Chandra X-ray Observations of Newly Discovered, $z \sim 1$ Clusters from the Red-Sequence Cluster Survey ⋆

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Abstract

Observational studies of cluster evolution over moderate redshift ranges (to $z \sim 1$) are a powerful tool for constraining cosmological parameters, yet a comprehensive knowledge of the properties of these clusters has been hitherto unattained. Using a highly efficient optical selection technique, the Red-Sequence Cluster Survey (RCS) has unearthed a large sample of high redshift cluster candidates. All six of the clusters from this sample which have been observed with the Chandra X-Ray Observatory were detected in the X-ray. These Chandra follow-up observations ($0.64 < z < 1.0$) indicate that the clusters are systematically less luminous than their similarly rich, X-ray selected counterparts at lower redshifts, though they are consistent with standard $L_x - T_x$ relationships. Comparisons with X-ray selected samples suggest that the discrepancy may be due in part to systematic differences in the spatial structure of the X-ray emitting gas. Our initial results from Chandra follow-up observations of six RCS clusters are presented, including β model parameters and spectral information.

Key words: Galaxy groups, clusters, and superclusters; large scale structure of the Universe, Galaxy clusters, X-ray sources, Observational cosmology
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1 The RCS Survey

The Red-Sequence Cluster Survey (Gladders and Yee, 2004) is a 90 square degree optical survey performed at CFHT and CTIO using R_C and z' filters. It utilizes the red sequence of elliptical galaxies to find galactic overdensities on the sky (Gladders and Yee, 2000). The color information also guards against projection effects, and provides photometric redshift estimates. The survey has identified between 3500 and 4000 clusters total (in the redshift range $0.2 < z < 1.2$), over 1500 of which are at least as optically rich as Abell class 0 clusters (Gladders and Yee, 2004). Simulations indicate that the survey is complete to Abell Class 1 at a redshift of 1 for blue fractions less than 0.45, and that false detection rates are less than 5%, which is significantly lower than that of single-passband optical cluster surveys (Postman et al., 1996; Donahue et al., 2002; Gilbank et al., 2004). Figure 1 shows an example of a z=0.773 RCS cluster.

2 The Chandra Subsample

So far we have observed six high redshift ($0.64 < z < 1.0$) cluster candidates with the Chandra X-ray Observatory. Table 1 lists our current sample of follow-up observations. All six clusters were detected in the X-ray, using the CIAO tool csmooth, to better than 3σ. The X-ray centroids of these clusters were all found within 10 arcseconds of their respective optical centers.

Spectra were extracted from 300 kpc (ΛCDM with $\mathrm{H_0} = 70$, $\Omega_\mathrm{m} = 0.3$, and $\Omega_\Lambda = 0.7$) radius regions around the X-ray centroids of these clusters, with backgrounds taken from each respective aimpoint chip. The spectra were fit in XSPEC using absorbed single temperature models with galactic column densities and abundances fixed at 0.3 solar. Five of the six observations yielded enough counts to constrain a temperature. Results are listed in Table 2.

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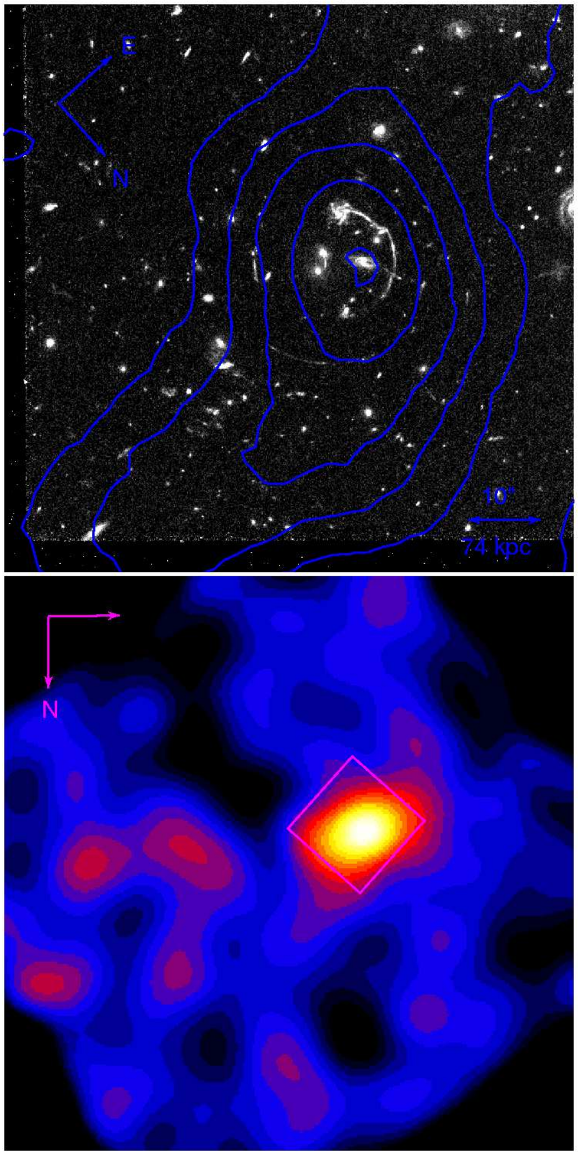

Fig. 1. Top: HST image of RCS 0224-0002 spectroscopically confirmed at z=0.773, with overlayed X-ray contours. The outer gravitational lensing arc has been spectroscopically confirmed at a redshift of z=4.87 (Gladders, Yee, and Ellingson, 2002), with the others expected to fall within the range 1.8< z <3.6 The five linearly spaced contours indicate values between 9.4×10^{-6} and 2.1×10^{-5} counts/pix^2/cm^2 and were created using a Gaussian smoothed (5 pixel FWHM) 0.29-7.0 keV Chandra flux image. Bottom: Adaptively smoothed flux image of RCS 0224-0002 created with the CIAO tool csmooth. The boxed area indicates the region shown in the upper panel.

3 Optical and X-ray Properties

3.1 Optical Richness

B_{gc}, explained in detail in Yee and Lopez-Cruz (1999), is a parameter which describes the optical richness of a cluster of galaxies. Technically it is the galaxy-cluster spatial covariance amplitude, but in essence it is simply a measure of galaxy overdensity within a given aperture, normalized for the expected spatial distribution of galaxies in the cluster and the evolving galaxy luminosity function. All of the RCS clusters that have been observed with Chandra have richnesses that imply Abell richness classes of at least 1.

There exist a few challenges in the calculation of B_{gc} at high redshift. One is the lack of a complete knowledge of the galaxy luminosity function at these redshifts. Another is uncertainty due to cluster galaxy evolution. The latter uncertainty can be minimized by employing the parameter $B_{gc,red}$, which is essentially the same as B_{gc}, but is calculated using only galaxies in the red-sequence. Throughout this paper we will use only the parameter $B_{gc,red}$

It is expected that B_{gc} should correlate strongly with X-ray temperature for relaxed clusters, and a trend has been seen when optical richness is plotted versus temperature for moderate redshift ($z \sim 0.3$), X-ray selected clusters (Yee and Ellingson, 2003). However, the same correlation is not apparent when RCS clusters are added to the plot (Figure 3.1).

In comparison with lower redshift clusters, high redshift optically selected clusters with similar B_{gc} values appear systematically cooler and less luminous than their X-ray selected counterparts, possibly suggesting that a smaller fraction of the intra-cluster gas in these objects has collapsed and become virialized. This interpretation may seem intuitive, given that X-ray cluster surveys preferentially select more relaxed clusters with deep potential wells and oftentimes cooling cores. Our findings reinforce the need to question what defines a cluster, and whether X-ray selected clusters primarily represent a highly virialized, high X-ray luminosity tail of the cluster distribution.

3.2 X-ray Surface Brightness

A radial surface brightness profile was computed over the range 0.29-7.0 keV in circular annuli for each cluster. We were able to constrain β models for four clusters. Best fit parameters are expressed in Table 2 and an example is shown in Figure 3.2. The results of these fits are interesting in that β values seem systematically low for these clusters, with the implication that, on average,

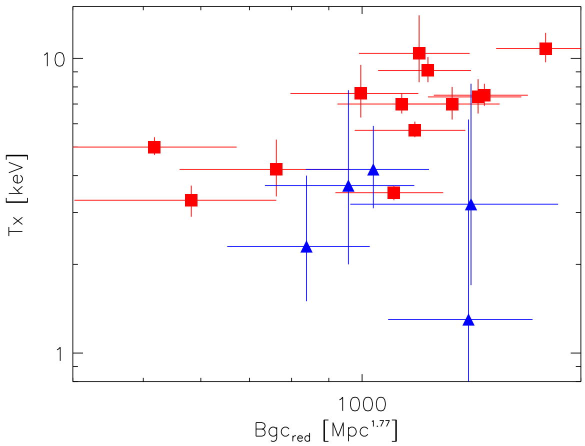

Fig. 2. T_x vs. $B_{gc,red}$. Each square represents one of 13 moderate redshift ($0.1 < z < 0.6$) CNOC clusters (Yee, Ellingson and Carlberg, 1996) taken from the Chandra archive, and triangles denote RCS clusters. Temperatures were calculated using spectra extracted within a 300 kpc (ΛCDM) radius region and fit over the 0.6-7.0 keV energy range. A single temperature model was used, with galactic absorption. The abundance of RCS clusters was fixed at 0.3. Temperature error bars show 90% confidence intervals, and $B_{gc,red}$ error bars are shown at 1σ.

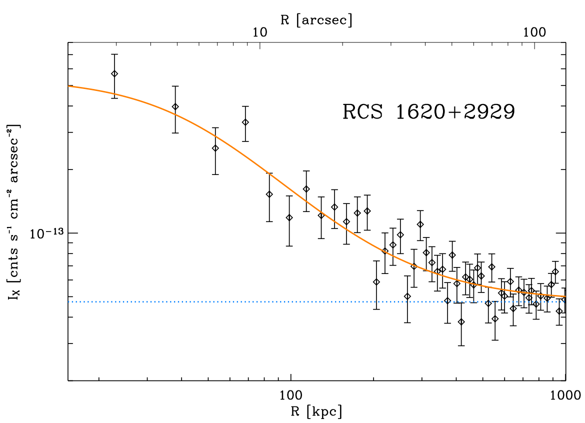

Fig. 3. Surface brightness was calculated for the 0.29-7.0 keV band in 2 arcsecond radial bins. The solid line represents the best fitting β model, and the dotted line indicates the fit-determined background value.

high redshift optically selected clusters are less centrally condensed than X-ray selected samples.

3.3 The $L_x - T_x$ Relationship

Though many of our results indicate that RCS clusters differ significantly from X-ray selected clusters, their X-ray properties are consistent with a standard $L_x - T_x$ relationship. Figure 3.3 is a plot of L_x vs. T_x for 13 CNOC and 5 RCS clusters. The consistency of RCS clusters with the $L_x - T_x$ relationship

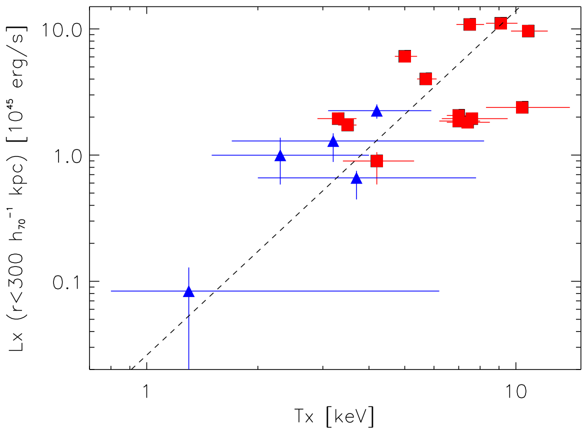

Fig. 4. L_x vs. T_x. Squares indicate 13 CNOC clusters and triangles represent the 5 RCS clusters. Unabsorbed luminosities were calculated with XSPEC and converted to bolometric X-ray luminosities with PIMMS. Temperatures were obtained with the same method as in Figure 3.1. The dashed line indicates a standard power law with slope 2.88 (Arnaud and Evrard, 1999)

of moderate redshift X-ray selected clusters implies that though RCS clusters may possess relatively low mass virialized cores of gas, the gas is in a similar physical state to that found in X-ray selected samples.

4 Summary and Discussion

The Red-Sequence Cluster Survey has uncovered a large sample of high redshift cluster candidates. All of the RCS clusters observed with Chandra were detected at greater than 3σ significance in the X-ray. This is evidence that the RCS method is a reliable way to detect high redshift clusters. The X-ray properties of RCS clusters are consistent with a standard $L_x - T_x$ relationship. This leads us to believe that the X-ray gas in these clusters is in a physical state very similar to that found in X-ray selected clusters.

The results of detailed X-ray analysis imply that though these clusters have extended structures of galaxies, they possess relatively small virialized cores. These findings are similar to those from a number of previously conducted optical surveys (Donahue et al., 2002; Lubin, Mulchaey and Postman, 2004; Gilbank et al., 2004). Optical, high redshift cluster surveys regularly find candidates with lower X-ray luminosities than those of X-ray selected clusters. Our study suggests that the RCS survey is detecting a different population of clusters from that found in X-ray selected samples, possibly including ultimately very rich clusters which are currently in the early stages of virialization. Similar objects have recently been described by Ford et al. (2004). Such systems may be expected to be more common at high redshifts in a low matter density universe. Optical surveys are much more sensitive to such systems than are X-ray surveys, especially if any related filamentary structures lie along the line of sight (though it is unlikely that all of the RCS cluster candidates that were followed-up with Chandra are associated with such structures).

Upcoming Chandra observations of five new and two previously observed RCS clusters in the next AO, along with ongoing velocity dispersion measurements and weak lensing analysis should help to provide more definitive constraints on the masses, dynamical states, and gas content of high redshift optically selected samples of galaxy clusters.

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Table 1
Chandra Observed RCS Cluster Sample

Cluster	z	Array	Exposure	Notes
RCS 0224-0002	0.77	ACIS-S	12620	gravitational lens
RCS 0439-2904	0.95	ACIS-S	77905	photometric redshift
RCS 1326+2903	0.95	ACIS-S	63590	photometric redshift
RCS 1417+5305	1.0	ACIS-I	62820	photometric redshift
RCS 1419+5326	0.64	ACIS-S	9910	gravitational lens
RCS 1620+2929	0.87	ACIS-S	36640	gravitational lens?

Table 2
Optical/X-ray Properties

Cluster	z	$B_{gc,red}$ [Mpc$^{1.77}$]	T_x [keV]	r$_c$ [arcsec]	r$_c$ [h$_{70}^{-1}$ kpc]	β
RCS 0224-0002	0.77	838^{+186}_{-186}	$2.3^{+1.7}_{-0.8}$	10^{+2}_{-2}	73^{+15}_{-12}	$0.41^{+0.07}_{-0.05}$
RCS 0439-2904	0.95	1412^{+449}_{-449}	$3.2^{+5.0}_{-1.5}$	8^{+2}_{-1}	66^{+13}_{-11}	$0.41^{+0.08}_{-0.05}$
RCS 1326+2903	0.95	1401^{+315}_{-315}	$1.3^{+4.9}_{-0.5}$	...	...	...
RCS 1417+5305	1.0	1325^{+362}_{-362}	...	...	...	...
RCS 1419+5326	0.64	1036^{+200}_{-200}	$4.2^{+1.7}_{-1.1}$	11^{+2}_{-2}	74^{+15}_{-12}	$0.67^{+0.1}_{-0.07}$
RCS 1620+2929	0.87	957^{+222}_{-222}	$3.7^{+4.1}_{-1.7}$	6^{+1}_{-1}	45^{+9}_{-8}	$0.44^{+0.07}_{-0.05}$