fedeli 2012; Oguri et al. 2012). The dark matter halo associated with a galaxy cluster is expected to have undergone an adiabatic collapse during the formation of the cluster. The baryonic matter in the cluster (concentrated in the BCG) would also have collapsed. The baryonic matter would likely have dragged the dark matter along with it, augmenting the collapse of the halo. Since we find some clusters to be more overconcentrated than expected, it may be that the halo collapsed more than expected due to the contribution of the baryons. It is suggested (Fedeli 2012; Oguri et al. 2012) that the overconcentration is most significant in lower-mass clusters because in these clusters the BCG makes up a larger percentage of the overall cluster mass. Thus, the baryons would contribute to the halo collapse more in a lower-mass cluster than in a higher-mass cluster.

6. CONCLUSION

We have reported on the properties of 10 galaxy clusters exhibiting strong gravitational lensing arcs which were discovered in the SDSS. These are a subset of the 19 systems discovered thus far by the SBAS.
mass clusters are collapsing more than SDSS. The scaled richness values for the clusters range from $M_{200} = 0.993 \times 10^{14} h^{-1} M_\odot$ to $M_{200} = 30.2 \times 10^{14} h^{-1} M_\odot$ and the velocity dispersions for the clusters range from $\sigma_v = 452 \, \text{km s}^{-1}$ to $\sigma_v = 1446 \, \text{km s}^{-1}$. Finally, the concentration parameters for the clusters range from 2.4 to 17.

We applied a simple SIS model to infer the lens masses and lens velocity dispersions from the measured Einstein radii. The smallest Einstein radius was $\theta_E = 5.4$ and the largest was $\theta_E = 13\,'$. The lens mass within the Einstein radius ranged from $M = 5.5 \times 10^{13} h^{-1} M_\odot$ to $M = 36 \times 10^{13} h^{-1} M_\odot$ and the lens velocity dispersion ranged from $\sigma_v = 336 \, \text{km s}^{-1}$ to $\sigma_v = 804 \, \text{km s}^{-1}$.

Finally, we considered the relation between $\theta_E$ and $M_{200}$ and compared this relation to the predictions of $\Lambda$CDM, both for lensing-selected and for general clusters. We also found the mass–concentration relation for our data. We found that most of our clusters are not overconcentrated, but our four lowest mass clusters show evidence of overconcentration, with values for $c_{200}$ between 9.6 and 17. This may suggest that the lowest mass clusters are collapsing more than $\Lambda$CDM would predict.

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