GALAXY CLUSTER ASSEMBLY AT z = 0.37

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ABSTRACT

We present X-ray and spectroscopic confirmation of a cluster assembling from multiple, distinct galaxy groups at z = 0.371. Initially detected in the Las Campanas Distant Cluster Survey, the structure contains at least four X-ray–detected groups that lie within a maximum projected separation of 4 Mpc and within Δv = 550 km s⁻¹ of one another. Using Chandra imaging and wide-field optical spectroscopy, we show that the individual groups lie on the local σ-T relation and derive a total mass of M ≥ 5 × 10¹⁴ M☉ for the entire structure. We demonstrate that the groups are gravitationally bound to one another and will merge into a single cluster with about one-third or more the mass of Coma. We also find that although the cluster is in the process of forming, the individual groups already have a higher fraction of passive members than the field. This result indicates that galaxy evolution on group scales is key to developing the early-type galaxies that dominate the cluster population by z ∼ 0.

Subject headings: galaxies: clusters: general — galaxies: evolution — X-rays: galaxies: clusters

1. INTRODUCTION

A fundamental prediction of hierarchical structure formation is that galaxy clusters assemble at late times from the merging and accreting of smaller structures (Peebles 1970). While many examples of the accretion of groups and galaxies onto massive clusters exist (e.g., Abraham et al. 1996; Hughes & Birkinshaw 1998; Tran et al. 2005), we lack clear early-stage examples of clusters being assembled from an ensemble of galaxy groups. The identification of such protoclusters is challenging because of the extensive mapping required to trace the substructure that will eventually form the cluster.

Nonetheless, detection of these rare systems is well worth the effort. They provide a detailed snapshot of the process of filamentary collapse and assembly in the quasi-linear regime and enable a direct study of a class of progenitors that does not yet include a massive cluster. The latter is particularly critical for determining if “preprocessing” in groups is responsible for the bulk of the observed differences in morphology and stellar populations between cluster and field galaxies (Zabludoff & Mulchaey 1998; Kodama et al. 2001)

We present confirmation of a protocluster identified optically in the Las Campanas Distant Cluster Survey (LCDCS; Gonzalez et al. 2001). Designed to provide a catalog of clusters at z ≈ 0.35–0.9, the LCDCS extends down to group masses at the lowest redshifts and hence can be used to identify filamentary structures at z ∼ 0.4. One such candidate structure includes four LCDCS candidates within a 3.5 radius region with estimated redshifts of z_{est} = 0.35–0.50. We demonstrate that we are witnessing the assembly of a cluster from what can be described in analogy to superclusters as a “supergroup.” Throughout this Letter, we use a standard cosmology (Ω_m = 0.3, Ω_Λ = 0.7, H_0 = 70 km s⁻¹).

1 Based on observations with the Chandra X-Ray Observatory, the VLT (program 072.A-0367), the Magellan Baade Telescope, and the MMT Observatory, a joint venture of the Smithsonian Astrophysical Observatory and the University of Arizona.

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2. X-RAY OBSERVATIONS WITH CHANDRA

The target field was observed with Chandra ACIS-I in “very faint” (VF) mode on 2002 March 24 (observation ID 3235) for 70.13 ks, with the detector oriented such that one LCDCS candidate was imaged in each ACIS-I chip. Data reduction was performed in the standard fashion using CIAO 3.0. The level 1 event file was reprocessed to correct for charge transfer inefficiency and to reduce the VF-mode particle background, and bad pixels and events with bad grades were removed in the standard fashion. Strong flares were removed using the lc_clean routine, written by M. Markevitch, yielding a net exposure time of 64 ks. The high-energy background in the remaining time interval is consistent with the quiescent rate from the “blank sky” background file to within 1%.

Image analysis is performed in the 0.8–3 keV band. Using wavelet detection, we identify six distinct extended sources at greater than 5σ significance (Fig. 1). Four of these sources are coincident to within 10″ with LCDCS candidates, while the other two extended sources have no LCDCS counterparts. One of these latter two (source 5) could not have been detected by the LCDCS, because of its proximity to a bright star; the other is the faintest of the six sources and appears to be a very poor group.

Spectral analysis is performed in the 0.7–8 keV band. Temperatures are measured within 400 kpc circular apertures to maximize signal-to-noise ratio (S/N), excluding point sources, and using the appropriately normalized ACIS “blank sky” file for the background. We fit the spectra using a MEKAL model, with the absorption fixed to the Galactic value n_H = 5.13 × 10¹⁰ cm⁻² and the metal abundance fixed at Z = 0.3 (Mushotzky & Loewenstein 1997). For four of the extended sources, we fix the redshift to the median velocity of the associated galaxies (see § 3), while for LCDCS 0259 (source 2), which lies outside the spectroscopic survey region, we use the single redshift obtained for the brightest associated galaxy. The best-fit temperatures T (Table 1, with 68% uncertainties) range from 1.7 to 3 keV and are consistent with the temperatures found for groups or poor clusters similar to Virgo (Shibata et al. 2001). Only for the faintest source do we lack sufficient S/N to obtain a temperature.

6 See http://cxc.harvard.edu/cal/Acis/Cal_prods/vfbkgrnd.

7 See http://cxc.harvard.edu/ciao/threads/acisbackground.
Fig. 1.—Smoothed X-ray map (13′2 × 13′2) of the structure with point sources excised: north is up, and east is to the left. The crosses denote the locations from the LCDCS catalogs and the numeric labels correspond to the designations in Table 1. Redshifts have been obtained for sources 1–5.

3. OPTICAL SPECTROSCOPY

3.1. MMT, Magellan, and VLT Observations

To confirm that the X-ray sources are part of a larger structure, long-slit spectra of the candidate brightest group galaxies (BGGs) associated with each of the six X-ray peaks were obtained with Magellan and the MMT in 2003 February and April, respectively. Redshifts obtained for the BGGs in groups 1–5 confirm that at least four of the X-ray regions are associated with a single physical complex at $z = 0.37$. Only the BGG candidate for group 1 was found to lie at a different redshift ($z = 0.48$). These initial results motivated a more extensive spectroscopic program with the VLT.

Using VIMOS (Le Fèvre et al. 2003), we measured redshifts and determined membership for galaxies near groups 1, 3, 4, and 5; group 2 was excluded because of an interchip gap. From a $14′ \times 16′$ $R$-band image (1820 s) taken with VIMOS, we generated a catalog of $\sim 2100$ objects with $R \leq 22.5$. Our observations used three multislit masks with $1′$ wide slits and targeted 443 of these objects; each mask had a total integration time of 2400 s. While ours is a magnitude-limited survey and targets were not selected by morphology, preference was given to objects in visually overdense regions. The intermediate-resolution (MR) grism on VIMOS gave us a spectral range of 0.5–1.0 $\mu$m and spectral resolution of 12.2 $\AA$.

To reduce and extract spectra, we use a combination of IRAF routines and custom software provided by D. Kelson (Kelson 1998); a more detailed explanation of the reduction pipeline can be found in Tran et al. (2005). We use a spectrophotometric standard to correct for the telluric A and B bands and flux-calibrate the spectra.

We determined redshifts with the IRAF cross-correlation routine XCSAO (Kurtz et al. 1992). Our final redshift catalog has 413 objects, corresponding to a target success rate of 93%. The average redshift uncertainty estimated by XCSAO is $\sim 30$ km s$^{-1}$; while XCSAO tends to underestimate the errors, this problem does not affect our results.

3.2. Redshift Distribution

From spectroscopy of four of the six regions with extended X-ray emission, we identify a peak corresponding to LCDCS 0258 ($z = 0.48$, source 1) and another corresponding to three X-ray groups at $z = 0.37$, hereafter referred to as SG 1120–1202 (SG standing for supergroup). The mean redshift of the 101 galaxies belonging to SG 1120–1202 is $z = 0.3710 \pm 0.0004$. Although the members lie in multiple, distinct X-ray–bright regions and trace a large structure with a projected spatial distance of $\sim 4$ Mpc, their redshift distribution is remarkably narrow (Fig. 2 and Table 1) and their velocity dispersion surprisingly small ($\sigma = 616 \pm 50$ km s$^{-1}$). The mean redshift, velocity dispersion, and associated errors are determined using the biweight and jackknife methods (Beers et al. 1990). To compare the dynamics of the three X-ray groups with each other, members of each group are selected as galaxies that lie within 500 kpc of their respective X-ray peaks. The redshift distributions of the three groups are shown in Figure 2, and their velocity dispersions are listed in Table 1.

3.3. Spectral Populations in SG 1120–1202

To quantify the recent star formation histories of galaxies in SG 1120–1202, we separate the members by [O ii] equivalent width into absorption-line ([O ii] $\lambda 3727 < 5$ Å; “passive”) and emission-line ([O ii] $\lambda 3727 \geq 5$ Å; “active”) galaxies. We use the same bandpasses as in Fisher et al. (1998) to measure the [O ii] doublet, and our wavelength coverage includes the [O ii] doublet for 95 of the 101 confirmed members.

Table 1

| Group Sample | ID | $\alpha$ (J2000) | $\delta$ (J2000) | LCDCS ID | $z$ | $T$ (keV) | $\sigma$ (km s$^{-1}$) | $N_g$ |
|-------------|----|-----------------|-----------------|---------|----|---------|----------------|----|
| 1           | 1  | 11 19 55.2      | $-12$ 02 28     | 0258    | 0.4794 | $2.3^{+0.4}_{-0.4}$ | 820 \pm 101 | 17 |
| 2           | 2  | 11 20 07.6      | $-12$ 05 13     | 0259    | 0.3707 | $2.2^{+0.4}_{-0.4}$ | ...           | 1  |
| 3           | 3  | 11 20 13.2      | $-11$ 58 44     | 0260    | 0.3704 | $1.7^{+0.3}_{-0.3}$ | 369 \pm 76  | 17 |
| 4           | 4  | 11 20 22.3      | $-12$ 01 45     | 0264    | 0.3713 | $1.8^{+0.3}_{-0.3}$ | 446 \pm 83  | 22 |
| 5           | 5  | 11 20 10.0      | $-12$ 08 50     | ...     | 0.3688 | $3.0^{+0.3}_{-0.3}$ | 557 \pm 93  | 11 |
| 6           | 6  | 11 20 15.6      | $-11$ 56 03     | ...     | ...   | ...     | ...           | ... |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$N_g$ Number of galaxies used to calculate the mean redshift and velocity dispersion.

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The fraction of passive galaxies in SG 1120–1202 is 61% ± 8%. This fraction is less than in CI 1358+62 (81% ± 6%), a more massive cluster at comparable redshift (\(z = 0.33, \sigma = 1027 \text{ km s}^{-1}\); Fisher et al. 1998), but twice as high as the field value (27% ± 4% at 0.2 < \(z < 0.5\); Tran et al. 2004). The passive galaxy fraction in SG 1120–1202 most closely resembles that found in X-ray–luminous groups in the nearby universe (69% ± 7%; Tran et al. 2001). Direct comparison with these other samples is valid because all four are magnitude selected and use the same [O ii] selection criteria.

4. CLUSTER ASSEMBLY

SG 1120–1202’s extended, roughly linear geometry is seen in both its X-ray emission and the spatial distribution of its galaxies. Coupled with the small dispersion in the mean group redshifts (\(\Delta z = 0.0025\)) and visible signs of interaction in the X-ray map (groups 2+5 and 3+6), this geometry argues that we are witnessing the initial stages of filamentary collapse and the formation of a more massive cluster. To test this hypothesis, we estimate SG 1120–1202’s total mass, assess the probability that the system is bound, and estimate the dynamical timescale for the system to merge. We include groups 2–5 in this analysis; we are confident that group 2 is part of the complex despite having only one redshift, both because the redshift is for the BGG (a 3\(L_{\odot}\) elliptical galaxy within 3’ of the X-ray peak) and because asymmetry in the X-ray map indicates that groups 2 and 5 are interacting.

4.1. Total Mass

Given the consistency of the groups with the local \(\sigma-T\) relation (Fig. 3), we assume hydrostatic equilibrium and use the local mass-temperature (\(M-T\)) relation of Shimizu et al. (2003, eq. [16]) to estimate the masses of the individual groups.\(^6\) The four spectroscopically confirmed groups at \(z = 0.37\) have \(T = 1.7–3\) keV, yielding a combined mass of \(M = 5.3^{+1.4}_{-1.2} \times 10^{14} \text{M}_\odot\). This mass is a lower limit on the total mass of the system because it does not include group 6, groups that may lie outside the Chandra field, or material in filaments between groups. It is equivalent to that of a single cluster with \(T = 5\) keV, and at least a third the mass of the Coma Cluster (Hughes 1989; Honda et al. 1996).

4.2. Dynamical State

That the individual groups in SG 1120–1202 lie on the local \(\sigma-T\) relation argues that each group is approximately virialized and that, if the larger structure is bound, the groups are infalling for the first time. We perform a simple dynamical analysis to assess the likelihood that the SG 1120–1202 complex is indeed gravitationally bound.

The individual groups will be bound to the larger system if

\[
\frac{GM}{R_i (\sin i)} \geq \frac{v_{pec}^2}{2},
\]

where \(M\) is the total mass, \(v_{pec}\) is the pairwise peculiar velocity for groups, \(R_i\) is the projected distance between the groups, and \(i\) is the opening angle. We assume the local value of \(v_{pec}\) = 325 ± 175 km s\(^{-1}\) from Padilla et al. (2001) and conser-
vatively take $R_p = 3$ Mpc; this value corresponds to the largest separation between the X-ray groups.

Using our X-ray estimate of the total mass, the above inequality holds for $i \approx 4^\circ$. Geometrically, the probability is $99.5\%$ that the opening angle is at least this large. Even assuming $v_{pec} = 500$ km s$^{-1}$ (1 $\sigma$ above the mean value from Padilla et al. 2001), the inequality holds for $i \approx 10^\circ$ and the probability that the groups are bound remains high (97%).

The above analysis indicates that an unbound system is unlikely, but it does not conclusively eliminate the possibility. We can strengthen the constraint by exploring the implications of an unbound system. For $i \approx 10^\circ$, the groups are separated by $\approx 20$ Mpc, and the corresponding Hubble flow redshift offset is $(\Delta z_H) \approx 0.0075$ (2250 km s$^{-1}$). In this case, $(\Delta z_H)$ is a factor of 3 greater than the observed maximum redshift separation between the groups. Thus, relative peculiar velocities of $\approx 1500$ km s$^{-1}$ would be required to counterbalance the Hubble flow and explain the small observed redshift separation; this is an implausibly large value if the groups are truly separated by $\approx 20$ Mpc and not infalling.

We conclude that the groups in SG 1120–1202 are bound to each other. The dynamical time for this system is

$$t_{dyn} \approx \frac{R}{\sqrt{GM}} \approx 1.2 (\sin i)^{-3/2} \text{Gyr},$$

for $R_e = 1.5$ Mpc and $M = 5 \times 10^{14} M_{\odot}$. For $i \approx 26^\circ$, $t_{dyn}$ is less than the look-back time.

An alternative treatment is to assume that the groups are bound and on radial orbits that have not yet crossed the center of the potential and to use the timing argument (Kahn & Woltjer 1959) to determine their line-of-sight distance by fitting the projected separation and radial velocity in the center-of-mass frame. For the four groups, we find solutions with line-of-sight distances from the center of mass between 7.5 and 10 Mpc. These solutions have $11^\circ < i < 27^\circ$ and hence suggest that the complete collapse of the system will occur after the current time. The main conclusion from this analysis is that a bound solution exists with the measured masses that can reproduce the positions and radial velocities of the groups. Detailed descriptions of the orbits and future merger history require more information.

5. CONCLUSIONS

Our observations confirm that SG 1120–1202 is a proto-cluster being built up by the assembly of multiple galaxy groups. From deep Chandra imaging and optical spectroscopy, we find that SG 1120–1202 contains a minimum of four X-ray–luminous groups at $z = 0.371$ within a projected 4 Mpc of one another. The groups have X-ray temperatures of $T = 1.7$–3 keV and their mean redshifts span a narrow range of $\Delta z = 0.0025$ (550 km s$^{-1}$). The group velocity dispersions and X-ray temperatures fall on the local $\sigma$-$T$ relation, indicating that they are each virialized systems with a combined mass $M \geq 5 \times 10^{14} M_{\odot}$. Using dynamical arguments, we demonstrate that the X-ray groups are gravitationally bound to one another and should merge into a single cluster; the resulting cluster will have about one-third or more the mass of Coma.

While SG 1120–1202 represents only one of a variety of accretion histories that can yield a moderate-mass cluster at $z = 0$, this assembly path—the late merging of multiple, roughly equal-mass subhalos—is of particular interest. SG 1120–1202 provides a unique laboratory for assessing the impact of local density upon the evolution of member galaxies, and for quantifying the degree to which the group environment acts to “pre-process” galaxies prior to cluster assembly. Already we see that the individual groups have twice as many passive galaxies as the field, indicating that galaxy evolution on group scales is key to developing the early-type galaxies that dominate the cluster population by $z \approx 0$.

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