The X-Ray Properties of Optically Selected Clusters of Galaxies

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ABSTRACT

We present the results of Chandra and Suzaku X-ray observations of nine moderate-redshift (0.16 < z < 0.42) clusters discovered via the Red-sequence Cluster Survey (RCS). Surface brightness profiles are fitted to β-models, gas masses are determined, integrated spectra are extracted within \( R_{2500} \), and X-ray temperatures and luminosities are inferred. The \( L_X - T_X \) relationship expected from self-similar evolution is tested by comparing this sample to our previous X-ray investigation of nine high-redshift (0.6 < z < 1.0) optically selected clusters.

We find that optically selected clusters are systematically less luminous than X-ray selected clusters of similar X-ray temperature at both moderate and high \( z \). We are unable to constrain evolution in the \( L_X - T_X \) relation with these data, but find it consistent with no evolution, within relatively large uncertainties. To investigate selection effects, we compare the X-ray properties of our sample to those of clusters in the representative X-ray selected REXCESS sample, also determined within \( R_{2500} \). We find that while RCS cluster X-ray properties span the entire range of those of massive clusters selected by other methods, their average X-ray properties are most similar to those of dynamically disturbed X-ray selected clusters. This similarity suggests that the true cluster distribution might contain a higher fraction of disturbed objects than are typically detected in X-ray selected surveys.

Key words: galaxies: clusters: general – cosmology: observations – large-scale structure of Universe – X-rays: galaxies: clusters.

1 INTRODUCTION

By virtue of their size, clusters of galaxies are an important source of information about the underlying cosmology of the Universe (e.g. Allen, Evrard & Mantz 2011, and references therein). Since the advent of the first cluster survey over 50 years ago (Abell 1958), the search for these impressive objects has grown in cosmological impact, and is currently being pursued with the ultimate objective of constraining \( w \), the dark energy equation of state. Improved technology has enabled large-area cluster searches in several wavebands (e.g. X-ray, optical, millimetre, submm, radio) and out to formative redshifts. Consequently, the number of recent, underway and planned cluster surveys is staggering: Böhringer et al. 2004 (REFLEX); Valtchanov et al. 2004 (XMM-LSS); Gladders & Yee 2005 [Red-sequence Cluster Survey (RCS)]; Wester & Dark Energy Survey Collaboration 2005 (DES); Content et al. 2008 (EUCLID); Wilson et al. 2009 (SpARCS); Conconi et al. 2010 (WFXT); Vanderlinde et al. 2010 (SPT); Lloyd-Davies et al. 2011 (XCS); Marviage et al. 2011 (ACT); Planck Collaboration VIII 2011 (Planck); Predehl et al. 2011 (eROSITA); Šuhada et al. 2012 (XMM-BCS) and many more.

One overarching goal of these endeavours is to chart the evolution of the cluster mass function, thereby providing key constraints on the progression of large-scale structure formation in the Universe. Constructing a mass function requires two key elements: the ability to find clusters, and an efficient method of mass estimation. Obtaining either piece necessitates an accurate understanding

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of relationships between the observable properties of clusters (i.e. baryons) and their underlying dark matter distributions.

The baryonic mass in clusters is dominated by the hot intracluster medium (ICM), therefore some of the most powerful methods of cluster identification (X-ray, Sunyaev–Zeldovich) use the ICM to both find clusters and estimate their masses. Several processes occur within clusters; however, that can alter the physical characteristics and distribution of cluster baryons. These include feedback (e.g. Voit & Donahue 2005), mergers (e.g. Chatzikos 2012) and radiative cooling (e.g. Pratt et al. 2009), among other non-gravitational processes (e.g. Nagai 2006). Additionally, the frequency with which those processes occur may vary with redshift (e.g. Barger et al. 2005).

Understanding the gamut of ICM properties requires X-ray observations of samples chosen independently of their X-ray characteristics. This has indeed been pursued multiple times (e.g. Holden et al. 1997; Donahue et al. 2001, 2002; Basilakos et al. 2004; Gilbank et al. 2004; Popesso et al. 2004; Sánchez et al. 2005). Most of these surveys have identified a significant population of low-$L_X$ clusters. Unfortunately, there is a striking dearth of adequate X-ray data for these samples. Without convincing $L_X$ and $T_X$ measurements it is impossible to verify alternatively obtained cluster masses or investigate trends in core gas density. Due largely to this lack of quality X-ray data, concrete physical explanations for the observed scatter in cluster properties have not yet been well determined.

In our previous work (Hicks et al. 2008), we use pointed Chandra observations to compare the ICM properties of high-$z$ optically selected clusters (RCS; Gladders & Yee 2005) with those of moderate-redshift X-ray selected clusters [Canadian Network for Observational Cosmology sample (CNOC; e.g. Yee, Ellinson & Carlb erg 1996b)]. Our results indicate that the typical central ($\sim R_{2500}$, where $\rho_{\text{clust}}/\rho_{\text{crit}} = 2500$) gas mass fractions of the RCS sample are strikingly lower than those found in X-ray selected systems. This is also illustrated by discrepancies in the normalization of the $L_X$–$T_X$ relationship between the two samples. These comparisons, however, were made between clusters of differing average redshift ($z_{\text{CNOC}} \sim 0.3$, $z_{\text{RCS}} \sim 0.8$), which were gathered via significantly different means of selection, making it difficult to disentangle the effects of selection bias from possible signatures of cluster evolution.

The main objectives of this work are to isolate these potential factors from one another and identify the cause of discrepancies in ICM properties between optically and X-ray selected cluster samples. In Section 2 we introduce the present cluster sample and describe the initial processing of our Chandra and Suzaku X-ray observations. In Sections 3 and 4 we probe the surface brightness, temperature, metallicity and density of the hot ICM present in each cluster. In Section 5 we compare the ICM properties of RCS clusters to X-ray selected samples, including the REXCESS sample for which quantities have been extracted within $R_{2500}$. Finally, we compare X-ray temperature to velocity dispersion for a subset of our targets (Section 6). Our results are summarized in Section 7.

Unless otherwise noted, this paper assumes a cosmology of $\Omega_M = 0.3$, $\Omega_X = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. All errors are quoted at 68 per cent confidence levels.

## 2 CLUSTER SAMPLE AND OBSERVATIONS

In an attempt to decouple the effects of sample selection from possible redshift evolution in X-ray properties, our targets were chosen to match our X-ray selected CNOC comparison sample in both redshift and mass. Velocity dispersion was used as a mass proxy for two-thirds of our targets, and initial masses for the remaining third were estimated from cluster richness (Yee & Lopez-Cruz 1999; Gladders & Yee 2005). The ranges of redshifts and velocity dispersions spanned by our sample are $0.16 < z < 0.42$ and $70 < \sigma < 1390$ km s$^{-1}$, compared to CNOC ranges of $0.17 < z < 0.55$ and $575 < \sigma < 1330$ km s$^{-1}$. Each target was observed in the X-ray by either Chandra or Suzaku. Table 1 lists the clusters in our sample along with their redshifts, the telescope used, observation ids and exposure times.

### 2.1 Chandra initial processing

Seven of our nine targets were observed with Chandra’s ACIS-S (Advanced CCD Imaging Spectrometer) array in VFAINT mode during the period 2009 November 24–2010 August 3. The field of view of the ACIS-S aimpoint chip is $8 \times 8$ arcmin$^2$. Chandra has exceptional 0.5 arcsec spatial resolution, enabling very detailed investigations of cluster cores. The spectral resolution of ACIS is 120–130 eV over the energy range of interest to this study (0.3–7 keV).

Preliminary reduction of the Chandra data was performed as in Hicks et al. (2008). After this initial cleaning, 0.3–7.0 keV and 0.3–2.5 keV images, instrument maps and exposure maps were created for each data set using the CIAO 4.2 tool `merge_all` and CALDB version 4.3.0. Point source detection was performed by running the tools `wtransform` and `wrecon` on the 0.3–7.0 keV flux images. Data

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**Table 1. Cluster sample.**

| Cluster       | $z$ | 1 arcsec | Telescope | Obsid     | Exposure (s) |
|---------------|-----|----------|-----------|-----------|--------------|
| RCS0222+0144  | 0.25$^a$ | 3.91 | Chandra   | 10485     | 23 335       |
| RCS1102–0319  | 0.33$^b$ | 4.75 | Suzaku    | 803065010 | 26 381       |
| RCS1102–0340  | 0.39$^c$ | 5.29 | Suzaku    | 803064010 | 37 797       |
| RCS1330+3043  | 0.27$^d$ | 4.14 | Chandra   | 10487     | 15 824       |
| RCS1447+0828  | 0.38$^e$ | 5.21 | Chandra   | 10481     | 11 999       |
| RCS1847+0949  | 0.20$^f$ | 3.30 | Chandra   | 10486     | 17 540       |
| RCS1615+3057  | 0.42$^g$ | 5.53 | Chandra   | 10482     | 27 777       |
| RCS2150–0442  | 0.16$^h$ | 2.76 | Chandra   | 10488     | 10 506       |
| RCS2347–3535  | 0.26$^i$ | 4.02 | Chandra/Suzaku | 10484/803057010 | 13 850/15 489 |

$^a$Spectroscopic (Blindert 2006).

$^b$From X-ray spectra (this work), see text.

$^c$Spectroscopic (Ellingson et al., in preparation).

$^d$Photometric.
with energies below 0.3 keV and above 7.0 keV were excluded due to uncertainties in the ACIS calibration and background contamination, respectively. These products were used solely for imaging analysis; our spectral analysis excludes all data below 0.6 keV.

2.2 Suzaku initial processing

The Suzaku X-ray Imaging Spectrometer (XIS) observed three of the clusters in our sample between 2008 May 31 and December 17, including one that was later observed by Chandra (RCS2347−3535). Suzaku’s field of view is $18 \times 18$ arcmin$^2$, and it has a spatial resolution of only $\sim 2$ arcmin. One of the advantages of Suzaku, however, is its excellent low-energy spectral resolution (60 eV at 0.25 keV).

Suzaku data were reprocessed to include the most recent calibration files using the HEASOFT 6.9 Suzaku software Version 16 tool AEPipeline. Calibration sources were removed from the data using XSELECT, and data from XIS0, XIS1 and XIS3 were combined to produce integrated images in the 0.2–12.0 keV energy range.

3 IMAGES AND SURFACE BRIGHTNESS PROFILE MODELLING

3.1 Images and cluster centres

Fig. 1 contains smoothed 0.3–7.0 keV Chandra flux and 0.2–12.0 keV Suzaku count images of each of the clusters in our sample (produced by the CIAO tool CSMOOTH). Using these images we determined the location of the X-ray emission peak of each cluster. Optical positions were taken from RCS cluster catalogues, which were computed from the smoothed galaxy distribution used for cluster identification (see Gladders & Yee 2005, for details). Suzaku observations were included in this exercise despite having $\sim 2$ arcmin spatial resolution. All clusters were found within 27 arcsec of their optical positions, and all Chandra observed clusters were found within 19 arcsec, with a mean offset of 10.4 arcsec. Table 2 lists optical positions, X-ray positions, net counts ($C - B$) and signal-to-noise ratios (S/N) derived from the method described in Appendix A. All clusters are detected at high significance. The median number of source counts per observation is 2911, with values ranging between 339 (RCS1615+3057) and 14 022 (RCS1447+0828).

3.2 Surface brightness profiles

Radial surface brightness profiles were extracted in circular annuli from both targeted observations and blank sky background files using 0.3–2.5 keV Chandra counts images. The cluster profiles were binned to ensure S/N $>$3 in each bin and background-subtracted. None of our surface brightness bins is narrower than 1 arcsec, therefore we do not expect to see any effects from Suzaku’s 0.5 arcsec full width at half-maximum point spread function on our profiles.

The surface brightness profiles were fitted to a $\beta$-model:

$$I(r) = I_0 \left(1 + \frac{r_c^2}{r^2}\right)^{-3\beta/2},$$

where $I_0$ is the normalization and $r_c$ is the core radius. We compared the measured surface brightness (with error bars computed from photon statistics) to the average model surface brightness integrated within each radial bin while performing a Levenberg–Marquardt least-squares fit to the model, as implemented in the IDL routine MPCURVEFIT$^1$.

Best-fitting model parameters for the seven Chandra-observed clusters are given in Table 3, and images of these fits are shown in Fig. B1. Though many of the clusters exhibit some substructure, most were reasonably well fitted by the $\beta$-model (see Table 3 for goodness-of-fit data). $\beta$ values for our sample are generally lower than the typical value of $2/3$ (Neumann & Arnaud 1999), with a sample average of only $0.42 \pm 0.01$, suggesting that the gas is less centrally concentrated in these targets compared to those studied by Neumann & Arnaud (1999).

RCS2347−3535 contains a region of excess emission in its central 10–20 kpc, suggesting that it may harbour a small cool core (CC). None of the other clusters in our sample exhibits a significant central surface brightness excess above the $\beta$-model.

4 SPECTROSCOPY

4.1 Initial spectral fits and redshift estimates

Initial spectra were extracted from each point-source-removed event file in a circular region with a 300 h$^{-1}$ kpc radius (Chandra) or 260 arcsec radius (Suzaku). These values were chosen to provide an initial spectrum with as close to an $R_{2500}$ extraction radius as possible. In the case of Suzaku observations, the smallest recommended radius for extracting spectral data is 260 arcsec. Individual spectra were extracted from each Suzaku XIS CCD and fitted simultaneously.

All spectra were analysed in XSPEC (Arnaud 1996), using weighted response matrices (RMFs) and effective area files (ARFs) generated with the CIAO tool SPECRECT (Chandra), and XISRMGEN and XISSIMARFGEN (Suzaku). For the Chandra observations, blank sky backgrounds were renormalized to match the 9.5–12.0 keV count rates of each exposure, then extracted in identical regions as source spectra. Suzaku backgrounds were compiled from the remaining data after calibration sources, point sources and the target cluster were removed.

Spectra were fitted with single temperature spectral models, inclusive of foreground absorption, using Cash statistics (Cash 1979). Each spectrum was fitted with the absorbing column frozen at its measured value (Dickey & Lockman 1990). Metal abundances were allowed to vary. Data with energies below 0.6 keV and above 7.0 keV were excluded from the Chandra fits, while Suzaku spectra were fitted in the 0.5–8.0 keV energy range (e.g. Bautz et al. 2007).

Redshifts were fitted for the three clusters in our sample that do not have spectroscopic measurements. We were unable to constrain a redshift for RCS1330+3043, and therefore use its photometric redshift ($z = 0.27$) in further analysis. The fits of the other two clusters resulted in $z = 0.334 \pm 0.007$ for RCS1102−0319, and $z = 0.162^{+0.008}_{-0.015}$ for RCS2150−0442, within 7 per cent and 20 per cent (respectively) of photometric redshift estimates obtained using the colour of the red sequence (e.g. Gladders & Yee 2005). Fits with redshift fixed at these values were used in subsequent analysis (Table 4). The small uncertainties in these values ($\leq 10$ per cent) do not substantially affect our analysis.

A core-removed (0.15 $R_{500}$) spectrum was extracted and fitted for RCS1447+0828, indicating that it possesses a strong CC, with

$^1$ Available courtesy Craig B. Markwardt, http://cow.physics.wisc.edu/craigm/idl/idl.html
Figur 1. Smoothed Flux Images. Adaptively smoothed 0.3–7.0 keV Chandra flux and 0.2–12.0 keV Suzaku counts images of our sample. RCS1102−0319, RCS1102−0340, and the second RCS2347−3535 panel are Suzaku observations. Circles denote calculated values of $R_{2500}$ for each cluster. In each image, north is up and east is to the left.
Table 2. Cluster positions and detection details.

| Cluster            | Optical position | X-ray peak | Separation | Net counts | S/N |
|--------------------|------------------|------------|------------|------------|-----|
| RCS0222+0144       | 02 22 40.6 +01 44 32.0 | 02 22 40.8 +01 44 40.3 | 8.8 | 1036 | 14.8 |
| RCS1102−0319       | 11 02 33.0 −03 19 04.8 | 11 02 33.6 −03 19 12.2 | 11.6 | 2440$^a$ | 29.9$^a$ |
| RCS1102−0340       | 11 02 39.1 −03 40 17.1 | 11 02 38.6 −03 40 42.7 | 26.7 | 4803$^c$ | 43.8$^c$ |
| RCS1330+3043       | 13 30 10.7 +30 43 30.6 | 13 30 10.7 +30 43 30.0 | 0.6 | 926 | 16.2 |
| RCS1447+0828       | 14 47 25.9 +08 28 17.5 | 14 47 25.9 +08 28 25.1 | 16.7 | 14022 | 112.8 |
| RCS1447+0949       | 14 47 08.1 +09 49 01.7 | 14 47 08.0 +09 49 14.2 | 12.6 | 1531 | 18.7 |
| RCS1615−3057       | 16 15 47.2 −30 57 18.0 | 16 15 47.8 −30 57 28.4 | 13.0 | 339 | 11.1 |
| RCS2150−0442       | 21 50 19.7 −04 42 25.4 | 21 50 20.5 −04 42 11.2 | 18.6 | 3001 | 48.3 |
| RCS2347−3535       | 23 47 49.2 −35 35 10.9 | 23 47 49.4 $^d$ | −35 35 12.3 $^d$ | 2.8 | 2911 | 54.6 |
|                    |                  |            |            |           |     |
| RCS0222+0144       | 24 ±13           | 0.32 ±0.02 | 2.0 ±0.7   | 276−297   | 11.0/11 |
| RCS1330+3043       | 30 ±8            | 0.39 ±0.02 | 5 ±1       | 286−366   | 28.3/28 |
| RCS1447+0828       | 28.9 ±0.8        | 0.581 ±0.003 | 820 ±20  | 836−875   | 135.6/116 |
| RCS1447+0949       | 30 ±7            | 0.36 ±0.01 | 4.4 ±0.7   | 450−515   | 40.6/52 |
| RCS1615+3057       | 37 ±22           | 0.34 ±0.04 | 1.8 ±0.6   | 235−276   | 6.5/8  |
| RCS2150−0442       | 55 ±6            | 0.51 ±0.02 | 9.1 ±0.8   | 370−411   | 63.8/64 |
| RCS2347−3535       | 70 ±12           | 0.45 ±0.02 | 5.1 ±0.6   | 454−476   | 53.2/53 |

$^a$All positions are given for equinox J2000.
$^b$0.3–7.0 keV band, within $R < 500 h_{70}$ kpc.
$^c$Suzaku observation, $R = 260$ arcsec.
$^d$Using Chandra data.
$^e$Using Suzaku data.

Table 3. $\beta$-model fits.

| Cluster            | $r_c$ (kpc) | $\beta$ | $I_0$ | Outermost bin (kpc)$^b$ | $\chi^2$/DOF |
|--------------------|-------------|---------|-------|------------------------|-------------|
| RCS0222+0144       | 24 ±13      | 0.32 ±0.02 | 2.0 ±0.7 | 276−297 | 11.0/11 |
| RCS1330+3043       | 30 ±8       | 0.39 ±0.02 | 5 ±1    | 286−366 | 28.3/28 |
| RCS1447+0828       | 28.9 ±0.8  | 0.581 ±0.003 | 820 ±20 | 836−875 | 135.6/116 |
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| RCS2347−3535       | 70 ±12      | 0.45 ±0.02 | 5.1 ±0.6 | 454−476 | 53.2/53 |

$^a$Surface brightness $I$ in units of $10^{-6}$ photons s$^{-1}$ pix$^{-2}$.
$^b$Radial range of outermost bin used in fitting procedure, in kpc.

Table 4. Spectral fits ($\Delta = 2500$).

| Cluster            | $z$ | $N_H$ $(10^{20}$ cm$^{-2}$) | $kT$ (keV) | $Z$ ($Z_\odot$) | Norm $(10^{-4}$ cm$^{-5}$) | $n_{e,0}$ $(10^{-3}$ cm$^{-3}$) |
|--------------------|----|-----------------|----------|----------------|-----------------------------|-----------------------------|
| RCS0222+0144       | 0.25 | 3.30 | 2.4$^{+0.0}_{-0.0}$ | 1.4$^{+0.0}_{-0.0}$ | 1.7$^{+0.0}_{-0.0}$ | 4.4$^{+0.0}_{-0.0}$ |
| RCS1102−0319$^b$  | 0.334$^{+0.007}_{-0.007}$ | 4.04 | 6.3$^{+0.0}_{-0.0}$ | 3.7$^{+0.0}_{-0.0}$ | 9$^{+0.0}_{-0.0}$ | ... |
| RCS1102−0340$^b$  | 0.39 | 4.06 | 6.3$^{+0.0}_{-0.0}$ | 3.7$^{+0.0}_{-0.0}$ | 9$^{+0.0}_{-0.0}$ | ... |
| RCS1330+3043       | 0.27 | 1.16 | 4.4$^{+0.0}_{-0.0}$ | 3.7$^{+0.0}_{-0.0}$ | 9$^{+0.0}_{-0.0}$ | ... |
| RCS1447+0828       | 0.38 | 2.24 | 6.8$^{+0.0}_{-0.0}$ | 3.7$^{+0.0}_{-0.0}$ | 9$^{+0.0}_{-0.0}$ | ... |
| RCS1447+0949$^b$  | 0.20 | 1.83 | 2.4$^{+0.0}_{-0.0}$ | 1.7$^{+0.0}_{-0.0}$ | 5.5$^{+0.0}_{-0.0}$ | ... |
| RCS1615+3057       | 0.42 | 2.6 | 3.8$^{+0.0}_{-0.0}$ | 1.7$^{+0.0}_{-0.0}$ | 5.5$^{+0.0}_{-0.0}$ | ... |
| RCS2150−0442$^d$  | 0.160$^{+0.008}_{-0.015}$ | 2.72 | 3.6$^{+0.0}_{-0.0}$ | 1.7$^{+0.0}_{-0.0}$ | 5.5$^{+0.0}_{-0.0}$ | ... |
| RCS2347−3535$^c$  | 0.26 | 1.22 | 4.9$^{+0.0}_{-0.0}$ | 7.3$^{+0.0}_{-0.0}$ | 5.9$^{+0.0}_{-0.0}$ | ... |
| RCS2347−3535$^d$  | 0.26 | 1.22 | 4.9$^{+0.0}_{-0.0}$ | 7.3$^{+0.0}_{-0.0}$ | 5.9$^{+0.0}_{-0.0}$ | ... |

$^a$Suzaku observation, $R = 260$ arcsec.
$^b$Central 0.15$R_{500}$ removed from spectrum.
$^c$Best simultaneous fit to Chandra and Suzaku spectra.
$^d$Chandra normalization; Suzaku normalization for this fit is 11.5$^{+0.4}_{-0.4}$ $\times 10^{-4}$ cm$^{-5}$.
$^e$Using only Chandra data.
$^f$Using only Suzaku data.
an integrated temperature of $6.8^{+0.3}_{-0.2}$ keV and core-removed temperature $T_X = 13^{+3}_{-2}$ keV (Table 4). Due to the central excess in its surface brightness profile, a core-excised spectrum was also fitted for RCS2347–3535; however, no conclusive evidence for soft central emission was found in this case.

4.2 Scaled aperture estimate

With an average of only 3000 counts per target, we do not have sufficient signal to undertake a full hydrostatic mass analysis, or even fit core-excised spectra out to $R_{2500}$. Due to the shallow nature of our observations, we choose $R_{2500}$ as the fiducial radius for our measurements.

We employ scaling relations in order to estimate $R_{2500}$. The present sample contains objects in a variety of dynamical states and thus it is essential to use an appropriate scaling relation. We measure $R_{2500}$ for our Chandra observations using $Y_X = M_{500}T_X$ as a mass proxy. The decision to use $Y_X$ was motivated by two principal factors. First, the simulations of Kravtsov, Vikhlinin & Nagai (2006) indicate that $Y_X$ is a robust mass proxy even in the presence of significant dynamical activity. Secondly, use of $Y_X$ facilitates comparison of our optically selected sample to the X-ray selected REXCESS sample, since REXCESS uses $Y_X$ exclusively.

We used an iterative process to estimate the cluster masses. First, we calculated central densities using the $\beta$-model parameters from Section 3.2 and initial spectral fits described in Section 4.1:

$$n^2_{e,0} = \frac{4\pi d^2_{\text{proj}}(1+z)^2}{0.824\pi^2 \varepsilon I}\text{ cm}^{-6}$$

(Ettori, Tozzi & Rosati 2003). Here $K$ is the normalization of the XSPEC model and $E1$ is the emission integral, estimated by integrating the spherical emission from the source out to 10 Mpc (see Ettori et al. 2003, for details). Values of $n^2_{e,0}$ were then used to determine total gas mass by integrating the cluster density profile out to $R_{500}$:

$$\rho_{\text{gas}}(r) = \rho_0 \left[1 + \frac{r^2}{r_c^2}\right]^{-3\beta/2}$$

where $\rho_0 = n_e m_p$, and $\mu_e = 1.17$. We then use the $M-Y_X$ relation of Arnaud, Pointecouteau & Pratt (2007) to estimate the mass and radius of each object. The Arnaud et al. (2007) $M-Y_X$ relation uses $T[0.15-0.75\,R_{500}]$ as well as $M_{500}[R_{500}]$. We translate our $T[R_{2500}]$ measurements to $T[0.15-0.75\,R_{500}]$ using the mean $T[R_{2500}]/T[0.15-0.75\,R_{500}]$ ratio from the REXCESS sample. $R_{500}$ was then converted to $R_{2500}$ using the simple relationship $R_{2500} = 0.44 \, R_{500}$ (Arnaud, Pointecouteau & Pratt 2005). The process of extracting spectra, fitting temperatures, determining gas mass, and re-estimating the mass and radius $R_{2500}$ was repeated until the radius values converged.

Given the lower spatial resolution of Suzaku, in these cases we instead determined $R_{2500}$ using the $M-T_X$ relationship of Arnaud et al. (2005). The cluster RCS2347–3535 has been observed by both Chandra and Suzaku. Here Chandra spatial information was used in tandem with combined temperature fitting of both Chandra and Suzaku spectra. To confirm that the larger extraction region of Suzaku was not impacting best-fitting temperatures, Chandra and Suzaku spectra were also fitted individually. All values of $T_X$ (including the core-excised value) are consistent with one another within 1σ errors.

4.3 Scaled quantities

Table 5 lists total gravitating masses ($M_{200}$), gas masses ($M_X$), gas mass fractions ($f_{\text{gas}}$) and temperatures ($T_X$) within $R_{2500}$. Total gravitating masses estimated from the scaling relationships $M-T_X$ and $M-Y_X$ were found to be in statistical agreement with one another, with a slight tendency for the latter to be smaller.

Bohometric (unabsorbed 0.01–100 keV) luminosities $L_X[R_{2500}]$ were calculated by extrapolating the best-fitting spectrum within XSPEC. Error bars on $L_X$ take into account uncertainties in $R_{2500}$, temperature, abundance and spectral normalization. To investigate whether different methods of determining $R_{2500}$ have a significant effect on resulting $L_X-T_X$ relationships, we also calculate $R_{2500}$ for the Chandra clusters using $M-T_X$ (Arnaud et al. 2005), and re-extract spectra at those radii to obtain additional luminosities. We find that even when $R_{2500}$ values differ by 20 per cent, measured luminosities do not change appreciably (Table 5). Since we do not expect $T_X$ to change drastically on ~50 kpc scales at radii $R \geq R_{2500}$, we find that $L_X-T_X$ relationships are robust to different methods of determining $R_{2500}$.

5 CLUSTER SAMPLE COMPARISONS

5.1 Context and comparison samples

In our previous work (Hicks et al. 2008) we found that high-redshift, optically selected clusters had noticeably different X-ray properties than our moderate-redshift, X-ray selected comparison sample (CNOC). With our current moderate-$z$ optically selected sample we are in a position to confirm whether these differences are due primarily to selection bias or to redshift evolution in cluster properties. We use the following comparison samples.

(i) 10 high-redshift ($0.6 < z < 1.0$) optically selected RCS clusters selected from among the optically richest of the 6483 candidates detected in the first 90 deg$^2$ of the RCS (Gladders & Yee 2005). The Chandra X-ray observations of these clusters are presented in Hicks et al. (2008).

(ii) 14 moderate-redshift ($0.2 < z < 0.55$) X-ray selected CNOC clusters. This sample (Yee et al. 1996b) is derived from detections in the Einstein Observatory Extended Medium-Sensitivity Survey (EMSS; Gioia et al. 1990). CNOC was originally chosen as a comparison sample because it has been extensively observed in optical, with galaxy redshifts of ~1200 cluster members as well as detailed photometric catalogues available (e.g. Yee et al. 1996a). It is not, however, necessarily representative of X-ray selected samples as a whole. As the highest-luminosity clusters from the X-ray flux-limited, wide-area EMSS survey, the CNOC sample is almost certainly drawn from the extreme X-ray bright tail of the cluster distribution. The Chandra X-ray observations of these clusters are detailed in Hicks et al. (2006).

(iii) 31 clusters from the REXCESS sample (Böhringer et al. 2007). REXCESS provides homogenous coverage of the luminosity range $0.4-20 \times 10^{44}$ $h_{50}^{-2}$ erg s$^{-1}$ in the 0.1–2.4 keV band ($T_X \geq 2$ keV) over the redshift range $0.055 < z < 0.183$. It is representative of the X-ray selected population, clusters having been selected in X-ray luminosity only, without regard for any other characteristic (apart from angular size, so that they would fit into the field of view of XMM–Newton). The X-ray scaling properties of the REXCESS

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2 Use of a constant $R_{2500}/R_{500}$ ratio assumes a constant concentration. This is a fair assumption given the mass range of interest (see e.g. Pointecouteau, Arnaud & Pratt 2005).
5.3 The $L_X-T_X$ relationship

Studying the relationships between global cluster properties ($L_X$, $T_X$, $M_{\text{hot}}$, etc.) over a broad range in redshift allows us to investigate the influence of non-gravitational processes on cluster formation and evolution. In addition, these relationships give us insight regarding cluster dynamical state and composition, as well as provide ready methods of comparison between different cluster samples. In this work we focus primarily on X-ray temperature ($T_X$) and luminosity ($L_X$), since they are tied most closely to the actual data and require fewer assumptions than extrapolated properties such as total cluster mass. To facilitate comparisons between optically selected and X-ray selected clusters, we make use of our previous Chandra analyses of the CNOC (Hicks et al. 2006) and high-$z$ RCS samples (Hicks et al. 2008).

In all $L_X-T_X$ relationships, $L_X$ has been scaled by the cosmological factor $E_z = H(z)/H_0 = [\Omega_m(1+z)^3 + \Omega_{\Lambda}]^{1/2}$ and the relationship has been fitted with the form

$$\log_{10}(E_z^{-1}L_X) = C_1 + C_2 \log_{10}(T_X) \quad (4)$$

with $T_X$ in units of 5 keV and $L_X$ in units of $10^{44}$ erg s$^{-1}$. New best-fitting relationships are determined using both the bisector and orthogonal modifications of the BCES algorithm in Akritas & Bershady (1996), with figures displaying bisector fits for ease of comparison to our previous work.

It is immediately clear from visual inspection of Fig. 3(a) that our current targets are overall less luminous for a given temperature than the CNOC sample, in keeping with our previously observed RCS sample. This result suggests that global discrepancies between the X-ray properties of X-ray and optically selected cluster samples are wholly attributable to selection bias. After correcting for self-similar evolution we find no convincing evidence of redshift evolution in cluster properties within the complete X-ray observed RCS sample ($0.15 < z < 1.0$). To further explore this point, we fitted the RCS moderate-$z$ and high-$z$ sample together with the function

$$\log_{10}(L_X) = A \log_{10}(E_z^{-1}) + B \log_{10}(T_X) + C \quad (5)$$

The best-fitting values are (bootstrap uncertainties): $A = 0.43 \pm 1.15$; $B = 2.69 \pm 0.84$; and $C = 3.23 \pm 1.24$, showing that we are quantitatively unable to constrain evolution with the current sample.

Fig. 3(b) shows RCS and REXCESS $L_X-T_X$ scaling relationships, for the entire REXCESS sample and for just the NCC clusters.

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Table 5. Sample quantities estimated within $R_{2500}$.

| Cluster      | $R_{2500}$ (kpc) | $M_{\text{hot}}$ (10$^{14}$ M$_\odot$) | $M_X$ (10$^{15}$ M$_\odot$) | $f_{\text{gas}}$ | $L_X$ (10$^{42}$ erg s$^{-1}$) | $R_{2500}$ (kpc) | $M_{\text{hot}}$ (10$^{14}$ M$_\odot$) | $M_X$ (10$^{15}$ M$_\odot$) | $f_{\text{gas}}$ | $L_X$ (10$^{42}$ erg s$^{-1}$) |
|--------------|-----------------|----------------------------------------|-----------------------------|-----------------|-------------------------------|-----------------|----------------------------------------|-----------------------------|-----------------|-------------------------------|
| RCS0222+0144 | 346$^{+14}_{-13}$ | 0.75$^{+0.09}_{-0.09}$ | 0.25$^{+0.02}_{-0.02}$ | 0.032$^{+0.005}_{-0.005}$ | 0.5$^{+0.02}_{-0.02}$ | 423$^{+22}_{-20}$ | 1.4$^{+0.4}_{-0.4}$ | 0.38$^{+0.03}_{-0.03}$ | 0.027$^{+0.008}_{-0.008}$ | 0.5$^{+0.4}_{-0.4}$ |
| RCS1102−0319 | ...             | ...                                   | ...                         | ...             | ...                           | ...             | ...                                   | ...                         | ...             | ...                           |
| RCS1102−0340 | ...             | ...                                   | ...                         | ...             | ...                           | ...             | ...                                   | ...                         | ...             | ...                           |
| RCS1330+3043 | 370$^{+17}_{-16}$ | 1.0$^{+0.1}_{-0.1}$ | 0.48$^{+0.03}_{-0.03}$ | 0.049$^{+0.007}_{-0.007}$ | 1.1$^{+0.4}_{-0.3}$ | 405$^{+26}_{-24}$ | 1.3$^{+0.4}_{-0.4}$ | 0.57$^{+0.04}_{-0.03}$ | 0.04$^{+0.01}_{-0.01}$ | 1.2$^{+0.4}_{-0.4}$ |
| RCS1447+0828 | 611$^{+22}_{-21}$ | 4.8$^{+0.7}_{-0.5}$ | 0.50$^{+0.04}_{-0.04}$ | 0.10$^{+0.01}_{-0.01}$ | 0.01$^{+0.005}_{-0.005}$ | 0.01$^{+0.005}_{-0.005}$ | 0.04$^{+0.002}_{-0.002}$ | 0.05$^{+0.002}_{-0.002}$ | 0.07$^{+0.001}_{-0.001}$ | 0.7$^{+0.2}_{-0.2}$ |
| RCS1615+3057 | 334$^{+17}_{-16}$ | 0.8$^{+0.1}_{-0.1}$ | 0.39$^{+0.03}_{-0.03}$ | 0.047$^{+0.007}_{-0.007}$ | 0.9$^{+0.2}_{-0.2}$ | 349$^{+16}_{-15}$ | 0.9$^{+0.4}_{-0.4}$ | 0.42$^{+0.01}_{-0.01}$ | 0.05$^{+0.02}_{-0.02}$ | 0.8$^{+0.4}_{-0.4}$ |
| RCS2150−0442 | 361$^{+9}_{-8}$   | 0.70$^{+0.06}_{-0.06}$ | 0.48$^{+0.03}_{-0.03}$ | 0.061$^{+0.005}_{-0.005}$ | 0.7$^{+0.2}_{-0.2}$ | 393$^{+17}_{-17}$ | 1.0$^{+0.1}_{-0.1}$ | 0.80$^{+0.07}_{-0.07}$ | 0.05$^{+0.02}_{-0.02}$ | 1.4$^{+0.3}_{-0.3}$ |
| RCS2347−3535 | 406$^{+7}_{-7}$   | 1.24$^{+0.06}_{-0.06}$ | 0.73$^{+0.02}_{-0.02}$ | 0.059$^{+0.003}_{-0.003}$ | 2.0$^{+0.4}_{-0.4}$ | 434$^{+14}_{-14}$ | 1.5$^{+0.1}_{-0.1}$ | 0.82$^{+0.02}_{-0.02}$ | 0.055$^{+0.004}_{-0.004}$ | 2.1$^{+0.4}_{-0.4}$ |

$^a$Suzaku observation, $L_X$ at $R_{2500}$ estimated within aperture of radius $R = 260$ arcsec.

$^b$Core-excised temperature used to determine $R_X$.

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The centroid shift parameter is defined as the standard deviation of the projected separations between the X-ray peak and the centroid at each radius in the [0.1−1] $R_{500}$ region (see e.g. Pratt et al. 2009; Böhringer et al. 2010).
but are in good agreement with the X-ray systems at large radii (\(\sim\) versus REXCESS morphologically disturbed subsample only. Here the mean profiles of the two samples are essentially identical.

### Table 6. REXCESS X-ray properties at \(R_{200}\).

| Cluster   | \(z\) | \(R_{200}\) (\(h^{-1}\) kpc) | \(T_X\) (keV) | \(L_X\) (10^{44} erg s\(^{-1}\)) | \(f_{gas}\) | CC | Disturbed |
|-----------|------|-----------------------------|--------------|-------------------------------|-----------|----|-----------|
| RXC J0003+0203 | 0.0924 | 388.3                      | 4.24_{-0.07}^{+0.07} | 1.64_{-0.01}^{+0.01}         | 0.072     |    |           |
| RXC J0006−3443 | 0.1147 | 469.1                      | 5.7_{-0.2}^{+0.2}   | 3.00_{-0.04}^{+0.04}         | 0.068     |    | \(\checkmark\) |
| RXC J0020−2542 | 0.1410 | 462.9                      | 6.3_{-0.1}^{+0.1}   | 5.96_{-0.03}^{+0.03}         | 0.095     |    |           |
| RXC J0049−2931 | 0.1084 | 357.7                      | 3.9_{-0.2}^{+0.2}   | 1.66_{-0.02}^{+0.02}         | 0.082     |    |           |
| RXC J0145−5300 | 0.1168 | 482.4                      | 5.8_{-0.1}^{+0.1}   | 3.80_{-0.03}^{+0.03}         | 0.074     |    | \(\checkmark\) |
| RXC J0211−4017 | 0.1008 | 303.4                      | 2.20_{-0.03}^{+0.03} | 0.688_{-0.005}^{+0.005}      | 0.075     |    |           |
| RXC J0225−2928 | 0.0604 | 307.3                      | 2.49_{-0.01}^{+0.01} | 0.417_{-0.004}^{+0.004}      | 0.055     |    | \(\checkmark\) |
| RXC J0345−4112 | 0.0603 | 304.9                      | 2.36_{-0.04}^{+0.04} | 0.701_{-0.005}^{+0.005}      | 0.068     |    | \(\checkmark\) |
| RXC J0547−3152 | 0.1483 | 502.1                      | 7.6_{-0.1}^{+0.1}   | 7.87_{-0.04}^{+0.04}         | 0.091     |    |           |
| RXC J0605−3518 | 0.1392 | 463.2                      | 4.58_{-0.04}^{+0.04} | 8.6_{-0.04}^{+0.04}          | 0.102     |    | \(\checkmark\) |
| RXC J0616−4748 | 0.1164 | 415.9                      | 4.45_{-0.09}^{+0.09} | 1.7_{-0.02}^{+0.02}          | 0.065     |    | \(\checkmark\) |
| RXC J0645−5413 | 0.1644 | 566.9                      | 7.3_{-0.1}^{+0.1}   | 15.9_{-0.1}^{+0.1}           | 0.099     |    |           |
| RXC J0821+0112 | 0.0822 | 334.8                      | 3.3_{-0.1}^{+0.1}   | 0.650_{-0.008}^{+0.008}      | 0.063     |    |           |
| RXC J0958−1103 | 0.1669 | 477.1                      | 5.6_{-0.3}^{+0.3}   | 11.0_{-0.1}^{+0.1}           | 0.107     |    | \(\checkmark\) |
| RXC J1044−0704 | 0.1342 | 412.7                      | 3.49_{-0.02}^{+0.02} | 6.9_{-0.02}^{+0.02}          | 0.112     |    | \(\checkmark\) |
| RXC J1114−1216 | 0.1195 | 392.0                      | 3.44_{-0.03}^{+0.03} | 3.3_{-0.01}^{+0.01}          | 0.087     |    | \(\checkmark\) |
| RXC J1236−3354 | 0.0796 | 333.7                      | 2.82_{-0.03}^{+0.03} | 0.866_{-0.006}^{+0.006}      | 0.068     |    |           |
| RXC J1302−0230 | 0.0847 | 372.9                      | 3.43_{-0.04}^{+0.04} | 1.17_{-0.007}^{+0.007}       | 0.060     |    | \(\checkmark\) |
| RXC J1311−0120 | 0.1832 | 584.2                      | 9.17_{-0.07}^{+0.07} | 33.7_{-0.07}^{+0.07}         | 0.116     |    | \(\checkmark\) |
| RXC J1516+0005 | 0.1181 | 438.4                      | 5.21_{-0.07}^{+0.07} | 3.59_{-0.02}^{+0.02}         | 0.083     |    |           |
| RXC J1516−0056 | 0.1198 | 410.5                      | 4.23_{-0.09}^{+0.09} | 1.66_{-0.01}^{+0.01}         | 0.062     |    | \(\checkmark\) |
| RXC J2014−2430 | 0.1538 | 511.6                      | 4.80_{-0.04}^{+0.04} | 19.3_{-0.06}^{+0.06}         | 0.110     |    | \(\checkmark\) |
| RXC J2023−2056 | 0.0564 | 327.5                      | 3.24_{-0.08}^{+0.08} | 0.52_{-0.006}^{+0.006}       | 0.059     |    | \(\checkmark\) |
| RXC J2048−1750 | 0.1475 | 477.4                      | 5.3_{-0.1}^{+0.1}   | 3.6_{-0.03}^{+0.03}          | 0.074     |    | \(\checkmark\) |
| RXC J2129−5048 | 0.0796 | 398.8                      | 4.2_{-0.1}^{+0.1}   | 1.02_{-0.01}^{+0.01}         | 0.056     |    | \(\checkmark\) |
| RXC J2149−3041 | 0.1184 | 392.6                      | 3.31_{-0.03}^{+0.03} | 3.10_{-0.01}^{+0.01}         | 0.083     |    | \(\checkmark\) |
| RXC J2157−0747 | 0.0579 | 332.8                      | 3.27_{-0.08}^{+0.08} | 0.29_{-0.003}^{+0.003}       | 0.041     |    | \(\checkmark\) |
| RXC J2217−3543 | 0.1486 | 452.9                      | 5.38_{-0.08}^{+0.08} | 5.3_{-0.02}^{+0.02}          | 0.090     |    |           |
| RXC J2218−3853 | 0.1411 | 500.5                      | 6.0_{-0.1}^{+0.1}   | 8.2_{-0.05}^{+0.05}          | 0.095     |    | \(\checkmark\) |
| RXC J2234−3744 | 0.1510 | 568.3                      | 8.6_{-0.1}^{+0.1}   | 17.0_{-0.08}^{+0.08}         | 0.108     |    |           |
| RXC J2319−7313 | 0.0984 | 349.3                      | 2.2_{-0.03}^{+0.03} | 1.69_{-0.01}^{+0.01}         | 0.080     |    | \(\checkmark\) |
Figure 3. $L_X$–$T_X$ relationships. X-ray temperatures are plotted against cosmologically consistent, intrinsic bolometric luminosities within $R_{2500}$. In all panels diamonds represent high-$z$ RCS clusters ($z_{\text{avg}} = 0.80$), triangles denote the current sample ($z_{\text{avg}} = 0.30$) and the dashed line shows the $L_X$–$T_X$ relationship for the entire X-ray observed RCS sample. (a) Squares designate moderate redshift CNOC clusters ($z_{\text{avg}} = 0.32$), and the solid line shows their best-fitting relationship. As in Hicks et al. (2008), the X-ray selected sample exhibits a higher normalization than optically selected clusters. (b) Circles represent the REXCESS sample. Here the solid line shows the fit to NCC REXCESS clusters (filled circles) and the dotted line is the best fit to the entire REXCESS sample. Open circles denote CC clusters. (c) Here circles show only the disturbed REXCESS clusters, and the solid line represents their best-fitting $L_X$–$T_X$ relationship, which is notably similar to that of the RCS combined sample (dashed line).

For the REXCESS sample, CCs define the upper envelope of the relation while morphologically disturbed systems define the lower envelope. The vast majority of the dispersion comes from the CCs. While REXCESS CC clusters look much like the high-$L_X$ CNOC sample, the NCC clusters are situated similarly to the optically selected sample.

It is clear that the normalization, in particular, that one will obtain for any $L_X$–$T_X$ fit will depend strongly on the sample composition. Note also that the intrinsic dispersion about the REXCESS $L_X$–$T_X$ relation is considerably larger than the 70 per cent dispersion about the $L_X$–$T_X$ relation for quantities measured within $R_{500}$ (Pratt et al. 2009). The larger dispersion we see is due to measuring quantities in the core regions, where the variation in density is strongest.

Building on the results of Section 5.2, we compare REXCESS morphologically disturbed clusters to the RCS sample (Fig. 3 c). Here we find an even closer similarity in X-ray properties, to the extent that even best-fitting relationships lie nearly on top of one another. This result is expected given the agreement in gas density profiles between our targets and the REXCESS morphologically disturbed subsample. $L_X$–$T_X$ fits for a variety of sample combinations are reported in Table 7.

### 5.4 Gas mass fractions

Using our estimated masses (Table 5) we calculate core gas mass fractions within $R_{2500}$. Our sample mean is $0.058 \pm 0.008$ using $Y_X$ to determine total mass (error computed by dividing the standard deviation by $\sqrt{N}$). In comparison, REXCESS clusters have a mean gas mass fraction of $0.081 \pm 0.003$ for the complete sample of 31 clusters, and $0.066 \pm 0.004$ when including only the 12 disturbed clusters, further evidence of similarities between optically selected clusters and morphologically disturbed X-ray selected clusters.

We perform statistical tests comparing the distributions of $f_{\text{gas}}$ values for a subset of the clusters in our moderate redshift RCS sample with two subsets of the REXCESS sample. In order to compare clusters of similar masses, and to be consistent with Hicks et al. (2008), we restricted the temperature range in all three samples to be between 3.5 and 8.0 keV, resulting in five clusters from the RCS, 17 clusters in the REXCESS sample and seven clusters in the REXCESS/disturbed sample. The mean gas fraction and standard deviation from each of the subsamples are $0.050 \pm 0.005$, $0.084 \pm 0.004$ and $0.071 \pm 0.005$, for the RCS subset, REXCESS subset and REXCESS/disturbed subset, respectively. The RCS subset shows
observed clusters in S/N from the same distribution. Right: using only the seven disturbed REXCESS clusters with $3.5 < T_X < 8 \text{keV}$. A KS test performed on these two samples resulted in $D=0.741$ and $P = 0.013$, indicating that the gas mass fractions of the two samples are unlikely to have been drawn from the same distribution. Right: using only the seven disturbed REXCESS clusters with $3.5 < T_X < 8 \text{keV}$.

**Table 7.** Scaling relationship: $\log_{10}(E_{\gamma}^{-1} L_X) = C_1 + C_2 \log_{10} T_X$.

| Sample              | Bisector | Orthogonal |
|---------------------|----------|-------------|
| CNOC$^a$            | 0.74 ± 0.08 | 2.3 ± 0.3  |
| RCS (high-$z$)$^a$  | 0.36 ± 0.06 | 2.1 ± 0.3  |
| RCS (total)         | 0.34 ± 0.06 | 2.7 ± 0.5  |
| REXCESS (disturbed) | 0.43 ± 0.05 | 2.8 ± 0.7  |
| REXCESS (NCC)       | 0.46 ± 0.03 | 3.2 ± 0.3  |
| REXCESS (total)     | 0.63 ± 0.06 | 3.1 ± 0.3  |

$^a$Hicks et al. (2008).

lower $f_{\text{gas}}$ than the REXCESS cluster subset, but similar $f_{\text{gas}}$ to the REXCESS/disturbed cluster subset, also visible in the histograms shown in Fig. 4.

We also performed a two-sided Kolmogorov–Smirnov (KS) test (the contributed *KSTWO* IDL routine, based on Press et al. 1992, Numerical Recipes), pairing the RCS subset with each of the REXCESS and REXCESS/disturbed subsets. The KS test comparing RCS clusters with the complete REXCESS sample showed a higher probability of having been randomly drawn from different parent populations than the test involving only the REXCESS/disturbed subsample; however, such a comparison is severely limited by the small number of clusters. The KS probability comparing the five RCS clusters with the 17 REXCESS clusters was 0.013, while the KS probability comparing the RCS clusters with seven REXCESS/disturbed clusters was 0.091.

**6 SUMMARY AND DISCUSSION**

We have presented a detailed X-ray investigation of a sample of moderate-redshift, optically selected clusters of galaxies from the RCS (Table 1). All of our targets were detected by *Chandra* and/or *Suzaku* at S/N $>11$ (Table 2) and were found within 27 arcsec of their optical positions. *Chandra* imaging reveals that most of these clusters possess at least some degree of substructure (Fig. 1).

Surface brightness profiles were extracted for the seven *Chandra*-observed clusters in S/N >3 annular bins. These profiles were reasonably well fitted by single $\beta$-models (Table 3 and Fig. B1). Cluster emission was modelled with *XSPEC*, beginning with a spectral extraction region of 300 kpc radius. The results of single-temperature spectral fits (Table 4), combined with gas masses obtained using best-fitting $\beta$-models, were used to determine $Y_X$ and consequently $R_{2500}$. This process was carried out iteratively until extraction regions and $R_{2500}$ estimates were in agreement.

Using both the $M$–$Y_X$ (Arnaud et al. 2007) and $M$–$T_X$ relationship (Arnaud et al. 2005), total masses were estimated out to $R_{2500}$. While both relationships are overall consistent within our errors, we find $M$–$Y_X$ mass estimates to generally be lower than those obtained via $M$–$T_X$ for the clusters in our sample, not entirely surprising given that $M$–$Y_X$ uses gas mass information as well as temperature. Reasonably, uncertainties in $R_{2500}$ do not lead to large uncertainties in $L_X[R_{2500}]$. Therefore for X-ray observations for which only global $T_X$ and $L_X$ measurements are possible due to poor spatial resolution and/or low net counts, using $M$–$T_X$ to determine $R_{2500}$ results in reasonably accurate $L_X$–$T_X$ relationships. Values of $R_{2500}$, total mass, gas mass, gas mass fraction and integrated luminosity are given in Table 5.

The scaled density profiles (Fig. 2) and global quantities of the moderate-redshift RCS sample are most consistent with the morphologically disturbed subset of the REXCESS X-ray selected sample. These density profiles explain trends in $L_X$–$T_X$ relationships (e.g. Fig. 3; Hicks et al. 2008) without having to resort to non-standard evolutionary effects. This result suggests that much of the non-standard evolution found by previous work may be due to the varying fractions of CCs in different samples, which in turn are affected by the various methods of cluster selection.

The properties of the scaled density profiles are reflected in the global quantities $T_X$ and especially $L_X$, and vice versa. Low $L_X$ systems have centrally suppressed pressure profiles; high $L_X$ systems have centrally peaked density profiles. Trends in the $L_X$–$T_X$ relation measured in an aperture corresponding to $R_{2500}$ are similar to those measured at $R_{500}$ (Pratt et al. 2009). CC systems populate the high-$L_X$ side of the relation; morphologically disturbed systems populate the low-$L_X$ side.

The fraction of CC clusters in the low-redshift RCS sample appears to be lower than in the REXCESS sample (1/7 versus 10/31).
This lower fraction is consistent with the differences seen in density profiles and scaling relations. However, the small numbers and potential mismatch in mass distributions keep this discrepancy in CC fraction from being statistically significant. If there is an increase in the CC fraction towards the present day, there is a possibility that the percentage of CCs found in X-ray and optically selected samples might converge at higher redshift. However, there are very few minimally biased X-ray selected cluster samples that probe the redshift ranges we are interested in. The eROSITA survey (Predehl et al. 2011) will definitely shed light on this issue.

Overall, we find that optically selected RCS cluster properties span the entire range of those of massive clusters selected via other methods, but contain a higher fraction of objects with gas density profiles and global properties similar to those of the morphologically disturbed systems in REXCESS. This result suggests that optical and X-ray selection do not sample exactly the same population of clusters. Recent results from Sunyaev–Zel’dovich surveys such as Planck (Planck Collaboration et al. 2011) further suggest that X-ray selection may preferentially pick up centrally concentrated systems. Selection effects such as these have the potential to affect the interpretation of cluster surveys that intend to use the evolution of the cluster population as a proxy for cosmic evolution. More investigations are clearly necessary.

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APPENDIX A: SIGNAL-TO-NOISE RATIOS

To estimate the significance of RCS cluster detections in the X-ray, we used the same simple statistics as in Hicks et al. (2008). For the Chandra observed clusters, counts were extracted in the 0.3–7.0 keV band from a 500 h^{-1} kpc radius region around the X-ray peak (C) and also from a region away from the aimpoint on the same chip which served as a background (B). Due to the ~2 arcmin spatial resolution of Suzaku, all analysis was performed using a 260 arcsec extraction radius, as recommended by the Suzaku Data Reduction Guide. Therefore to determine S/N for our Suzaku observations, counts were extracted in the 0.2–12.0 keV band from a 260 arcsec radius region centred on the cluster (C), and the remainder of the chip minus calibration sources were used as the background (B). Obvious point sources were removed from each region in all observations. Final S/N were calculated based on dividing net counts, \( N = C - B \), by the standard deviation, \( \sigma = \sqrt{C + B} \). Using this method, all clusters were solidly detected at a S/N greater than 11 (Table 2), with an average S/N of 41 for the sample.

APPENDIX B: \( \beta \)-MODEL FITS

4 http://heasarc.nasa.gov/docs/suzaku/analysis/abc/
Figure B1. Surface brightness profiles. Background-subtracted radial surface brightness profiles for the 0.3–2.5 keV band accumulated in S/N>3 annular bins for seven of the nine clusters in our sample. A solid line traces the best-fitting single $\beta$-model of each cluster. Vertical dashed lines indicate $R_{2500}$. Many of the profiles exhibit some substructure; however, most were reasonably well fitted by a standard $\beta$-model (see Table 3 for goodness-of-fit data). The surface brightness profile of RCS2347–3535 suggests that it harbours a modest CC in the inner 10–20 kpc.

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