INFALL REGIONS AND SCALING RELATIONS OF X-RAY SELECTED GROUPS

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ABSTRACT

We use the Fifth Data Release of the Sloan Digital Sky Survey (SDSS) to study X-ray-selected galaxy groups and compare their properties to clusters. We search for infall patterns around the groups and use these to measure group mass profiles to large radii. In previous work, we analyzed infall patterns for an X-ray-selected sample of 72 clusters from the ROSAT All-Sky Survey. Here, we extend this approach to a sample of systems with smaller X-ray fluxes selected from the 400 deg² serendipitous survey of clusters and groups in ROSAT pointed observations. We identify 16 groups with SDSS DR5 spectroscopy, search for infall patterns, and compute mass profiles out to 2–6 $h^{-1}$ Mpc from the group centers with the caustic technique. No other mass estimation methods are currently available at such large radii for these low-mass groups, because the virial estimate requires dynamical equilibrium and the gravitational lensing signal is too weak. Despite the small masses of these groups, most display recognizable infall patterns. We use caustic and virial mass estimates to measure the scaling relations between different observables, extending these relations to smaller fluxes and luminosities than many previous surveys. Close inspection reveals that three of the groups are subclusters in the outskirts of larger clusters. A fourth group is apparently undergoing a group–group merger. These four merging groups represent the most extreme outliers in the scaling relations. Excluding these groups, we find $L_X \propto \sigma_p^{3.1\pm1.6}$, consistent with previous determinations for both clusters and groups. Understanding cluster and group scaling relations is crucial for measuring cosmological parameters from clusters. The complex environments of our group sample reinforce the idea that great care must be taken in determining the properties of low-mass clusters and groups.

Key words: cosmology; observations – galaxies: clusters: individual – galaxies: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

A large fraction of all galaxies are members of groups. Groups are a less extreme and much more common type of system than galaxy clusters. Because they are less massive than clusters, groups are currently less well understood than clusters. Here, we investigate the optical properties of a sample of X-ray-selected groups to determine whether they can be modeled as scaled-down versions of clusters.5 In particular, we study the outskirts of the groups to determine if their infall regions are readily identifiable as they are in the outskirts of clusters. With large samples of spectroscopic members, we then estimate the virial masses of the groups and determine if the groups obey the same scaling relations as clusters.

Galaxy clusters and groups are surrounded by infall regions in which galaxies are bound to the system but are not in equilibrium. The Cluster Infall Regions in the Sloan Digital Sky Survey (Rines & Diaferio 2006, hereafter CIRS) project showed that X-ray-selected clusters display a characteristic trumpet-shaped pattern in radius–redshift phase space diagrams. These patterns, termed caustics, were first predicted for simple spherical infall onto clusters (Kaiser 1987; Regös & Geller 1989), but later work showed that these patterns reflect the dynamics of the infall region (Diaferio & Geller 1997, hereafter DG) and (Diaferio 1999, hereafter D99). CIRS and earlier similar studies (e.g., Geller et al. 1999; Rines et al. 2003) showed that the amplitude of the caustics yields an estimate of cluster mass profiles consistent with both virial and X-ray mass estimates where the techniques overlap. More recently, Diaferio et al. (2005) and Lemze et al. (2009) showed that caustic masses also agree well with mass estimates based on gravitational lensing. Because neither galaxies nor gas is expected to be in equilibrium outside the virial radius of a cluster, the caustic technique and weak lensing are the only well-studied methods for determining cluster mass profiles at large radii (see Diaferio 2009, for a recent review of the caustic technique).

CIRS showed that infall patterns are ubiquitous in nearby massive clusters selected by X-ray emission. The CIRS clusters are fairly massive clusters and generally have little surrounding large-scale structure (but see Rines et al. 2001, 2002). One might suspect that the presence of infall patterns is limited to massive, isolated clusters. However, other investigators have found infall patterns around the Fornax Cluster (Drinkwater et al. 2001), the Shapley Supercluster (Reisenegger et al. 2000), an ensemble cluster comprised of poor clusters in the Two Degree Field Galaxy Redshift Survey (Biviano & Girardi 2003), and even the galaxy group associated with NGC 5846 (Mahdavi et al. 2005). Here, we extend the study of infall patterns by studying a large number of systems with smaller X-ray fluxes than the CIRS clusters. Because these systems typically have smaller masses and fewer member galaxies (more typical of groups), infall patterns might not be identifiable in these systems.

In particular, we use the new 400 deg² (400d) survey of clusters and groups in ROSAT PSPC pointed observations (Burenin et al. 2007). The 400d survey covers the largest area of...
any cluster survey that extends to flux limits of $\approx 1.4 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$. This flux limit is a factor of 20 smaller than the flux limit of catalogs based on the ROSAT All-Sky Survey (RASS; Voges et al. 1999). We search for 400d clusters and groups in the spectroscopic footprint of the Sloan Digital Sky Survey Data Release 5 (Adelman-McCarthy et al. 2007, SDSS DR5). This approach is similar to CIRS and to the RASS–SDSS (Popesso et al. 2004, 2005) analysis of clusters in DR2. Compared to both the CIRS and RASS–SDSS samples, the 400d groups are expected to have significantly smaller masses on average.

One motivation for this study is to improve our understanding of cluster scaling relations, in particular to extend these relations to the regime of high-mass groups. Ambitious cluster surveys like the South Pole Telescope and Atacama Cosmology Telescope require a good understanding of cluster scaling relations to accurately measure cosmological parameters from the abundance and evolution of clusters. Quantifying the scatter in these relations and any Malmquist-like bias is crucial for obtaining robust cosmological constraints from cluster surveys (e.g., Stanek et al. 2006). Many forecasts for dark energy constraints from cluster surveys assume that scatter in the mass-observable scaling relations has a log-normal distribution (e.g., Mantz et al. 2008). Deviations from this assumption could significantly impact the constraining power of these surveys.

Recent studies of scaling relations that extend into the group regime have often reached contradictory conclusions. For instance, a common scaling relation is the $L_X - \sigma_v$ relation between the X-ray luminosity $L_X$ of a cluster or group and its projected velocity dispersion $\sigma_v$. For massive clusters, this relation is typically found to have a steep slope of $4.4^{+0.7}_{-0.3}$ (Mahdavi & Geller 2001) or $3.7 \pm 0.3$ (Popesso et al. 2005). For groups, various studies have found slopes as shallow as $0.37$ (Mahdavi et al. 2000, the fit is a broken power law with a slope of 4.02 for clusters) and as steep as $4.7 \pm 0.9$ (Helsdon & Ponman 2000). A detailed optical-X-ray study by Osmond & Ponman (2004) recently found a slope of $2.5 \pm 0.4$. The variety in slopes is produced by many factors, including differing definitions of $L_X$, and in some cases, possible evolution of the galaxies via dynamical friction (Helsdon et al. 2005). One problem is that few large, complete group catalogs are available, so many existing studies utilize either heterogeneous samples or include many groups with limited data on each group. One solution is to utilize X-ray selection (e.g., Mulchaey & Zabludoff 1998; Mahdavi et al. 2000), but existing cluster/group catalogs based on RASS (Popesso et al. 2005, CIRS) have been limited to systems with relatively high X-ray fluxes (and therefore including few groups). The fainter X-ray flux limits of the 400d survey allow detection of several groups. Combining this catalog with optical data from the SDSS (Stoughton et al. 2002), we can test whether the scaling relations show similar behavior for systems with smaller fluxes typical of galaxy groups. A complementary approach (that we do not apply here) to understanding scaling relations for low-mass systems is to identify the systems optically and use stacking analysis to measure their ensemble properties. This approach has been applied previously with RASS data (Dai et al. 2007; Rykoff et al. 2008).

We describe the data and the group sample in Section 2. In Section 3, we review the caustic technique and use it to estimate the group mass profiles, discuss cluster scaling relations, and compare the caustic mass profiles to simple parametric models. We discuss some individual groups in Section 4. We compare the caustic mass profiles to X-ray and virial mass estimators in Section 5. We discuss our results and conclude in Section 6. We assume $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ throughout.

2. THE 400D-SDSS GROUP SAMPLE

2.1. Sloan Digital Sky Survey

The SDSS (Stoughton et al. 2002) is a wide-area photometric and spectroscopic survey at high Galactic latitudes. The Fifth Data Release (DR5) of SDSS includes 8000 deg$^2$ of imaging data and 5740 deg$^2$ of spectroscopic data (Adelman-McCarthy et al. 2007).

The spectroscopic limit of the main galaxy sample of SDSS is $r = 17.77$ after correcting for Galactic extinction (Strauss et al. 2002). CAIRNS and CIRS found that infall patterns were detectable in clusters sampled to about $M^* + 1$, or $z \lesssim 0.1$ for SDSS data. For the current sample, the X-ray fluxes are much smaller than those of CAIRNS or CIRS, so these groups may not be as well sampled. If the 400d groups are less massive on average, they should contain fewer luminous galaxies than the CAIRNS and CIRS clusters. We therefore expect that infall patterns may be less common and/or poorly sampled in the 400d groups.

Note that SDSS is $\approx 85\%$–$90\%$ complete to the nominal spectroscopic limit. The survey has $\approx 7\%$ incompleteness due to fiber collisions (Strauss et al. 2002), which are more likely to occur in dense cluster fields. Because the target selected in a fiber collision is determined randomly, this incompleteness can theoretically be corrected for in later analysis. From a comparison of SDSS with the Millennium Galaxy Catalog, Cross et al. (2004) conclude that there is an additional incompleteness of $\approx 7\%$ due to galaxies misclassified as stars or otherwise missed by the SDSS photometric pipeline. For our purposes, the incompleteness is not important provided sufficient numbers of group galaxies do have spectra.

2.2. X-ray Surveys for Clusters and Groups

In CIRS, we studied clusters contained in catalogs based on the RASS (Voges et al. 1999). RASS is a shallow survey but it is sufficiently deep to include nearby, massive clusters and groups. RASS covers virtually the entire sky and is thus the most complete X-ray cluster survey for nearby clusters and groups. The flux limits of RASS-based surveys are $\approx 3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Ebeling et al. 1998; Böhringer et al. 2000).

The wide field of view of the ROSAT PSPC instrument provides a large area for serendipitous discovery of sources in pointed observations. Several cluster catalogs have been created with this goal. The largest of these catalogs is the 400d survey, which contains essentially all pointed observations suitable for extragalactic surveys (Burenin et al. 2007), yielding a total survey of about 400 deg$^2$. Extended X-ray sources are detected with a wavelet technique and fluxes are measured in the ROSAT band $(0.1$–$2.4 \text{ keV})$. The flux limit of the 400d survey is $\approx 1.4 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$, a factor of $\approx 20$ fainter than the RASS-based catalogs. The effective area of the survey depends on the flux limit and is calibrated with simulated observations of real ROSAT cluster data. The detection algorithm is optimized for luminous clusters ($L_X > 5 \times 10^{43} \text{ erg s}^{-1}$) at moderate redshift ($z > 0.3$). The groups studied here have smaller X-ray luminosities and are thus expected to be physically smaller than higher-luminosity clusters, but they are also at much lower redshifts, so their angular sizes are not too different from the
luminous clusters at \( z > 0.3 \). The ROSAT observations are typically not deep enough to separate diffuse group emission from contributions from individual galaxy halos.

We restrict our analysis to clusters and groups with \( z \leq 0.10 \) (Section 2.1). Our sample contains 16 groups within the SDSS DR5 spectroscopic survey region. We will refer to this sample as the 400d-SDSS groups hereafter. Figure 1 shows the X-ray luminosity vs. redshift diagrams for all groups in the 400d-SDSS sample. The caustic pattern is evident as the trumpet-shaped regions with high density. The solid lines indicate the location of the caustics in each group. Vertical lines in each panel indicate the radial extent of the caustics. The dashed lines show the radial extent of the caustics. The solid lines show the radial extent of the caustics. The top solid line shows the radial extent of the caustics. The dashed line shows the radial extent of the caustics.

3. RESULTS

3.1. Infall Patterns around X-ray Groups

We first search for well-defined infall patterns around the 400d-SDSS groups. Analogously to CIRS, we plotted radius–redshift diagrams for all groups in the 400d X-ray catalog covered by DR5 with \( z < 0.10 \). We assign a “by-eye” classification of each group’s infall pattern: “clean” for groups with few foreground and background objects, and “weak” for groups with little apparent infall pattern. The hierarchical clustering algorithm used by the caustic technique to clusters classified as “intermediate” or “weak” is thus fairly conservative. We use this classification scheme only to show the dependence of the infall pattern appearance on group mass (using \( L_X \) as a proxy) and the sampling depth.

Figure 1 shows the dependence of the subjective classification on X-ray luminosity and redshift. The 400d-SDSS sample contains 16 groups; six contain “clean” infall patterns and three (19%) show weak infall patterns. The percentage in the last category is larger than for the CIRS clusters (4%), although the significance of this difference is difficult to assess (the 400d-SDSS sample is small and the categories are not robustly defined).

Figure 1 demonstrates the expanded parameter space covered by the 400d-SDSS groups compared to the CIRS sample. In particular, the 400d-SDSS sample includes many more systems with \( L_X \sim 10^{42} \) erg s\(^{-1}\) than CIRS. Table 1 lists the properties of each group in the 400d-SDSS sample, their X-ray positions and luminosities, their central redshifts and velocity dispersions (see below), and the projected radius where the spatial coverage of the SDSS DR5 spectroscopic survey provides complete spatial coverage. For several groups, the caustic pattern disappears beyond the projected radius because of this edge effect. Figures 2 and 3 show the infall patterns for the 400d-SDSS sample.

Figure 2 shows the redshift–radius diagrams for all groups in the 400d-SDSS sample. The caustic pattern is evident as the trumpet-shaped regions with high density. The solid lines indicate the location of the caustics in each group. Vertical lines in each panel indicate the radial extent of the caustics. The dashed lines show the radial extent of the caustics. The top solid line shows the radial extent of the caustics. The dashed line shows the radial extent of the caustics. The solid lines show the radial extent of the caustics. The dashed line shows the radial extent of the caustics.

Figure 3 shows the redshift–radius diagrams for all groups in the 400d-SDSS sample. The caustic pattern is evident as the trumpet-shaped regions with high density. The solid lines indicate the location of the caustics in each group. Vertical lines in each panel indicate the radial extent of the caustics. The dashed lines show the radial extent of the caustics. The top solid line shows the radial extent of the caustics. The dashed line shows the radial extent of the caustics. The solid lines show the radial extent of the caustics. The dashed line shows the radial extent of the caustics.
We attempt to quantify this difference more robustly by defining a simple statistic to quantify the contrast of the infall pattern with respect to the local background. We define the contrast $C_{200}$ to be the ratio of the number of galaxies within projected radius $r_{200}$ within the caustics $N_{\text{mem}}$ to the number of “near-background” galaxies $N_{\text{bkgd}}$, those within $\pm 5\sigma_{200}$ of the cluster redshift but outside the caustics. The radius $r_{200}$ is determined from the caustic mass profile (see below) and $\sigma_{200}$ is the projected velocity dispersion of galaxies within the caustics and within the projected radius $r_{200}$. Using this definition of contrast, there is no significant correlation of $C_{200}$ with mass for the CIRS clusters. Further, there is no significant difference between the distributions of the $C_{200}$ statistic between the 400d-SDSS (excluding the four problematic groups) and CIRS samples (the samples differ at 59% confidence using a Kolmogorov–Smirnov $D$-statistic test, K–S test).

This result suggests that any difference between the contrasts of the two samples is too subtle for our simple contrast statistic. We caution the reader that this contrast statistic is not well tested and may have subtle dependences on the caustic method used to define membership. It does provide a simple, quantitative way of comparing the 400d-SDSS sample to the CIRS sample.

We discuss the individual groups in more detail in Section 3.3.

### 3.2. Caustics and Mass Profiles

CAIRNS and CIRS showed that caustic masses of clusters agree well with mass estimates from both X-ray observations and Jeans’ analysis at small radii, where dynamical equilibrium is expected to hold (Rines et al. 2003, CIRS). Łokas & Mamon (2005) showed that caustic masses of clusters agree with weak lensing masses in three clusters at moderate redshift.

![Figure 3. See Figure 2.](image-url)
We briefly review the method DG and D99 developed to estimate the mass profile of a galaxy cluster by identifying caustics in redshift space. The method assumes that clusters form in a hierarchical process. Application of the method requires only galaxy redshifts and sky coordinates. Toy models of simple hierarchical process. Application of the method requires only galaxy redshifts and sky coordinates. Toy models of simple spherical infall onto clusters produce sharp enhancements in the phase space density around the system. These enhancements, known as caustics, appear as a trumpet shape in scatter plots of redshift versus projected clustercentric radius (Kaiser 1987). DG and D99 show that random motions smooth out the sharp pattern expected from simple spherical infall into a dense envelope in the redshift-projected radius diagram (see also Vedel & Hartwick 1998). The edges of this envelope can be interpreted as the escape velocity as a function of radius. Galaxies outside the caustics are also outside the turnaround radius. The caustic technique provides a well-defined boundary between the infall region and interlopers; one may think of the technique as a method for defining membership that gives the cluster mass profile as a byproduct. In fact, the caustic technique can be used as a membership classification for any gravitationally bound system. For instance, Serra et al. (2009) used caustics to identify interloper stars in five dwarf spheroidal galaxies, and Brown et al. (2010) use caustics to identify stars not bound to the Milky Way.

Operationally, we identify the caustics as curves which delineate a significant decrease in the phase space density of galaxies in the projected radius–redshift diagram. The details of the caustic technique used here are identical to those described in CIRS, with the following exception. Because 400d-SDSS groups are expected to be less massive than CIRS clusters, we isolate the groups initially by studying only galaxies within $R_p \leq 7h^{-1}\text{Mpc}$ and $\pm4000\text{\,km\,s}^{-1}$ of the nominal group centers from the X-ray catalogs (compared to $10h^{-1}\text{Mpc}$ and $\pm5000\text{\,km\,s}^{-1}$ for the CIRS clusters). We perform a hierarchical structure analysis to locate the centroid of the largest system in each volume. This analysis sometimes finds the center of another system in the field. In these cases, limiting the galaxies to a smaller radial and/or redshift range enables the algorithm to center on the desired group. For some groups, no satisfactory match between the hierarchical center and X-ray center is possible; for these groups we impose the X-ray center on the analysis. Table 2 lists the hierarchical centers (sky coordinates and redshift) and indicates which center is used in plotting the redshift diagrams (Figures 2 and 3) and computing the caustic mass profiles.

We discuss the groups individually in Section 3.3. Figures 2 and 3 show the caustics and Figures 4 and 5 show the associated mass profiles. Note that the caustics extend to different radii for different groups. D99 shows that the appearance of the caustics depends strongly on the line of sight; projection effects can therefore account for most of the differences in profile shape in Figures 2 and 3 without invoking non-homology among clusters. We use the caustics to determine group membership. Here, the term “group member” refers to galaxies both in the virial region and in the infall region and inside the caustics. Figures 2 and 3 show that the caustics effectively separate group members from background and foreground galaxies, although some interlopers may lie within the caustics. Note that, for some groups, the small samples of galaxies yield unrealistically low estimates of the uncertainties in the caustic mass profiles.

The D99 algorithm we use to identify the caustics generally agrees with the lines one would draw based on a visual impression. This consistency suggests that systematic uncertainties in the caustic technique are dominated by projection effects rather than the details of the algorithm. We now discuss the individual groups in more detail.

### 3.3. Comments on Individual Groups

Groups share many common features, but each system is unique. We describe the most relevant aspects of each 400d-SDSS group below.

**cl0810+4216.** The X-ray emission is centered on a $r = 14.2$ ($M_r \approx 22.3$) galaxy. The hierarchical center is located at the position of a strongly bound galaxy pair $387h^{-1}\text{kpc}$ to the NE. The X-ray center corresponds to the position of the brightest...
Figure 4. Comparison of caustic mass profiles to those estimated from the virial theorem and the projected mass estimator. The thick solid lines show the caustic mass profiles and the thin lines show the $1\sigma$ uncertainties in the mass profiles (for some systems, the thin lines blend with the thick lines). The axes are identical in all panels. The vertical bars indicate $r_{200}$ and the maximum radius of the caustic mass profile (the smaller of $r_{\text{max}}$, the extent of the infall pattern, and $r_t$, the turnaround radius). Vertical dashed lines indicate $r_t$ for groups where the infall pattern truncates before $r_t$. Red and green (dark gray and light gray in the printed version) shaded regions show the formal $1\sigma$ uncertainties in the virial and projected mass profiles. Squares around group names indicate groups with contamination from nearby groups or clusters (see Section 3.3). Figure 5 shows similar plots for the rest of the sample.

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

Figure 5. See Figure 4.

(A color version of this figure is available in the online journal.)
Group Galaxy (BGG) and is probably the dynamical center of this system. The infall diagram produced when adopting the X-ray center as the system center suggests that four sub-$L^*$ galaxies have slightly higher redshifts than the bulk of the group members. Excluding these galaxies from the caustic-selected sample would reduce the inferred velocity dispersion by $\sim 20\%$. The caustic technique classifies these four galaxies as members using either the X-ray or the hierarchical center.

c10820+5645. The X-ray emission is centered on a pair of interacting galaxies with $r = 15.7$ and $r = 16.0$. A plot of group members on the sky reveals two main clumps of galaxies, one on the X-ray center and the other approximately centered on a $r = 14.6$ galaxy (MCG +09-14-024) without a redshift. This system is possibly a group–group merger.

c10900+3920. The X-ray emission is centered $<1'$ from a pair of galaxies with $r = 15.9$ and $r = 17.1$. The BGG ($r = 15.4$) lies $\sim 4'$ north of the X-ray center.

c11010+5430. The X-ray emission is centered on a $r = 14.2$ galaxy, UGC 06057. This galaxy has no SDSS redshift, but a redshift from Carballo et al. (1995) places it in the group.

c11033+5703. The X-ray emission is centered on a $r = 14.2$ galaxy. The spatial distribution of galaxies near this group shows that the X-ray group is located $\sim 800 h^{-1}$ kpc from a group of galaxies at the same redshift centered on CGCG 290–048 ($r = 13.5$), a radio galaxy with a jet $1.3 h^{-1}$ Mpc in extent (Masson 1979). The 400d ROSAT pointing does not include the CGCG 290–048 group, but it has been classified as an optically selected group by Miller et al. (2005) and Merchán & Zandivárez (2005). The dynamics of c11033+5703 are probably perturbed by the proximity of the CGCG 290–048 group (for an analogous configuration, see A2197E/W and A2199, Rines et al. 2002). Indeed, the CGCG 290–048 group displays a more symmetric infall pattern than does c11033+5703, suggesting that the former system dominates the dynamics of the two systems.

c11039+3947. The X-ray emission is approximately centered on a $r = 15.0$ galaxy. A bright ($r = 15.2$) spiral galaxy with several fainter companions lies about $2 h^{-1}$ Mpc NW of the group center. This latter system may be an infalling group.

c11058+0136. The X-ray emission is centered on UGC 06057, a $r = 13.5$ galaxy without a SDSS redshift but confirmed as a group member using a redshift from Smith et al. (2000). This group is 6.6 from the optical position of Abell 1139 (Abell et al. 1989) and previously has been identified with A1139 by Ebeling et al. (1998) and Böhmer et al. (2000).

c11159+5531. The X-ray emission is centered on a $r = 14.1$ ($M_r \approx -23.0$) galaxy. This group was classified as an X-ray overluminous elliptical galaxy (OLEG) by Vikhlinin et al. (1999).

c11227+0858. The X-ray emission is centered on a $r = 15.0$ galaxy without a SDSS redshift. A redshift from Slänglend et al. (1998) shows this galaxy to be a member. The group lies $\sim 0.7 h^{-1}$ Mpc from the Brightest Cluster Galaxy (BCG) of Abell 1541, a cluster at the same redshift. The hierarchical center is coincident with the core of A1541, so we instead use the X-ray center to estimate the caustics. Böhmer et al. (2000) report an X-ray flux of $(2.5 \pm 0.5) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ for A1541, $\sim 6$ times larger than the flux from c11227+0858. This difference suggests that A1541 dominates the dynamics of c11227+0858 (see c11033+5703 above). The dynamical parameters reported for c11227+0858 thus partially reflect the properties of A1541, a more massive and more X-ray luminous system. Consistent with this idea, seven galaxies within $0.4 h^{-1}$ Mpc of the X-ray center have a velocity dispersion $(594^{+252}_{-135})$ km s$^{-1}$) $20\%$ smaller than the value reported in Table 1; at slightly larger radii there is a large spike in redshift space due to A1541 (Figure 3).

c11236+1240. This extended X-ray source is approximately centered on IC 3574, a $r = 14.1$ ($M_r \approx -22.4$) galaxy at $z = 0.067$ (Burenin et al. 2007, no SDSS spectrum available). SDSS spectra, however, show that there are 15 galaxies at $z \approx 0.044$ within $0.5 h^{-1}$ Mpc of the X-ray center, while there are no other galaxies within this radius at $z \approx 0.067$. The brightest of these galaxies is $r = 15.5$ ($M_r \approx -20.2$). The X-ray emission is therefore associated with a single bright galaxy (similar to a fossil group, although most fossil groups do contain faint galaxies at the same redshift) or with a group of less luminous galaxies (or some combination). We adopt the latter interpretation that c11236+1240 is associated with the group of less luminous galaxies.

c11329+1143. The X-ray emission is centered between NGC 5179 ($r = 13.3$) and NGC 5171 ($r = 12.9$). The latter has no SDSS spectrum, but a redshift from Falco et al. (1999) places NGC 5171 in the group. This group is also known as MKW 11 and its infall region was previously analyzed in CIRS. Note that the X-ray flux from the 400d catalog $(1.3 \pm 0.2) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ is significantly smaller than the flux from RASS data Böhringer et al. (2000) used in CIRS $(5.7 \pm 0.8) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$. The smaller flux from the 400d catalog would place this system below the flux limit used in CIRS. Osmond et al. (2004) analyze an XMM-Newton observation of this group and determine a flux of $(2.5 \pm 0.4) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ in the $(0.5$–$2.0$ keV) band, intermediate between the RASS and 400d values. A possible explanation of the varying flux estimates is that a background group southeast of NGC 5171 (centered on a red galaxy with SDSS photometric redshift $z = 0.21 \pm 0.01$) may have been included in the RASS flux, while the 400d flux may exclude some emission associated with group members. Osmond et al. (2004) further find evidence for interactions between the group members NGC 5171 and NGC 5176 and the surrounding gas. We find a slightly smaller velocity dispersion $(363^{+30}_{-33}$ km s$^{-1}$) than do Osmond & Ponman (2004, $494 \pm 99$ km s$^{-1}$), who noted that their value of $\sigma_p$ was larger than expected based on the measured $T_X = 0.96 \pm 0.04$ keV. Our smaller value of $\sigma_p$ mitigates this discrepancy. The NGC 5129 X-ray group lies $\sim 3 h^{-1}$ Mpc northeast of c11329+1143 at a similar redshift; it is possible that these groups are physically associated.

c11343+5546. The X-ray emission is centered on a $r = 15.8$ galaxy. The group is located $11.4 \approx 500 h^{-1}$ kpc from the optical center of A1783. The hierarchical center is coincident with the core of A1783, so we instead force the algorithm to use the X-ray spatial center and the hierarchical redshift center, similar to the treatment of c11227+0858/A1541 above. Similarly, there is a noticeable spike in redshift space at the radius of A1783. The reported dynamical properties of c11343+5546 thus partially reflect those of A1783. Ledlow et al. (2003) report an X-ray flux of $(0.51 \pm 0.12) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ for A1783, $\sim 2.5$ times larger than the flux of c11343+5546. The galaxy distribution in A1783 exhibits significant substructure, perhaps indicating that the cluster is not yet relaxed.

c11533+3108. The X-ray emission is centered on a $r = 15.3$ galaxy possibly undergoing a merger with $r = 16.7$ galaxy;
no redshift available from either SDSS or the literature. Additional redshifts, especially for these groups, are needed to confirm the nature of the system.

c12137+0026. The X-ray emission is centered between a $r = 14.3$ early-type galaxy and a $r = 14.4$ spiral galaxy. Both are group members, although the early-type galaxy has no SDSS spectrum (Falco et al. 1999).

### 3.4. Virial and Turnaround Masses and Radii

The caustic mass profiles allow direct estimates of the virial and turnaround radius in each group. For the virial radius, we estimate $r_{200}$ ($r_{\Delta}$ is the radius within which the enclosed average mass density is $\Delta\rho_c$, where $\rho_c$ is the critical density) by computing the enclosed density profile $[\rho(<r) = 3M(<r)/4\pi r^3]$; $r_{200}$ is the radius which satisfies $\rho(< r_{200}) = 200\rho_c$. In our adopted cosmology, a system should be virialized inside the slightly larger radius $\sim r_{100} \approx 1.3r_{200}$ (Eke et al. 1996). We use $r_{200}$ because it is more commonly used in the literature and thus allows easier comparison of results. For the turnaround radius $r_t$, we use Equation (8) of Regos & Geller (1989) assuming $\Omega_n = 0.3$. For this value of $\Omega_n$, the enclosed density is $3.5\rho_c$ at the turnaround radius. Varying $\Omega_n$ in the range 0.02–1 only changes the inferred value of $r_t$ by $\pm 10\%$; the uncertainties in $r_t$ from the uncertainties in the mass profile are comparable or larger (D99; Rines et al. 2002). If the $w$ parameter in the equation of state of the dark energy ($P_\Lambda = w\rho_\Lambda$) satisfies $w \geq -1$, the dark energy has little effect on the turnaround overdensity (Gramann & Suhhonenko 2002).

Table 3 lists $r_{200}$, $r_t$, and the masses $M_{200}$ and $M_t$ enclosed within these radii. For c10820+0945, c1329+1143, and c1631+2121, the maximum extent of the caustics $r_{\Delta}$ is smaller than $r_{200}$. For these groups, $r_t$ is a minimum value assuming that there is no additional mass outside $r_{\Delta}$. The best estimate of the mass contained in infall regions clearly comes from those groups for which $r_{\Delta} \geq r_t$. The average mass within the turnaround radius for these groups is $2.5 \pm 0.4$ times the virial mass $M_{200}$, demonstrating that groups are still forming in the present epoch and consistent with the CIRS estimate of $2.19 \pm 0.18$. Similarly, the average turnaround radius is $(5.07 \pm 0.26)r_{200}$ for groups with $r_{\Delta} \geq r_t$, again in agreement with the CIRS result of $(4.96 \pm 0.08)r_{200}$. Simulations of the future growth of large-scale structure (Gramann & Suhhonenko 2002; Nagamine & Loeb 2003; Busha et al. 2003) for our assumed cosmology ($\Omega_n = 0.3, \Omega_\Lambda = 0.7$) suggest that galaxies currently inside the turnaround radius of a system will continue to be bound to that system. Our results for the turnaround radius and mass agree with the predictions of Busha et al. (2005), who find that the ultimate mass of dark matter halos in simulations is $1.9M_{200}$. The agreement between the estimates of $M_t/M_{200}$ and $r_t/r_{200}$ between the CIRS and 400d-SDSS samples suggests that the overall shapes of cluster mass profiles into their infall regions are not strongly dependent on cluster mass into the group regime. We compare the virial masses $M_{200}$ from the caustics with masses calculated using the virial theorem in Section 3.5.

### Table 3

| Group            | $r_{200}$  | $r_{200}$  | $r_t$    | $r_{max}$  | $M_{200}$  | $M_t$  | $M_t/M_{200}$ |
|------------------|------------|------------|----------|------------|------------|--------|---------------|
|                  | (h^-1 Mpc) | (h^-1 Mpc) | (h^-1 Mpc)| (h^-1 Mpc) | (10^{14} M⊙)| (10^{14} M⊙)|               |
| c10810+4216      | 0.52       | 0.83       | 4.05     | 9.49       | 1.32 ± 0.05 | 2.70 ± 0.14 | 2.05          |
|                  | 0.67       | 1.09       | 4.55     | 9.39       | 3.03 ± 0.02 | 3.84 ± 0.02 | 1.27          |
|                  | 0.35       | 0.58       | 4.17     | 9.19       | 0.45 ± 0.06 | 2.95 ± 0.48 | 6.58          |
|                  | 0.20       | 0.42       | 2.66     | 9.80       | 0.17 ± 0.04 | 0.77 ± 0.25 | 4.45          |
|                  | 0.38       | 0.60       | 3.14     | 9.60       | 0.51 ± 0.02 | 1.26 ± 0.06 | 2.48          |
|                  | 0.29       | 0.45       | 2.08     | 3.64       | 0.21 ± 0.04 | 0.37 ± 0.08 | 1.74          |
|                  | 0.51       | 0.86       | 4.17     | >10        | 1.51 ± 0.00 | 2.96 ± 0.00 | 1.96          |
|                  | 0.39       | 0.63       | 2.86     | 9.29       | 0.57 ± 0.00 | 0.95 ± 0.00 | 1.67          |
|                  | 0.56       | 0.97       | 4.09     | 4.34       | 2.13 ± 0.83 | 2.79 ± 1.16 | 1.31          |
|                  | 0.49       | 0.71       | 2.88     | 9.70       | 0.84 ± 0.00 | 0.97 ± 0.00 | 1.16          |
|                  | 0.40       | 0.59       | >2.66    | 1.82       | 0.48±0.00   | 0.77 ± 0.00 | 1.58          |
|                  | 0.39       | 0.76       | 4.56     | 9.60       | 1.03 ± 0.01 | 3.85 ± 0.04 | 3.74          |
|                  | 0.32       | 0.54       | 2.50     | 2.63       | 0.36 ± 0.23 | 0.64 ± 0.47 | 1.76          |
|                  | 0.52       | 0.76       | 3.12     | 9.09       | 1.03 ± 0.18 | 1.24 ± 0.23 | 1.20          |
|                  | 0.40       | 0.60       | 2.72     | 1.82       | 0.49 ± 0.39 | 0.82 ± 0.71 | 1.67          |
|                  | 0.35       | 0.51       | 2.67     | 8.99       | 0.32 ± 0.01 | 0.78 ± 0.05 | 2.45          |

Notes. Columns 1–3 list $r_t$ for three values of overdensity $\delta$, where $r_t$ is the radius within which the enclosed mass density is $\delta$ times the critical density (we adopt $\delta = 3.5$ as the turnaround overdensity). Column 4 gives the turnaround radius $r_t$ for each group. Column 5 gives the maximum radius $r_{max}$ within which the caustics are detected. Note that when $r_{max} < r_t$, the estimate of $r_t$ is an underestimate if any mass lies between $r_{max}$ and $r_t$.

a Strongly affected by a nearby group or cluster. See Section 3.3 for details.
Table 4
400d-SDSS Virial and Projected Masses

| Group       | \(r_{200}\) (kpc) | \(M_{200}\) (\(10^{14} M_\odot\)) | \(M_{proj}\) (\(10^{13} M_\odot\)) | \(M_{vir}\) (\(10^{13} M_\odot\)) |
|-------------|-----------------|-------------------------------|---------------------------------|---------------------------------|
| c0810+4216  | 0.83            | 1.32 ± 0.05                  | 0.79 ± 0.19                     | 1.14 ± 0.17                     |
| c0820+1345a | 1.09            | 3.03 ± 0.02                  | 3.15 ± 0.65                     | 3.15 ± 0.41                     |
| c0890a+3920 | 0.58            | 0.45 ± 0.06                  | 0.21 ± 0.06                     | 0.27 ± 0.04                     |
| c1101+5430  | 0.42            | 0.17 ± 0.04                  | 0.20 ± 0.06                     | 0.12 ± 0.02                     |
| c1103a+5703 | 0.60            | 0.51 ± 0.02                  | 0.45 ± 0.14                     | 0.35 ± 0.06                     |
| c1103a+3947 | 0.45            | 0.21 ± 0.04                  | 0.08 ± 0.04                     | 0.18 ± 0.00                     |
| c1105+4016  | 0.86            | 1.51 ± 0.00                  | 1.02 ± 0.18                     | 0.76 ± 0.09                     |
| c1115+5531  | 0.63            | 0.57 ± 0.00                  | 0.24 ± 0.08                     | 0.41 ± 0.08                     |
| c1127a+0858 | 0.97            | 2.13 ± 0.83                  | 1.09 ± 0.21                     | 3.58 ± 0.45                     |
| c1123+1240  | 0.71            | 0.84 ± 0.00                  | 0.39 ± 0.16                     | 0.59 ± 0.12                     |
| c1132+1143  | 0.59            | 0.48 ± 0.00                  | 0.58 ± 0.12                     | 0.52 ± 0.07                     |
| c1134b+5546 | 0.76            | 1.03 ± 0.01                  | 0.74 ± 0.17                     | 0.60 ± 0.08                     |
| c1153+3108  | 0.54            | 0.36 ± 0.23                  | 0.46 ± 0.13                     | 0.63 ± 0.10                     |
| c1163b+2434 | 0.76            | 1.03 ± 0.18                  | 0.35 ± 0.09                     | 0.64 ± 0.10                     |
| c1163b+2121 | 0.60            | 0.49 ± 0.39                  | 0.31 ± 0.13                     | 0.97 ± 0.20                     |
| c1213+0026  | 0.51            | 0.32 ± 0.01                  | 0.07 ± 0.03                     | 0.09 ± 0.02                     |

Notes. Columns 4 and 5 give the projected and virial mass estimates for each group computed with all galaxies inside the radius \(r_{200}\) determined from the caustic mass profile.

\(^a\) Strongly affected by a nearby group or cluster. See Section 3.3 for details.

One striking result of this analysis is that the caustic pattern is often visible beyond the turnaround radius of a group (similar to some CIRS clusters). This result suggests that even groups may have strong dynamic effects on surrounding large-scale structure beyond the turnaround radius. For our assumed cosmology, this large-scale structure is probably not bound to the group.

3.5. Comparison to Virial and Projected Mass Estimates

We apply the virial mass and projected mass estimators (Heisler et al. 1985) to the 400d-SDSS groups. For the latter, we assume the galaxies are on isotropic orbits. We must define a radius of virialization within which the galaxies are relaxed. We use \(r_{200}\) (Table 3) and include only galaxies within the caustics. We thus assume that the caustics provide a good division between group galaxies and interlopers (see Figures 2 and 3). For details on these mass calculations, see CIRS. Table 4 lists the virial and projected mass estimates.

Figure 6 compares the virial and caustic mass estimates at \(r_{200}\). The mean ratios of these estimates are \(M_v/M_c = 0.91 ± 0.12\). The caustic mass estimates are consistent with virial mass estimates even assuming a correction factor \(C \approx 0.1-0.2 M_{vir}\) for the surface pressure, consistent with the best-fit NFW profiles (see also Carlberg et al. 1997; Girardi et al. 1998; Koranyi & Geller 2000; Rines et al. 2003, CIRS). Note that Lemze et al. (2009) suggest a possible modification of the form factor \(f_{20}\) used in the caustic technique based on a comparison of the caustic and lensing mass profiles of A1689. Lopes et al. (2009) find a smaller scatter in scaling relations using virial masses rather than caustic masses for the CIRS clusters.

Figures 4 and 5 compare the mass profiles estimated from the caustics, virial theorem, and projected mass estimator. The virial and projected mass profiles \(M(< R_p)\) are calculated using all galaxies within the projected radius \(R_p\) (note that the virial assumptions hold only at the virial radius). The projected mass estimator consistently overestimates the mass at small radii and underestimates the mass at large radii relative to the other profiles. This behavior suggests that this estimator is best for estimating virial masses but not mass profiles. The virial and caustic mass profiles generally agree although there are many groups with large disagreements. The caustic mass profiles do not appear to consistently overestimate or underestimate the mass relative to the virial mass profiles. This result supports our use of caustic mass profiles as a tracer of the total group mass profile in the following section.

3.6. The Shapes of Group Mass Profiles

We fit the mass profiles of the 400d-SDSS groups to three simple analytic models. The simplest model of a self-gravitating system is a singular isothermal sphere (SIS). The mass of the SIS increases linearly with radius. Navarro et al. (1997) and Hernquist (1990) propose two-parameter models based on CDM simulations of halos. We note that the caustic mass profiles mostly sample large radii and are therefore not very sensitive to the inner slope of the mass profile. Thus, we do not consider alternative models which differ only in the inner slope of the density profile (e.g., Moore et al. 1999). At large radii, the best constraints on cluster mass profiles come from galaxy dynamics and weak lensing. The caustic mass profiles of Coma (Geller et al. 1999), A576 (Rines et al. 2000), A2199 (Rines et al. 2002) and the rest of the CAIRNS and CIRS clusters (Rines et al. 2003; Rines & Diaferro 2006) provided strong evidence against a SIS profile and in favor of steeper mass density profiles predicted by Navarro et al. (1997, NFW) and Hernquist (1990). Only recently have weak lensing mass estimates been able to distinguish between SIS and NFW density profiles at large radii (Clowe & Schneider 2001; Kneib et al. 2003; Mandelbaum et al. 2006).

At large radii, the NFW mass profile increases as \(\ln(r)\) and the mass of the Hernquist model converges. The NFW mass profile is

\[
M(< r) = \frac{M(a)}{\ln(2)} - \frac{1}{2} \left[ \ln \left( 1 + \frac{r}{a} \right) - \frac{r}{a + r} \right].
\]
that the most massive quartile (ordered by mass profiles with concentration c = 3, 5, 10 from top to bottom at large radii). The short-dashed lines are Hernquist profiles with scale radii different by a factor of 2. Right: scaled caustic mass profiles for the most massive quartile (ordered by $M_{200}$) of CIRS clusters with the same model profiles.

Figure 7. Left: scaled caustic mass profiles for the 400d-SDSS groups (excluding those contaminated by nearby large-scale structure) compared to simple model profiles. The thin solid lines show the caustic mass profiles normalized by $r_{200}$ and $M_{200}$. The long-dashed line shows a SIS, the colored solid lines show NFW profiles (with concentrations $c_{200} = 3, 5, 10$ from top to bottom at large radii). The short-dashed lines are Hernquist profiles with scale radii different by a factor of 2. Right: scaled caustic mass profiles for the most massive quartile (ordered by $M_{200}$) of CIRS clusters with the same model profiles.

where $a$ is the scale radius and $M(a)$ is the mass within $a$. We fit the parameter $M(a)$ rather than the characteristic density $δ_c$ (see Navarro et al. 1997). Numerical simulations suggest that $δ_c$ should decrease slightly ($\sim 30\%$) with increasing mass over this mass range, but this decrease is comparable to the scatter in $δ_c$ in simulated strong lensing data. The concentration $c$ is much less correlated than $M(a)$ and $a$ are much less correlated than $δ_c$ and $a$ (Mahdavi et al. 1999). The Hernquist mass profile is

$$M(< r) = M \left( \frac{r}{a_H} \right)^2,$$

where $a_H$ is the scale radius and $M$ is the total mass. Note that $M(a_H) = M/4$. The SIS mass profile is $M(< r) \propto r$. We minimize $χ^2$ and list the best-fit parameters $a, r_{200}$, the concentration $c_{200} = r_{200}/a$, and $M_{200}$ for the best-fit NFW model and indicate the best-fit profile type in Table 5. We also list the parameter $c_{101} = r_{101}/a$; some authors prefer to use $r_{101}$ as the virial radius for this cosmology. We perform the fits on all data points within the maximum radial extent of the caustics $r_{max}$ listed in Table 3 and with caustic amplitude $A(r) > 100$ km s$^{-1}$.

Because the individual points in the mass profile are not independent, the absolute values of $χ^2$ are indicative only, but it is clear that the NFW and Hernquist profiles provide acceptable fits to the caustic mass profiles; the SIS is never the best-fit profile and it is actually excluded for nearly all groups. The NFW profile provides a better fit to the data than the Hernquist profile for five of the 16 400d-SDSS groups; the remaining 11 are better fit by a Hernquist profile.

Figure 7 shows the shapes of the caustic mass profiles scaled by $r_{200}$ and $M_{200}$ along with SIS, NFW, and Hernquist model profiles. The straight dashed line is the SIS, the solid lines are NFW profiles with $c_{200} = 3, 5, 10$, and the curved dashed lines are Hernquist profiles with two different scale radii. The average value of $c_{200}$ is 6.5, consistent with CIRS and with the values expected from simulations for clusters (Navarro et al. 2001). All three model profiles agree fairly well with the caustic mass profiles in the range (0.1–1)$r_{200}$. The SIS only fails beyond $\sim 1.5 r_{200}$; that is why lensing has had trouble distinguishing

| Group | $c_{200}$ | $r_{200}/a$ | $c_{101}$ | Best-fit | $c_{101}$ |
|-------|-----------|-------------|-----------|----------|-----------|
| cl0810+4216 | 0.185 | 0.79 | 4.26 | 1.14 | N | 5.75 |
| cl0820+5645 | 0.205 | 0.95 | 4.63 | 1.98 | H | 6.23 |
| cl0900+3920 | 0.590 | 0.60 | 1.02 | 0.50 | N | 1.49 |
| cl1010+5430 | 0.415 | 0.40 | 0.96 | 0.15 | H | 1.42 |
| cl1033+5703 | 0.160 | 0.61 | 3.83 | 0.53 | H | 5.19 |
| cl1039+3947 | 0.072 | 0.41 | 5.75 | 0.16 | H | 7.68 |
| cl1058+0136 | 0.297 | 0.77 | 2.59 | 1.06 | H | 3.58 |
| cl1159+5531 | 0.160 | 0.58 | 3.64 | 0.46 | H | 4.95 |
| cl1227+0858 | 0.415 | 0.75 | 1.80 | 1.01 | H | 2.59 |
| cl1236+1240 | 0.081 | 0.62 | 7.70 | 0.57 | H | 10.20 |
| cl1329+1143 | 0.064 | 0.60 | 9.32 | 0.49 | N | 12.30 |
| cl1343+5546 | 0.200 | 0.86 | 4.29 | 1.46 | N | 5.78 |
| cl1533+1108 | 0.138 | 0.48 | 3.46 | 0.25 | H | 4.71 |
| cl1630+2434 | 0.051 | 0.68 | 13.40 | 0.75 | H | 17.56 |
| cl1631+2121 | 0.092 | 0.58 | 6.32 | 0.47 | H | 8.52 |
| cl1237+0026 | 0.081 | 0.50 | 6.20 | 0.30 | N | 8.27 |

Notes. Columns 2 and 3 give the scale radius $r_{200}$ and $M_{200}$ of the best-fit NFW profile. Columns 4 and 7 give the NFW concentration parameters $c_{101} = r_{101}/a_H$, where $r_{101}$ is the radius within which the enclosed density is $δ$ times the critical density.

* Strongly affected by a nearby group or cluster. See Section 3.3 for details.

The SIS mass profile is $M(< r) = M a_H^2/r^2$. The SIS only fails beyond $\sim 1.5 r_{200}$; that is why lensing has had trouble distinguishing between SIS and NFW profiles. As discussed in D99, the caustic technique can be subject to large variations for individual groups due to projection effects. The best constraints on the shapes of cluster and group mass profiles are obtained by averaging over many lines of sight, or for real observations, over many different clusters and groups.

The concentration parameters $c_{200} = r_{200}/a$ for the NFW models are in the range 1–15 (Table 5), in good agreement with the predictions of numerical simulations (Navarro et al. 1997). Numerical simulations suggest that $c$ should decrease slightly ($\sim 30\%$) with increasing mass over this mass range, but this decrease is comparable to the scatter in $c$ in simulated
Clusters (Navarro et al. 1997; Bullock et al. 2001). The errorbars in Figure 8 indicate the average values and 1σ scatter in \( c_{101} = r_{101}/a \) in simulations (Bullock et al. 2001).

Observations of mass profiles using X-ray mass estimates (Buote et al. 2007) and weak lensing (Comerford & Natarajan 2007) appear to confirm a decrease in \( c \) with increasing mass, although some massive clusters apparently have high concentrations (e.g., Lemze et al. 2009). In contrast, the CIRS clusters showed a weak positive correlation between \( c \) and mass (Figure 8). The 400d-SDSS groups do not confirm this correlation (Figure 8). A Spearman rank-sum test indicates that there is no significant correlation between \( c_{101} \) and \( M_{101} \) for the 400d-SDSS groups. A Spearman test for the CIRS clusters suggests a correlation at the 92.8% confidence level. By combining the CIRS and 400d-SDSS data, a Spearman test indicates a correlation between concentration and mass at the 93.9% confidence level (correlation coefficient 0.20). This result indicates possible tension between caustic mass profiles and simulations, as the caustic mass profiles indicate that concentrations increase rather than decrease with increasing cluster mass. More data for groups at lower masses would help clarify the situation.

To further explore the dependence of mass profile shapes on mass, the right panel of Figure 7 shows the scaled mass profiles of the most massive quartile of CIRS clusters. Comparing the two panels reveals no obvious trend with increasing mass: the profiles of 400d-SDSS groups have larger scatter, but the average of the profiles appears similar to that of the massive CIRS clusters.

4. SCALING RELATIONS OF CLUSTERS AND GROUPS

Scaling relations between simple cluster/group observables and masses provide insight into the nature of cluster/group assembly and the properties of various cluster/group components. Establishing these relations for local clusters and groups is critical for future studies of clusters in the distant universe with the goal of constraining dark energy (Majumdar & Mohr 2004; Lin et al. 2004).

We apply the prescription of Danese et al. (1980) to determine the mean redshift \( c_{200}/a \) and projected velocity dispersion \( \sigma_p \) of each group from all galaxies within the caustics. We calculate \( \sigma_p \) using only the group members projected within \( r_{200} \) estimated from the caustic mass profile. Note that our estimates of \( r_{200} \) do not depend directly on \( \sigma_p \).

One of the simplest X-ray observables of clusters and groups is X-ray luminosity. For optical data, the projected velocity dispersion \( \sigma_p \) is a straightforward observable. In particular, Lopes et al. (2009) re-analyze the CIRS clusters and find that the velocity dispersions are robust to the particular choice of interloper removal algorithms, while their virial masses have significant scatter relative to the CIRS values (primarily due to differences in estimates of \( r_{200} \)). The \( L_X-\sigma_p \) relation is expected to have the form \( L_X \propto \sigma_p^4 \) under simple theoretical models (Quintana & Melnick 1982). For clusters, most recent estimates of the slope of this relation are consistent with a slope of 4. For galaxy groups, however, some authors find shallower slopes (Mahdavi et al. 2000; Xue & Wu 2000), while others find slopes comparable to clusters (Ponman et al. 1996; Mulchaey & Zabludoff 1998). In the Group Evolution Multiwavelength Survey (GEMS), Osmond & Ponman (2004) find a slope of 2.31 ± 0.61 for groups, but the slope for a combined sample of groups and clusters is 4.55 ± 0.25. In a similar vein, Mahdavi et al. (2000) find that the best-fit relation for a sample of groups and clusters is a broken power law with a shallower slope for groups than for clusters. Unusual systems may affect the \( L_X-\sigma_p \) relation; for instance, Helson et al. (2005) show that galaxy groups with apparently very small \( \sigma_p \) and large \( L_X \) may have larger \( \sigma_p \) than earlier estimates, bringing these groups more in line with a steeper relation. Khosroshahi et al. (2007) find that fossil groups follow a \( L_X-\sigma_p \) relation with slope 2.74 ± 0.45, shallower than clusters (they also note a tendency for fossil groups to have slightly larger \( L_X \) for a given \( \sigma_p \) than non-fossil groups). In the 400d-SDSS sample, we selected the groups based on their X-ray emission, whereas most previous studies (Ponman et al. 1996; Mulchaey & Zabludoff 1998; Mahdavi et al. 2000; Osmond & Ponman 2004) begin with catalogs of optically selected groups and then analyze either pointed X-ray observations or RASS data.

The 400d-SDSS X-ray luminosities are measured in the ROSAT band (0.1–2.4 keV) and corrected for Galactic absorption (see Burenin et al. 2007, for details). Figure 9 shows the \( L_X-\sigma_p \) relation for the CIRS clusters along with the best-fit \( L_X-\sigma_p \) relation of the RASS–SDSS (Popesso et al. 2005) and CIRS clusters, the GEMS groups, and the GEMS groups+clusters fit (Osmond & Ponman 2004). The 400d-SDSS groups roughly follow the relations of the RASS–SDSS and CIRS samples, but the scatter is large. Squares, triangles, and crosses in Figure 9 show systems from CIRS, Mahdavi et al. (2000), and Osmond & Ponman (2004), respectively. Note that the 400d observations are typically not deep enough to separate group emission from contributions from individual galaxy halos, so the X-ray luminosities are not necessarily directly comparable to those in some other studies (e.g., Mahdavi et al. 2000; Osmond & Ponman 2004). However, because the 400d-SDSS groups lie close to RASSCALS and GEMS groups, this effect is probably small.

The groups previously identified as undergoing mergers are highlighted with large circles in Figure 9. These groups are the
Figure 9. Velocity dispersions at $r_{200}$ compared to X-ray luminosities. The solid line is the bisector of the least squares fits for the CIRS clusters. The dashed lines show the $\sigma_p$–$L_X$ relations from RASS–SDSS (Popesso et al. 2005). Symbol types are explained in Figure 1; large open circles highlight groups strongly affected by nearby structures. The two arrows indicate the locations of these data points for the larger clusters located close to two of these groups (A1541 near cl1227+0858 and A1783 near cl1343+5546).

most extreme outliers from the CIRS and RASS–SDSS scaling relations and the locus of points from earlier studies. This result can be easily understood as a result of confusing an $L_X$ measured for a subcluster with the velocity dispersion $\sigma_p$ reflecting the velocity dispersion of the parent cluster. Consistent with this explanation, the arrows in Figure 9 show where cl1227+0858 (cl1343+5546) would appear if we used the X-ray luminosity of the nearby, more luminous system A1541 (A1783); both points move closer to the CIRS $L_X$–$\sigma$ relation. Note that only one of the 400d-SDSS groups (cl11159+5531) is a likely fossil group (Vikhlinin et al. 1998), so the sample is not dominated by these unusual systems. Specifically, Voevodkin et al. (2010) search for fossil groups and clusters in the 400d survey; cl11159+5531 is the only fossil group at $z<0.1$, and it only qualifies under a relaxed definition of fossil groups.

Excluding the four groups contaminated by large-scale structure, the bisector of the least-squares fits has a slope of $3.1 \pm 1.6$, intermediate between the shallow slopes found by some investigators for groups and the steeper slopes found for clusters (see Figure 9). Because the uncertainty in the slope for the 400d-SDSS groups is large, the slope is not significantly different from any of these relations.

We test the consistency of the $L_X$–$\sigma_p$ relation for 400d-SDSS groups with that of the CIRS clusters by fitting these relations for the CIRS clusters alone and for the CIRS clusters with the 400d-SDSS groups (excluding those contaminated by large-scale structure) added to the sample. For the CIRS data alone, the slope of the bisector of least-squares fits is $3.7 \pm 0.6$, and the slope for the combined CIRS and 400d-SDSS data is $4.1 \pm 0.4$.

From the limited sample, we conclude that the X-ray-selected 400d-SDSS groups have an $L_X$–$\sigma_p$ relation consistent with previous studies of both larger-mass clusters (e.g., CIRS) and smaller-mass groups (e.g., GEMS). We find no evidence of large biases in this relation between X-ray-selected and optically selected systems. An important caveat to this conclusion is that some recent studies of clusters (Popesso et al. 2007) and groups (Rasmussen et al. 2006) find that there may be some systems that are significantly “X-ray underluminous,” perhaps because these systems are dynamically young.

Figure 10 shows $L_X$ versus $M_{500}$ as estimated from the caustics for the 400d-SDSS groups. Figure 10 also shows the data from CIRS and the best-fit $M_{500}$–$L_X$ relations for CIRS (caustic masses) and RASS–SDSS (both virial masses and $T_X$-based masses, Popesso et al. 2005).

Figure 10. Left: caustic masses at $r_{500}$ compared to X-ray luminosities. The solid line is the bisector of the ordinary least squares fits to the CIRS data. The dashed and dash-dotted lines show the $M_{500}$–$L_X$ relations for RASS–SDSS (Popesso et al. 2005) for optical and X-ray masses respectively. Symbol types are explained in Figure 1; large open circles highlight groups strongly affected by nearby structures. The two arrows indicate the locations of these data points for the larger clusters located close to two of these groups (A1541 near cl1227+0858 and A1783 near cl1343+5546). Right: same for $M_{200}$–$L_X$. 
Figure 11. Caustic masses at \( r_{200} \) compared to velocity dispersions within \( r_{200} \). The solid line is the bisector of the ordinary least squares fit for the CIRS clusters. Symbol types are explained in Figure 1; large open circles highlight groups strongly affected by nearby structures. The dashed line shows the virial mass–\( \sigma_p \) relation for dark matter halos in simulations (Evrard et al. 2008).

Figure 11 shows the \( M_{200}–\sigma_p \) relation. The tight relation indicates that the caustic masses are well correlated with velocity dispersion estimates. The good correlation is perhaps not surprising because both parameters depend on the galaxy velocity distribution. The best-fit slope for the CIRS clusters is \( M_{200} \propto \sigma_p^{3.18\pm0.19} \) with the uncertainty estimated from jackknife resampling. The dashed line in Figure 11 shows the virial mass–\( \sigma_p \) relation for dark matter halos in simulations (Evrard et al. 2008, slope 3.035 \( \pm \) 0.023). The agreement between these relations from CIRS and simulations further supports the use of caustics as a mass estimator (we compare the caustic masses to virial mass estimates in Section 3.5). The four merging groups in 400d-SDSS represent the most extreme outliers from the CIRS relation. The remaining 400d-SDSS groups approximately follow the CIRS relations, but we do not attempt to fit a relation for the 400d-SDSS groups.

In the previous section, we found that many of the 400d groups are either group–group mergers (c10820+5645) or group–cluster mergers (c11033+5703, c11227+0858, c11343+5546). These groups represent the most extreme outliers in the \( L_X–\sigma_p \) relation (Figure 9) and the \( L_X–M \) relations (Figure 10). This result reinforces the idea that a detailed understanding of the large-scale structure surrounding low-mass systems is critical to obtaining accurate scaling relations. Previous studies (e.g., Helsdon & Ponman 2000; Mahdavi et al. 2000) usually exclude such systems for similar reasons.

5. DISCUSSION

We use the Fifth Data Release of the SDSS to study galaxy groups and compare their properties to more massive clusters. In particular, we study the presence of infall patterns around galaxy groups, use these patterns to measure mass profiles, and use these masses to compare the scaling relations of groups and clusters. This study extends our previous work on infall patterns around X-ray clusters in SDSS (Rines & Diaferio 2006) to smaller X-ray fluxes more typical of groups. These systems typically have smaller X-ray luminosities and masses than the systems studied in previous investigations. Despite their smaller masses (compared to CAIRNS and CIRS clusters), well-defined infall patterns are present in most of these groups. Four of the 16 groups are contaminated by large-scale structure, preventing an accurate determination of their infall patterns.

We use the infall patterns to compute mass profiles for the groups and compare them to model profiles. Group infall regions are well fit by NFW and Hernquist profiles and poorly fit by SISs, similar to the results from CAIRNS and CIRS for clusters. Observed clusters and groups resemble those in simulations, and their mass profiles are well described by extrapolations of NFW or Hernquist models out to the turnaround radius. The shapes of the best-fit NFW group mass profiles agree reasonably well with the predictions of simulations; the average concentration is \( c_{200} \approx 6.5 \), slightly smaller than the value for group size halos extrapolated from Bullock et al. (2001) and with similar scatter. These mass profiles test the shapes of dark matter haloes on a scale difficult to probe with weak lensing or any other mass estimator.

There has been much discussion of whether galaxy groups follow different scaling relations than clusters, particularly with respect to the \( L_X–\sigma_p \) relation (e.g., Mahdavi et al. 2000; Helsdon & Ponman 2000; Osmond & Ponman 2004). Using the caustics to determine group membership, velocity dispersions, and mass profiles, the 400d-SDSS groups generally follow the same scaling relations as clusters, but the small number of 400d-SDSS groups does not allow us to exclude results suggesting that groups have a shallower \( L_X–\sigma_p \) relation.

Understanding scaling relations of clusters and groups is critical for future attempts to constrain dark energy with cluster abundance measurements. Detailed mass estimates are difficult to obtain for groups and low-mass clusters because their X-ray emission is typically faint and because they contain fewer galaxies than massive clusters. This work represents part of an effort to increase the sample of groups and low-mass clusters with detailed mass estimates. Future work is needed to measure cluster scaling relations robustly across a wide mass range. In particular, deep high-resolution X-ray observations of groups like those studied here could enable measurements of group masses and X-ray temperatures, while additional optical spectroscopy could improve measurements of velocity dispersions and dynamical masses.

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