Fossil Group Origins. VI. Global X-ray scaling relations of fossil galaxy clusters

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ABSTRACT

We present the first pointed X-ray observations of ten candidate fossil galaxy groups and clusters. With these Suzaku observations, we determine global temperatures and bolometric X-ray luminosities of the intracluster medium (ICM) out to $r_{500}$ for six systems in our sample. The remaining four systems show signs of significant contamination from non-ICM sources. For the six objects with successfully determined $r_{500}$ properties, we measure global temperatures between $2.8 \text{ keV} \leq T_X \leq 5.3 \text{ keV}$, bolometric X-ray luminosities of $0.6 \times 10^{44} \text{ ergs s}^{-1} \leq L_{X,\text{bol}} \leq 7.2 \times 10^{44} \text{ ergs s}^{-1}$, and estimate masses, as derived from $T_X$, of $M_{500} \geq 10^{14} M_\odot$. Scaling relations are constructed for an assembled sample of fossil and non-fossil systems using global X-ray luminosities, temperatures, optical luminosities, and velocity dispersions. The fit of the scaling relations for fossil systems is found to be consistent with the fit of the relations for normal groups and clusters. We find fossil systems have global ICM X-ray properties similar to those of comparable mass non-fossil systems.

Key words: X-rays: galaxies: clusters - galaxies: clusters: general - galaxies: groups: general - galaxies: evolution

1 INTRODUCTION

Fossil galaxy systems are group and cluster mass objects characterized by extended, relaxed X-ray isophotes and an extreme magnitude gap in the bright end of the optical luminosity function of their member galaxies. Typically, fossils are identified with the criteria of a halo luminosity of $L_{X,\text{bol}} \geq 0.5 \times 10^{42} \text{ ergs s}^{-1}$ and a first ranked galaxy more than 2 $R$-band magnitudes brighter than the second brightest galaxy within half the virial radius (Jones et al. 2003). Fossil systems comprise 8-20 per cent of groups and clusters in the same X-ray luminosity regime (Jones et al. 2003), and thus determining the origin of the features characterizing these systems is important for understanding the nature and evolution of a significant fraction galaxy groups and clusters.

The features of fossil systems seem to fulfill theoretical predictions that the Milky Way luminosity ($L^*$) galax-
ies in a group will merge into a central bright elliptical in less than a Hubble time, but the timescale for the cooling and collapse of the hot gas halo is longer (Barnes 1987; Ponman & Bertram 1993). Indeed the first fossil group discovered, RX J1340.6+0127, appeared as a solitary bright elliptical located in the centre of a group sized X-ray luminous halo. It was thought the central galaxy of this group was the final merger remnant of the former group galaxies, and hence this object was named a ‘fossil group’. Since then, deeper observations have found this system to consist of galaxies other than the bright central galaxy (BCG) (Jones et al. 2000) and as a result the magnitude gap criterion of fossils has been established. The motivation for this criterion is that over time, an increasingly growing difference between the two brightest galaxies will form as a result of the merging of the most massive galaxies into a single bright central elliptical if no infall occurs. This formation scenario is well suited for group mass fossils where the velocity dispersion is low and the dynamical friction timescale is short.

A number of objects meeting the fossil criteria have also been observed in the cluster mass regime as well (Khosroshahi et al. 2006, Cypriano et al. 2006, Voevodkin et al. 2010, Aguerri et al. 2011, Harrison et al. 2012). It is possible fossil clusters may form as the result of two systems merging, where one group has had its bright galaxies merge due to dynamical friction, and the other has comparatively fainter galaxies (Harrison et al. 2012). Should merging occur between systems with similarly bright galaxies, any previously existing magnitude gaps may become filled in. Therefore, meeting the fossil criteria may only be a transitory phase in the evolution of a group or cluster (von Bend-A beckmann et al. 2008; Dariush et al. 2010).

Numerical and hydrodynamic simulations indicate the large magnitude gaps characterizing fossil groups and clusters are associated with an early formation time: fossil systems have been found to assemble more of their total dynamical mass than non-fossil systems at every redshift (Dariush et al. 2007), where half the dynamical mass is assembled by z ≳ 1 (D’Ooughia et al. 2003). Evidence that fossils have formed and evolved in a different manner than normal groups and clusters should then manifest in differences in their respective properties.

The bright central galaxy which dominates the optical output of fossil systems has a number of unique characteristics, although whether this demonstrates a clearly distinct formation scenario from non-fossil BCGs is still uncertain. The BCGs of fossils are more massive in both the stellar component and in total than the central ellipticals in non-fossil systems of the same halo mass (Harrison et al. 2012). Méndez-Abreu et al. (2012) find fossil BCGs are consistent with the fundamental plane of non-fossil BCGs, but show lower velocity dispersions and higher effective radii when compared to non-fossil intermediate mass elliptical BCGs of the same Ks-band luminosity. These results suggest the fossil BCG has experienced a merger history of early gas-rich dissipational mergers, followed by gas-poor dissipationless mergers later.

On the global scale, the scaling relations of fossil systems remain a point of contentention due to the limited data, and the inhomogeneity of studies. Khosroshahi et al. (2006) thereafter KPJ07) performed a comprehensive analysis of a sample of group mass fossil systems and found their sample fell on the same LX-TX relation as non-fossils. However, the fossil groups were found to have offset LX and TX for a given optical luminosity Lopt or velocity dispersion σr when compared to normal groups, which was interpreted as an excess in the X-ray properties of fossil systems for their mass. In a comparable study, Proctor et al. (2013) found similar deviations between fossils and non-fossils. This offset, however, was interpreted as fossils being under-luminous in the optical which is supported by their large mass-to-light ratios. These features would not result from galaxy-galaxy merging in systems with normal luminosity functions and thus, this analysis calls into question the formation scenario commonly attributed to generating the characteristic large magnitude gap of fossil systems. Later studies, such as Harrison et al. (2012) and Girardi et al. (2014, hereafter G14), find no difference in the LX-Lopt relation of fossil systems and non-fossils. Even so, most recently Khosroshahi et al. (2014) present a sample of groups, one of which qualifies as a fossil, that lies above the LX-Lopt relation of non-fossil systems, reopening the debate on fossil system scaling relations.

In this paper we have undertaken a X-ray study of 10 candidate fossil systems, never previously studied with detailed pointed observations in the X-ray regime. Using Suzaku data, we present the first measurements of ICM temperatures, bolometric X-ray luminosities, and estimates of the M500 masses of our systems. This work comprises the sixth installment of the FOssil Group Origins (FOGO) series. The FOGO project is a multi-wavelength study of the Santos et al. (2007) candidate fossil system catalogue. In FOGO I (Aguerri et al. 2011), the FOGO project is described in detail and the specific goals of the collaboration are outlined. FOGO II (Méndez-Abreu et al. 2012) presents a study of the BCG scaling relations of fossil systems and the implications for the BCG merger history. Global optical luminosities of our FOGO sample are measured in FOGO III (G14) and used to construct the global LX-Lopt relation which reveals no difference between the fossil and non-fossil fits. Deep r-band observations and an extensive spectroscopic database were used to redetermine the magnitude gaps of the FOGO sample and reclassify our fossil candidate catalogue in FOGO IV (Zarattini et al. 2014, hereafter Z14). In FOGO V (Zarattini et al. 2013), the correlation of the size of the magnitude gap and the shape of the luminosity function is investigated. In this work (FOGO VI) we advance the characterization of the X-ray properties of fossil systems and constrain the global scaling relations of these objects.

The details and observations of our Suzaku sample are described in Section 2 and Section 3. A discussion on how non-ICM sources may contribute to the observed emission of our systems follows in Section 4 Tests to determine the contribution of these non-ICM sources are presented in Sections 5-6. Measurements of the global ICM properties of the thermally dominated subset of our sample are recorded in Section 7. Global scaling relations and their implications are presented in Section 8. For our analysis, we assume a ΛCDM cosmology with a Hubble parameter H0=70 km s⁻¹ Mpc⁻¹, a dark energy density parameter of ΩΛ=0.7, and a matter density parameter ΩM=0.3.
2 THE SAMPLE

Our sample of ten observed galaxy groups and clusters was selected from the Santos et al. (2007, hereafter S07) catalogue of candidate fossil systems. The S07 catalogue was assembled by first identifying luminous r <19 mag red galaxies in the LRG catalog (Eisenstein et al. 2001), and selecting only those galaxies associated with extended X-ray emission in the ROSAT All-Sky Survey (RASS). Sloan Digital Sky Survey (SDSS) Data Release 5 was then used to spatially identify companion galaxies to these bright galaxies. Group or cluster membership was assigned to galaxies identified within a radius of 0.5 $h_{70}^{-1}$ Mpc from one of the bright LRGs and with a redshift consistent with that of the LRG. While spectroscopic redshifts were used when available, galaxy membership was primarily determined using photometric redshifts. Groups and clusters with more than a 2 r-band magnitude difference between the brightest and second brightest member galaxies within the fixed 0.5 $h_{70}^{-1}$ Mpc system radius were then selected, and those with an early-type BCG were identified as fossils.

Z14 observed the S07 fossil candidate list with the Nordic Optical Telescope, the Isaac Newton Telescope, and the Telescopio Nazionale Galileo to obtain deeper r-band images and spectroscopic redshifts for candidate group members allowing for improved system membership. Additionally, the search radius for galaxy system members was extended to the viral radius of the system as calculated from the RASS X-ray luminosity. The Z14 study confirms 15 targets out of 34 S07 candidates are fossil galaxy systems. According to this characterization, our sample contains five confirmed fossil systems and five non-confirmed or rejected fossil systems (see Table 1).

3 OBSERVATIONS AND DATA REDUCTION

The ten systems in our sample were observed with the Suzaku X-ray telescope between May-October 2012 (Table 1). Our analysis uses the data from Suzaku’s three X-ray Imaging Spectrometers (XIS) sensitive to the 0.5-10 keV band. Our single-pointing observations were taken with a normal clocking mode, and an editing mode of 3 x 3 or 5 x 5 which were combined when both were available. The stacked XIS0+XIS1+XIS3 raw count images of the sample are shown in Fig. 1.

The analysis of our study was conducted using the HEASOFT version 6.15 software library with the calibration database CALDB XIS update version 20140520. Spectra were extracted using XSELECT version 2.4c and fit using XSPEC version 12.8.1g. The event files were reprocessed using aepipeline with the CALDB XIS update version 20140203 using the default settings with an additional criterion of COR>6. In our spectral analysis, emission from the 55Fe calibration sources, located in the corners of each XIS detector, was removed. Additionally, the XIS0 damaged pixel columns caused by micro-meteorites were masked.

A Redistribution Matrix File (RMF) was created for all spectral extraction regions with xisrmfgen. For each RMF, two Ancillary Response Files (ARFs) were created with xisarnfgen, one to be convolved with the background spectral model, and the other to be convolved with the source model following the method of Ishisaki et al. (2007). Background ARFs were created out to a radius of 20 arcmin using a uniform emission source mode. For the source ARFs, an image of the stacked XIS FOV was used to model the emission.

4 TREATMENT OF NON-ICM EMISSION

High fidelity measurements of the ICM temperature and luminosity require careful consideration of non-ICM sources of emission during our analysis.

4.1 Background and foreground sources

The standard Suzaku XIS background consists of a non-X-ray particle background (NXB) (Tawa et al. 2008), the cosmic X-ray background (CXB) (Fabian & Barcons 1992), and foreground galactic emission from the Local Hot Bubble (LHB) and the Milky Way Halo (MWH) (Kuntz & Snowden 2000).

The contribution of the NXB for each object was assessed using the night earth database within 150 days of the observation using the FTOOLS xisnxbgen (Tawa et al. 2008). Our XIS1 observations were taken in a charge injection mode of CI = 6 keV which increases the NXB. Accordingly, the xisnxbgen calibration file was used as input for XIS1 to counteract this.

The contribution of the galactic foreground to a XIS spectrum is well described by two thermal plasma models: apecLHB + wabs × apecMWH where $z_{LHB} = z_{MWH} = 0$, $Z_{LHB} = Z_{MWH} = 1 Z_{⊙}$, and $kT_{LHB} = 0.1$ keV (Kuntz & Snowden 2000). The CXB was modeled by an absorbed power-law: $wabs \times \text{powerlaw}_{\text{CXB}}$ with $\Gamma = 1.412$ (Kushino et al. 2002). During spectral analyses, the summed background and foreground model: $apec_{LHB} + wabs(apec_{MWH} + \text{powerlaw}_{\text{CXB}})$ was convolved with the uniform emission ARF.

4.2 Solar Wind Charge Exchange

The interaction of ions in the solar wind with neutral atoms in the heliosphere and in Earth’s atmosphere can produce <1 keV photons in the X-ray regime (Cravens 2004, Fujimoto et al. 2007). To check for contamination from solar wind charge exchange (SWCX), proton flux light curves with a sampling frequency of 90 s were obtained from the NASA WIND-SWE database over the time span of each observation. The intensity of proton flux has been found to be related to the strength of geocoronal SWCX contaminating photons, where flux levels above $4 \times 10^{9}$ protons cm$^{-2}$ s$^{-1}$ commonly indicate potentially significant contamination to the X-ray spectra from charge exchange (Yoshino et al. 2004). Following Fujimoto et al. (2007), 2700 s were added to the time points in the WIND-SWE light curve to account for the travel time between the WIND satellite, located at the L1 point, and Earth, where the geocoronal SWCX emission is produced.

Much of the FGS24 observation occurs during an elevated period of proton flux; however, the light curve of FGS24 displays no significant duration flares. Furthermore,
Figure 1. The Suzaku combined raw counts XIS0+XIS1+XIS3 images in the 0.5 - 10 keV band. The image is Gaussian smoothed with $\sigma = 0.42$ arcmin. White circles demarcate the initial spectral extraction region $r_{ap, opt}$ defined to optimize the S/N ($r_{ap, opt}$ values in Table 4). $^{55}$Fe calibration source events have been removed.
we have performed our spectral analysis on the time windows where the proton flux was $< 4 \times 10^8$ cm$^{-2}$s$^{-1}$ and found the results were consistent with the spectral analysis of the full baseline. We therefore consider the effects of SWCX to be small and have recorded the results of the analysis of the full observation in the main text and include the FGS24 light curve and shortened exposure time analysis in Appendix A.

### 4.3 Point Source Contamination

Our Suzaku observations are the first pointed X-ray observations of the objects in our sample. Consequently we must assess point source contamination primarily relying on the Suzaku data alone. Visual inspection of the XIS images (Fig. 4) reveal two obvious point sources in the FGS15 FOV which we are able to exclude in our analysis using circular regions of radius 2.5 arcmin. Additionally, FGS03 and FGS09 show diffraction spikes from a strong point-like sources near the peak of the X-ray emission. However, the large 2 arcmin half-power diameter (HPD) of the Suzaku XRT point-spread function (PSF) [Serlemitsos et al. 2007] inhibits the exclusion of these sources and the robust identifications of other point sources.

Optical and radio studies of the objects in our sample have found a number of AGN in spatial proximity to our objects. Especially concerning are the radio loud AGN, located near the projected location of the BCGs, found in 7 out of the 10 objects in our sample [Hess et al. 2012]. To determine if these radio loud AGN, and other optical and radio AGN in the FOV, are significant contributors to the source emission in the X-ray regime, we perform image (Section 5) and spectral (Section 6) analyses. In the 0.5-10 keV range of the XIS, the strength of AGN emission increases towards the harder energies of the spectrum. As a result, the harder photons from an AGN may falsely boost the measured temperature of the ICM if only a thermal model is used to fit the spectrum. Assessing AGN contribution is therefore a crucial step in determining the properties of the ICM.

### 4.4 Implementation of RASS Data

Because most of our objects extend over the entire single Suzaku pointing, a local Suzaku background region is not consistently available to assess the background contamination in our source regions. To aid in constraining the LHB, MWH, and CXB, we employ ROSAT All-Sky Survey (RASS) background spectra sensitive to the 0.1-2.4 keV X-ray regime. RASS spectra were obtained through the HEASARC X-ray background tool [http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xraybg/xraybg.pl] in an annulus of inner radius 0.5 degrees and outer radius 1 degree centred on each of our sources. The size of this annulus is sufficient to minimize contamination from the source itself where the largest $r_{500}$ radius found for an object in our sample only extends to $\sim 20$ per cent of the inner radius of the RASS background region.

### 5 IMAGE ANALYSIS

#### 5.1 Determination of the optimal aperture for the spectral analysis region

The region of our initial spectral analysis for each object was established to encircle where the emission from the source dominates the emission from the background. Then, this allows the parameters describing the source spectrum to be determined in a high S/N region. This optimal region was determined from vignetting and exposure corrected images of the source as well as simulated images of the background estimated from RASS spectra.

For each Suzaku pointing, an exposure map was created with xisexpmapgen and a flat field using xissim. The flat field was simulated over the XIS 0.5-10 keV energy range at a monochromatic photon energy of 1 keV for a uniform sky out to 20 arcmin.

An image of the NXB particle background for each pointing was produced with xisnxbgen over the same energy range. This image was estimated from night Earth observations within 150 days of the Suzaku observation date. The NXB image was uniformly corrected by dividing the count rates by the exposure time.

Emission from the CXB, LHB, and MWH was estimated from RASS background spectra. These spectra were fit with the background model: $apec_{LHB} + wabs(apec_{MWH} + powerlaw_{CXB})$. Because the RASS background spectrum consists of only 7 data points, only the normalizations of the three background components were allowed to vary; the

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**Table 1. Summary of Observations**

| Object | Sequence Number | RA    | Dec   | Start Date    | Exposure [ks] | type |
|--------|----------------|-------|-------|---------------|---------------|------|
| FGS03  | 807052010      | 07:52:44.2 | +45:56:57.4 | 2012 Oct 28 18:39:14 | 14.3 | F   |
| FGS04  | 807053010      | 08:07:30.8 | +34:00:41.6 | 2012 May 06 16:24:20 | 10.1 | NC  |
| FGS09  | 807050010      | 10:43:02.6 | +00:54:18.3 | 2012 May 30 05:18:38 | 9.9  | NC  |
| FGS14  | 807055010      | 11:46:47.6 | +09:52:28.2 | 2012 May 29 17:06:08 | 12.4 | F   |
| FGS15  | 807057010      | 11:48:03.8 | +56:25:26.5 | 2012 May 26 17:58:41 | 13.6 | NF  |
| FGS24  | 807058010      | 15:33:41.1 | +03:36:57.5 | 2012 Jul 28 08:10:10 | 13.2 | NF  |
| FGS25  | 807049010      | 15:39:50.8 | +30:43:04.0 | 2012 Jul 28 18:06:02 | 10.6 | NF  |
| FGS26  | 807054010      | 15:48:55.9 | +08:50:44.4 | 2012 Jul 29 02:05:54 | 8.6  | F   |
| FGS27  | 807056010      | 16:14:31.1 | +26:43:50.4 | 2012 Aug 05 07:14:36 | 10.6 | F   |
| FGS30  | 807051010      | 17:18:11.9 | +56:39:56.1 | 2012 May 02 11:43:31 | 14.0 | F   |

* The fossil status column contains the Z14 updated fossil characterizations of the S07 catalogue. In the fossil status column, ‘F’ is a confirmed fossil, ‘NF’ is a rejected fossil, and ‘NC’ is not confirmed as either a fossil or non-fossil according to Z14 and remains a fossil candidate.
other parameters were fixed at the standard literature values as described in Section 4.1. The ROSAT PSPC response matrix provided by the background tool was implemented for the fit. In calculating the background photon flux in the Suzaku XIS 0.5-10 keV energy range, the XSPEC dummyrsp command was used to extrapolate beyond the ROSAT PSPC sensitivity range of 0.1-2.4 keV.

An image of the estimated CXB+LHB+MWH emission was produced with xissim out to a radius of 20 arcmin from the coordinates of the X-ray centre of the systems. The emission was modeled with the best-fitting spectral model and photon flux of the RASS background data. Due to the low count rate of CXB+LHB+MWH photons over the exposure time for each object, the exposure time was increased by a factor of 10 to improve the statistics of the surface brightness profile of the resulting image following the method of Kawaharada et al. (2010).

An image of the source could then be created from the images constructed during this procedure. Because the NXB background is not affected by vignetting, the exposure corrected image of the NXB was subtracted from the exposure corrected image of the XIS detector. The resulting image was then vignetting corrected with the flat field and the vignetting and exposure corrected image of the CXB+LHB+MWH was subtracted to obtain the estimated image of source emission.

Surface brightness profiles were created using ds9 for the vignetting corrected source, NXB, and CXB+LHB+MWH images as shown for example in Fig. 2. The coordinates of peak X-ray emission (Table 2) were used as the centre of the surface brightness profile. The profile was constructed from 20 uniformly spaced circular annuli out to the radius of the largest circle that could be inscribed within the XIS FOV from the centre coordinates. The source and combined background profiles were then averaged for the three XIS detectors and the radius at which the source and background emission were equal was identified. This radius delimits the region where the source emission accounts for at least 50 per cent of the total emission and it is this optimal radius $r_{ap, opt}$ which we have used to define our region of initial source spectral analysis.

5.2 Surface Brightness Analysis

Observed surface brightness profiles were constructed for each object using the stacked 0.5-10 keV XIS0+XIS1+XIS3 observed image. The number of annuli for each profile was determined such that each annulus had at minimum 225 counts, which, assuming Poissonian noise, requires the number of counts to be 15 times the error.

The brightness profile of a spherically symmetric and isothermal ICM in hydrostatic equilibrium will follow a $\beta$-model (Cavaliere & Fusco-Femiano 1976, 1978). These are appropriate assumptions for virialized and relaxed groups and clusters. Disparity between the data and the single $\beta$-model can therefore result from processes such as merger asymmetries, multiple thermal components, and non-thermal emission, for example, as produced by an AGN. Here we test for deviations from the $\beta$-model and if these deviations can be ascribed to contribution from a non-thermal point source.

\begin{align}
S_{\text{MI}}(r) &= S_0(1 + (r/r_c)^2)^{-3\beta + 1/2} + k, \quad (1)
\end{align}

where $S_0$ is the central surface brightness, $r_c$ is the core radius, and $k$ is the background surface brightness. Fits were performed with the Sherpa Python module (Doe et al. 2007). To determine if there is a point source contribution to the surface brightness of the system, a second model is then fit, consisting of a Gaussian component added to the first model.

Table 2. General information

| FGS | Coordinates of Peak X-ray $a$ | Dec | $z^c$ | $n_H^d$ [$10^{20}$ cm$^{-2}$] |
|-----|-------------------------------|-----|-------|-------------------------------|
| 03$^*$ | 07:52:46.48 | +45:56:48.04 | 0.052 | 5.06 |
| 04 | 08:07:29.47 | +34:01:02.95 | 0.208 | 4.27 |
| 09 | 10:43:03.33 | +00:54:33.26 | 0.125 | 3.88 |
| 14$^*$ | 11:46:47.37 | +09:52:33.38 | 0.221 | 2.89 |
| 15 | 11:48:02.43 | +56:54:49.57 | 0.105 | 0.998 |
| 24 | 15:33:43.74 | +03:37:03.74 | 0.293 | 3.65 |
| 25 | 15:39:49.57 | +30:42:58.40 | 0.097 | 2.29 |
| 26$^*$ | 15:48:56.03 | +08:50:51.27 | 0.072 | 3.14 |
| 27$^*$ | 16:14:30.77 | +26:44:02.18 | 0.184 | 3.61 |
| 30$^*$ | 17:18:11.79 | +56:39:51.33 | 0.114 | 2.21 |

$^a$ [SMS2007] ID

$^b$ Coordinates determined from the stacked XIS0+XIS1+XIS3 raw count image in the 0.5-10 keV band

$^c$ Spectroscopic redshift of the central bright galaxy in the fossil cluster (S07)

$^d$ Weighted average galactic hydrogen column density in the direction of the target (Kalberla et al. 2005)

$^e$ Confirmed fossil system

Figure 2. An example of the source and background surface brightness profiles for FGS30. The bottom right panel shows the average source and background profile for the three XIS detectors.

Our initial fit of the profiles consists of a $\beta$-model plus a background constant.
where $A$, $r_0$, and $\sigma$ are parameters of the Gaussian: $A$ is the normalization, $r_0$ is the radial location of the peak, and $\sigma$ is the standard deviation. To ensure the point like nature of the Gaussian, the standard deviation of this component was fixed to $\sigma = 51$ arcsec, corresponding to the Suzaku PSF of 2 arcmin.

To determine if the addition of a Gaussian component to the $\beta$-model produces a statistically significant decrease in the $\chi^2$ of the fit, we adopt the $p$-value estimation method of [Protassov et al. (2002)]. To do this, we define $S_{M1}$ as our null model and $S_{M2}$ as the alternative model. The F-statistic [Bevington & Robinson (2003)]

$$F = \frac{\chi^2_{M1} - \chi^2_{M2}}{\chi^2_{M2}/\text{dof}_{M2}}$$

was computed for the observed profile. The best-fitting parameters of $S_{M1}$ were then used to simulate 10,000 fake profiles. Each simulated profile had noise applied to the $y$-values where the noise was created at each data point by randomly sampling a Gaussian distribution centred on the observed $y$-value with a standard deviation equal to the difference between the observed data and original best-fitting null model. The $S_{M1}$ and $S_{M2}$ models were fit at every iteration and the F-statistic was recorded. The final $p$-value is approximated as the fraction of simulations with a F-statistic greater than the F-statistic for the observed profile. The lower the $p$-value, the less likely the improved fit of $S_{M2}$ is due to noise.

The results of these fits are recorded in Table 3 along with the corresponding $p$-values. Fig. 3 shows the observed surface brightness profiles and the fitted profiles. We note FGS09, FGS30, and FGS03 have low $p$-values of $p \leq 0.05$. Because the annuli used are much smaller than the Suzaku XRT PSF and, additionally, discrepancy from a $\beta$-model could be attributed to multiple phenomena, we interpret the results as merely suggestive and to be used in conjunction with our spectral analysis.

6 SPECTRAL ANALYSIS

Our spectral analysis consists of measuring spectral properties within a region of high signal to noise (Section 6.1) and using these results to classify these objects as thermally dominated or AGN contaminated (Section 6.2). The results of this section will then be used to measure or estimate the global properties of the thermally dominated systems within $r_{300}$ (Section 7).

6.1 Spectral fitting in an optimal region

In order to disentangle ICM emission from potential contaminating point source emission, we perform our analysis on the optimal aperture region where the background emission is less than half of the total emission from the object. By determining this optimal aperture size, $r_{ap, opt}$ as described in Section 5.1, we make no assumptions on the type of source emission. Extracting a spectrum from this region therefore optimizes the spectral analysis of any type of source over the background whether the source is dominated by thermal emission from the ICM or non-thermal emission from an AGN.

The results of our surface brightness profile analysis indicate some objects in our sample may have a strong non-thermal point-like component to the total emission. As a result, we compare the fit of three source models to our spectra:

(i) an absorbed thermal plasma model, $wabs \times apec$, to model the intracluster medium,
(ii) an absorbed power-law, $wabs \times \text{powerlaw}$, to model an AGN,
(iii) an absorbed combined thermal and power-law model, $wabs(apec + \text{powerlaw})$, to describe contribution from both the ICM and an AGN,

where the $wabs$ absorption component models galactic absorption for all three models.

The background and foreground sources consist of the NXB, LHB, MWH, and CXB. The NXB spectrum was used as the background file for the extracted $r_{ap}$ region to be subtracted directly during the spectral fit. The CXB, LHB, and MWH were accounted for through modeling as described in Section 4.1.

The XIS spectra were grouped with grppha such that each bin had a minimum 25 counts. The binned Suzaku XIS0, XIS1, and XIS3 spectra were fit simultaneously with the RASS background spectrum. The Suzaku spectra were fit with the source and background model while the RASS spectra were fit only with the background model. The RASS best-fitting parameters were tied to that of the Suzaku spectra with a scaling factor to account for the difference in the angular size of the spectral extraction regions. Bad channels were ignored for all spectra. The Suzuki XIS0 and XIS3 spectra were fit over 0.7-10 keV (Sec. 6.1.1), the XIS1 spectra were fit only with the background model. The RASS spectra were fit over 0.7-7 keV, and the RASS spectra over the range 0.1-2.4 keV.

In all three models, the neutral hydrogen column density was assigned the weighted average galactic value in the direction of the source [Kalberla et al. (2005)]. The redshifts of our systems were taken to be the spectroscopic redshifts of the bright central galaxies as determined by S07. During the fit, the column density and redshift were always fixed. The metal abundance $Z$ component of the $apec$ model was calculated using the abundance tables of [Anders & Grevesse (1989)]. The photon index of the $\text{powerlaw}$ model was constrained to be within $\Gamma = 1.5 - 2.5$ [Ishibashi & Courvoisier (2010)]. Initially, all other parameters were left free to be fit. However, if during the fit, convergence on a parameter within the physically reasonable limits did not occur, the fit was performed again with the parameter fixed. In all further tables, parameters presented without error bars were fixed to a reasonable value. Parameters with infinite error bars are unconstrained, but have a value resulting from the convergence of the fit - these parameters have very little effect on the final result of the fit.

The resulting best-fitting parameters are listed in Table 4 and the best-fitting models to the spectra are shown in Fig. 3. The background parameters resulting from each of the model fits were consistent with each other within one sigma errors.
Figure 3. Surface brightness profiles of the stacked XIS image in the 0.5-10 keV band. The best-fitting $\beta$-model is plotted in solid red; the best-fitting $\beta+$Gaussian model is plotted in solid blue. Dashed lines represent the component to one of the models. If the $p$-value was $\leq 0.05$ the $\beta+$Gaussian model components are shown in red, otherwise the $\beta$-model components are plotted in blue. Residuals for the $\beta$-model are plotted as red squares, while the blue triangles are associated with the $\beta+$Gaussian model.
6.1.1 A soft energy excess

While the XIS is sensitive to photons with energy as low as 0.5 keV, we have excluded the $E < 0.7$ keV energy channels from our spectral analysis. In the majority of our observations, an apparent excess in counts was found in the 0.5-0.7 keV range when compared to the fit of the apec or powerlaw models in the $E > 0.7$ keV range. Potential origins of this soft excess include a second thermal component in the source, an AGN, or statistical fluctuations. Adding a second thermal model to the ICM model did not improve the fit. If an AGN was the origin of the excess, removing the softest energies should not greatly deter detecting the presence of its emission in the spectra because an AGN will contribute most strongly to the harder energies of the spectrum. Because the origin of this excess is uncertain and thus cannot be appropriately modeled in the spectra, and furthermore the excess only affects the first few low energy channels in the spectrum, we exclude this softest energy regime from our fits. We note however, that this will make it more difficult to measure the ICM properties of groups with cooler temperatures.

6.2 Comparison and interpretation of the model fits

When comparing the fits of the three models, the combined apec + powerlaw model is found to poorly fit every object in our sample. In this combined fit, the apec and powerlaw components are never simultaneously constrained. As a result, while some apec + powerlaw fits return $\chi^2$ values less than that for the respective simpler fits of apec or powerlaw only, we decide to choose the simpler model that has all parameters constrained.

By the $\chi^2$ values, the powerlaw model provides a better fit over the thermal apec model for FGS09, FGS03, FGS15, and FGS24. We consider these four objects to be dominated by a non-ICM source and with our current observations, we cannot disentangle the ICM and non-ICM emission. Further discussion on these objects is provided in Appendix E.

7 GLOBAL ICM TEMPERATURES AND LUMINOSITIES

In order to compare the ICM temperatures and luminosities of our fossil systems with those of other groups and clusters, we calculate these properties within the fiducial radius of $r_{500}$, the radius at which the average enclosed density is 500 times the critical density of the universe. We calculate $r_{500}$ and the spectral properties within this radius, using an iterative procedure.

Using the temperature calculated within some aperture, $T_{ap}$, we calculate $r_{500}$ using the $r_{500} - T_{ap}$ relation of Arnaud et al. (2005):

$$ r_{500} = 1.104 \times \frac{h_{70}^{-1} E(z)^{-1}}{kT} \left(\frac{5}{4} \text{ keV}\right)^{0.57} \text{ Mpc} \quad (4) $$

where $h_{70} = H_0/(70 \text{ km s}^{-1} \text{ Mpc}^{-1})$ and $E(z) = H(z)/H_0 = \sqrt{\Omega_M (1 + z)^3 + \Omega_k (1 + z)^2 + \Omega_{\Lambda}}$ (Hogg 1994). This value of $r_{500}$ is used as our next radius of extraction to determine a new $T_{ap}$, and continue this process until convergence is reached between $r_{500}$ and the temperature, and we have thus determined $T_{500}$. This analysis is performed on the subset of our sample that is thermally dominated (Section 6.2). The iterative process is begun with the $T_{ap}$ determined from the apec only fit as recorded in Table 3.

For two of our objects, FGS25 and FGS26, the final estimation of $r_{500}$ extends beyond the largest aperture radius that can be inscribed within the XIS FOV. However, our estimated $r_{500}$ is very similar to the largest aperture size that was used to extract spectral parameters, where the ratio between max($r_{ap}$) and $r_{500}$ is 0.98 and 0.84 for FGS25 and FGS26 respectively. As a result the $T_{ap}$ values for these two objects should reasonably describe the true global temperature within $r_{500}$. When considering the luminosity, $L_{500}$ is estimated from $L_{ap}$ using a surface brightness profile model that well describes the ICM emission. By integrating this surface brightness model over area, the conversion factor between $L_{500}$ and $L_{ap}$ is calculated using the relation

$$ \frac{L_{500}}{L_{ap}} = \frac{\int_{r=0}^{r_{500}} S(r) r dr}{\int_{r=0}^{r_{ap}} S(r) r dr} \quad (5) $$

where $S$ is an azimuthally averaged radial surface brightness profile. For our surface brightness model, we use the $\beta$-model where $S_0$, $r_c$, and $\beta$ have the values recorded in Table 3 for the $\beta$-model only fit. We find there is little difference between $L_{X_bol,ap}$ and $L_{X_bol,500}$.

Table 3. A comparison of 0.7-10 keV fits in the optimized aperture radius

| FGS  | $r_{ap}$  | $r_c$  | $\beta$  | $kT$ [keV] | $\chi^2/(\nu-1)$ |
|------|-----------|--------|----------|------------|------------------|
| 03   | 82.41±2.2 | 51.3   | 0.70     | 0.7-0.7   | 209/77           |
| 04   | 6.3±0.2   | 23.7   | 0.73     | 0.6-0.7   | 29/20            |
| 09   | 19.4±1.0  | 95.9   | 0.64     | 0.5-0.6   | 124/5.6          |

Note: Units of $\text{cts s}^{-1} \text{ Mpc}^{-2}$.

* Confirmed fossil system.

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With the global temperature values listed in Table 5, we estimate the masses within \( r_{500} \) for our systems using the \( M_{500} - T_X \) relation of Arnaud et al. (2005)

\[
M_{500} = 3.84 \times 10^{14} \, h_{70}^{-1} \, E(z)^{-1} \left( \frac{kT}{5 \text{keV}} \right)^{1.71} \, M_\odot
\]

We find our thermally dominated objects have masses consistent with clusters (\( M_{500} \gtrsim 10^{14} \, M_\odot \)).

8 SCALING RELATIONS

We combine our newly measured global \( L_X \) and \( T_X \) with previously measured fossil systems properties, to constrain the scaling relations of these objects with the goal of assessing if fossil systems display different scaling relations than those for normal groups and clusters. Our analysis of fossil system scaling relations is distinguished from previous studies through several updates including the fitting of the largest assembled fossil system data set, using recent X-ray and optical data for our control sample of normal groups and clusters, and a substantial effort of homogenizing both the fossil and non-fossil data sets. We furthermore record the best-fitting \( L_X - L_r \) relation, and for the first time record the slope and y-intercepts of the \( L_X - T_X \), \( L_X - \sigma_v \), \( T_X - \sigma_v \) scaling relation fits for fossil systems.

Figure 4. The XIS0 (black), XIS1 (red), and XIS3 (green) spectra from the optimized \( r_{\text{opt}} \) region determined in Section 5.1. The best-fitting model to the observed spectra as determined by the \( \chi^2 \) values in Table 4 is plotted in a solid line. The RASS spectrum that was simultaneously fit with the Suzaku background model is not shown.
Table 5. Global Properties of the ICM dominated subsample

| FGS | \( r_{500}/r_{200} \) | \( kT_{\text{arc}} \) | \( Z_{\text{arc}} \) | \( L_{X,\text{bol},ap} \) | \( r_{500} \) | \( L_{X,\text{bol},r_{500}} \) | \( M_{500} \) |
|-----|-----------------|-------------|-------------|-----------------|-------------|-----------------|------------|
| 04  | 1               | 2.81±0.19   | 0.40±0.11   | 5.03±0.19       | 3.5" (0.71 Mpc)| 5.03±0.19       | 1.32±0.1  |
| 14* |                 | 5.26±0.44   | 0.21±0.09   | 7.71±0.29       | 4.8" (1.03 Mpc)| 7.71±0.29       | 3.8±0.5   |
| 25  | 0.98            | 3.92±0.15   | 0.26±0.09   | 3.80±0.09       | 8.5" (0.92 Mpc)| 3.83±0.09       | 2.43±0.2  |
| 26* | 0.84            | 3.33±0.34   | 0.19±0.09   | 0.70±0.04       | 10.3" (0.85 Mpc)| 0.76±0.04       | 1.9±0.3   |
| 27* | 1               | 3.30±0.33   | 0.18±0.13   | 3.38±0.16       | 4.3" (0.80 Mpc)| 3.38±0.16       | 1.7±0.3   |
| 30* | 1               | 3.39±0.15   | 0.30±0.05   | 3.06±0.06       | 6.8" (0.84 Mpc)| 3.06±0.06       | 1.9±0.1   |

* Confirmed fossil system

Note: \( L_{X,\text{bol}} \) is the unabsorbed X-ray luminosity in the 0.1-100 keV energy range.

8.1 Sample Assembly, Correction, and Fitting

We have assembled data from a number of studies to investigate how the global X-ray and optical properties of fossil systems compare to non-fossil groups and clusters. To ensure a reliable comparison, we have made an effort to use quantities determined within the same fiducial radius and defined the same way. For our analysis we use bolometric X-ray luminosities \( L_{X,\text{bol}} \), temperatures \( T_X \), and optical SDSS \( r \)-band luminosities \( L_r \) all calculated within \( r_{500} \), and global velocity dispersions \( \sigma_c \). While we have removed known fossils from our sample of non-fossil groups and clusters, we do not have information on the magnitude gap between the first and second brightest galaxies in all of the systems making up our control sample. However, the large magnitude gap characterizing fossil systems should be found in only a fraction of \( L_{X,\text{bol}} \geq 5 \times 10^{41} \text{ ergs s}^{-1} \) systems (Jones et al. 2003, Milosavljević et al. 2006). Thus, we expect our control sample is contaminated by at most a few unidentified fossil systems.

To assemble our group sample, we use the \( \sigma_c \) of the ‘G-sample’ from Osmond & Ponman (2004). Group \( T_X \) values are pulled from Rasmussen & Ponman (2007), Sun et al. (2009), Hudson et al. (2010), Eckmiller et al. (2011), and Lovisari et al. (2013). Lovisari et al. (2013) \( L_{X,0.1-2.4\text{keV}} \) are transformed to \( L_{X,\text{bol}} \) using the conversion tables of Böhringer et al. (2004).

For the cluster sample, we use the G14 \( r \)-band optical luminosities calculated within \( r_{500} \). The corresponding velocity dispersions are taken from Girardi et al. (1998), Girardi & Mezzetti (2001), Girardi et al. (2002), Popesso et al. (2007) and Zhang et al. (2011). Bolometric X-ray luminosities within \( r_{500} \) and temperatures were sourced from Pratt et al. (2009) and Maughan et al. (2012), and supplemented with additional \( L_{X,\text{bol}} \) from Zhang et al. (2011) and \( T_X \) from Wu et al. (1999) and Hudson et al. (2010).

Taking our sample of fossil systems observed with Suzaku, we match the global X-ray properties of the systems in Table 5 with the corresponding \( L_r \) from G14 and \( \sigma_c \) from Z14. For the remainder of the Z14 confirmed fossil catalogue, we supplement the \( L_{X,\text{bol}} \) from G14. For improved consistency with the X-ray luminosities of our cluster sample, we approximate \( L_X \) that more closely resemble those computed using the growth curve analysis (GCA) method (Böhringer et al. 2008) from the G14 luminosities derived from RASS counts (see Section 3.3 of G14 for details). These corrected luminosities also show good agreement with the Suzaku measured \( L_X \) for the sample of objects shared between both the G14 study and ours.

We add to the fossil sample with the X-ray luminosities and temperatures from KP107 and Miller et al. (2012), matched with the \( L_r \) and \( \sigma_c \) data from Proctor et al. (2011). The KP107 \( L_{X,\text{bol},200} \) are rescaled to \( r_{500} \) using their best-fitting \( \beta \)-model parameters and our luminosity conversion Eq. [5]. To ensure consistency with our Suzaku sample, the \( r_{500} \) of KP107 is recalculated from their temperatures using our Eq. [4] and we use this value to estimate \( L_{X,\text{bol},500} \). To rescale the \( L_{r,200} \) of Proctor et al. (2011) to \( r_{500} \), we assume the light follows the mass, which is a good approximation on the global scale of groups and clusters (Bahcall & Kulkier 2014). For a NFW density profile with concentration parameter \( c = 5 \), \( M_{500}/M_{200} = 0.70 \) (Navarro et al. 1997).

The assumption of \( c = 5 \) was chosen for agreement with the concentrations of normal clusters of similar temperature and mass (Pointecouteau et al. 2005; Pratt & Arnaud 2007; Vikhlinin et al. 2006; Bronte et al. 2007; Ettori et al. 2010) because the typical concentration parameter for fossil systems is poorly characterized. Thus, we can rescale using \( L_{opt,500}/L_{opt,200} \propto 0.70 \). Here, the correction relation is applied only to the non-BCG light.

We also implement the fossil catalogue of Harrison et al. (2012). We take their \( L_{X,\text{bol},200} \) and rescale by assuming a \( \beta \)-model with \( r_c \) estimated using the \( r_c - L_X \) relation of Böhringer et al. (2008) and \( \beta = 0.67 \), then correcting to \( L_{X,\text{bol},500} \) using Eq. [5]. The optical luminosities provided are calculated for \( r = 0.5r_{200} \sim r_{1000} \). By the reasoning described previously, this luminosity is corrected to \( L_{r,500} \) using the relation \( M_{500}/M_{1000} \propto 1.3 \). Because the magnitudes of the BCG were not recorded, we rescale all of the optical light for these objects. The Harrison et al. (2012) \( \sigma_c \) are also used, and we assign a 0.1 dex error to these values during our fit of the fossil scaling relations.

With the above data sets, we have enough data to assemble and quantitatively compare the \( L_X - T_X \), \( L_X - \sigma_c \), \( L_X - L_r \), \( T_X - \sigma_c \) scaling relations for a sample of fossils and a control sample of normal groups and clusters. We do not investigate the \( T_X - L_r \) relation due to the small subsample of our control population with both \( T_X \) and \( L_r \) measurements.

We fit the equation

\[
\log(Y) = a + b \log(X)
\]

to the data using the BCES orthogonal method (Akritas & Bershady 1996) which accounts for measurement errors in the data as well as intrinsic scatter in the fitted relation. We choose to compare the fit of the fossil sample to a combined sample of groups and clusters (G+C)
in the same parameter range as the fossil sample. For the fossil system data set we exclude NGC 6482 from KPJ07 and XMMXCS J030659.8+000824.9 from Harrison et al. (2012) as they are clear outliers.

We cross-checked the results obtained with the BCES method with the IDL Astronomy library tool LINMIX_ERR (Kelly 2007), a Bayesian fitting method for linear regression. The plotted scaling relations and BCES fits are shown in Fig. 5 and the best-fitting parameters of the relations are recorded in Table 6. Uncertainties on the BCES best-fitting parameters are estimated using 10,000 bootstrap resamplings. For the LINMIX_ERR fits, the quoted values are the mean and the standard deviation of the posterior distributions for the regression parameters. We investigate changing the pivot point of the fits i.e. rescaling the $X$ and $c$. 

---

**Figure 5.** $L_X$, $T_X$, $L_r$, $σ_v$ scaling relations for fossils and non-fossil samples. We abbreviate this current work as K15, Zarattini et al. (2014) as Z14, Girardi et al. (2014) as G14, Miller et al. (2012) as M12, Proctor et al. (2011) as P11, Khosroshahi et al. (2007) as KPJ07 and Harrison et al. (2014) as H12. The plotted lines are the orthogonal BCES fits to the fossil sample (dashed line) and to our sample of groups and clusters (solid line) in the same parameter range as the fossils.
Y values in Eq. [7] by a constant, but no difference is found in the returned fits.

We find the BCES fits to the fossil sample are consistent within error to the combined groups and clusters fit for each scaling relation investigated in this work. The LINMIX fossil and non-fossil fits are consistent with the exception of $L_X-\sigma_v$. Because the remaining three fits are in agreement with each other, the discrepancy in the $L_X-\sigma_v$ fits is most likely due to inhomogeneities in the data or the small sample size of both the fossil and control populations.

The global properties involved in these scaling relations: $L_X$, $T_X$, $L_{opt}$, $\sigma_v$, are determined predominantly by the shape and depth of the potential well, and are thus well documented proxies for the total mass of the system. Additional important effects that determine the X-ray properties of the ICM include the entropy structure [Donahue et al. 2001] and non-gravitational heating and cooling processes, such as can be caused by AGN or mergers. These factors can produce dispersions in the scaling relations between X-ray and optical mass proxies. Finding no difference in the scaling relations between fossil and non-fossil groups and clusters thus indicates fossil systems are of similar mass as non-fossils, and on the global scale, the combined effect of mass, ICM entropy, and non-gravitational processes that have occurred in fossil systems are similar to the combined effect of those that have occurred in normal groups and clusters.

### 8.2 Comparison with previous studies

Our result that fossil share the same $L_X-T_X$ relation as non-fossil groups and clusters is consistent with previous studies [Proctor et al. 2011; Harrison et al. 2012, KPJ07, G14]. However, the comparison of optical and X-ray properties of fossil and non-fossil systems is a contentious issue in the literature.

Our $L_X-L_r$, $L_X-\sigma_v$, $T_X-\sigma_v$ scaling relation fits show the relations of fossil systems are consistent within error to normal groups and clusters. This is in good agreement with the findings of Harrison et al. [2012] and G14. G14 recorded the first quantitative values of their fit to the $L_X-L_r$ relation and found no difference between fossil systems ($L_X \propto L_r^{1.82\pm0.3}$) and a sample of non-fossil clusters ($L_X \propto L_r^{1.78\pm0.08}$). Qualitatively we both find no difference in the $L_X-L_r$ fossil and non-fossil scaling relations. Differences between the slopes and y-intercepts of our fits and those of G14 could be due to multiple reasons: (i) we use bolometric $L_X$ in our fits, while G14 uses $L_X,0.1-2.4keV$, (ii) our $L_X$ are defined within $r_{500}$ while the fitted G14 $L_X$ represent a total luminosity that has not been defined within a precise radius, (iii) we use different fitting methods. Again, we emphasize that although numerically the fits are different, the interpretation is the same: fossil systems follow the same $L_X-L_r$ scaling as non-fossil systems. Furthermore, our new measured fits for the $L_X-\sigma_v$ and $T_X-\sigma_v$ relations support the conclusion that on the global scale, fossil systems have optical and X-ray properties congruent with those of normal groups and clusters.

Accumulation of multiple differences in data and methodology explain the differences in conclusions between our study and those of earlier studies [Proctor et al. 2011, KPJ07] that find discrepancies in the optical and X-ray scaling relations for fossil and non-fossils. We have compared

### Table 4

| $kx$ | $z$ | $\chi^2$ | $\chi^2$ | $\chi^2$ |
|------|------|----------|----------|----------|
| 0.1  | 0.2  | 0.3      | 0.4      | 0.5      |
| 0.6  | 0.7  | 0.8      | 0.9      | 1.0      |
fossil and non-fossil optical luminosities measured from the same photometric catalogue and band, avoiding the need to make approximative luminosity estimations for comparisons between samples. We have also used optical luminosities defined within the same fiducial radius, thus ensuring a more equal comparison between data pulled from multiple catalogues. Additionally, our large sample size of fossils reduces the effect of noise to ensure a more reliable comparison between the fossil and non-fossil samples.

We note however, that our best-fitting parameters for both the fossil and non-fossil samples have large errors. Thus, a study of fossil scaling relations could be greatly improved in the future by larger and more homogeneous data sets. Furthermore, our results probe the relations of clusters and high mass groups, and consequently it is possible differences in the scaling relations exist in the low mass end (Khosroshahi et al. 2014).

9 SUMMARY AND CONCLUSIONS

We have presented a detailed study of the ICM X-ray properties for a sample of 10 candidate fossil galaxy systems measured in the X-ray regime for the first time. In particular, Suzaku XIS data have been used to measure their global X-ray temperatures and luminosities and estimate the masses of these galaxy clusters. We determine 6 of our 10 objects are dominated in the X-ray by thermal bremsstrahlung emission and thus we are able to measure the global temperatures and luminosities of their ICM. This sample of six objects has temperatures of 2.8 keV $\leq T_X \leq 5.3$ keV, luminosities of $0.6 \times 10^{44}$ ergs s$^{-1}$ $\leq L_{X,\text{bol}}$ $\leq 7.2 \times 10^{44}$ ergs s$^{-1}$ and occupies the cluster regime in plotted scaling relations.

We have used our sample of newly determined fossil cluster X-ray properties to constrain the scaling relations of fossil systems. We assembled and homogenized a large sample of global $L_X$, $T_X$, $L_r$, and $\sigma_v$ data for both fossil systems and a control sample of non-fossil groups and clusters. Plotting the $L_X-T_X$, $L_X-\sigma_v$, $L_X-L_r$, and $T_X-\sigma_v$ relations reveals no difference between the properties of fossil and non-fossil systems. Furthermore, we provide the first fits to three of these relations which show the relations of fossils systems agree within error to the relations of normal groups and clusters. Our work indicates that on the global scale, fossil systems are no different than non-fossil systems. However, the identifying large magnitude gap in the bright end of the fossil system luminosity function is still unexplained and thus further studies are necessary to characterize the properties of these objects and understand their nature.

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APPENDIX A: TESTING FGS24 FOR SWCX CONTAMINATION

The NASA WIND-SWE proton flux light curve displays elevated flux levels > 4 × 10^6 cm^-2 s^-1 during a significant portion of the FGS24 observation (Fig. A1) which indicates SWCX photons may contaminate the lower <1 keV region of the spectrum (see Section I.2). To test for evidence of this contamination, we repeat the spectral analysis of Section 4.2 for the time intervals where the flux was > 1 keV region. These results are recorded in Table A1 and we find these results are consistent within error with those of using the full timespan of the observation (Table 1).

APPENDIX B: NOTES ON THE SAMPLE

FGS03 is a Z14 verified fossil system. The AGN (2MASX J07524421+4556576) associated with the BCG of this system is both confirmed in the optical (Véron-Cetty & Véron 2012) and radio. The radio emission from this object consists of strong bipolar jets extending 57 arcsec (Hess et al. 2012). This AGN has also been identified as a Type I Seyfert (Stern & Laor 2012). This AGN appears to dominate the X-ray emission observed from FGS03. Our imaging analysis returns a best-fitting model consisting of a β-model+Gaussian, where the Gaussian dominates over the
Table A1. A comparison of fits in 0.7–10 keV

| FGS  | spec | norm | $\chi^2$/d.o.f. | $\chi^2$/d.o.f. | $\chi^2$/d.o.f. |
|------|------|------|----------------|----------------|----------------|
| FGS24 |      |      |                |                |                |
| FGS15 |      |      |                |                |                |
| FGS19 |      |      |                |                |                |
| FGS04 |      |      |                |                |                |
| FGS09 |      |      |                |                |                |

$a$ norm has units of photons keV$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ at 1 keV

Figure A1. Top: XIS1 light curve for FGS24 during the span of its observation. Bottom: The WIND-SWE proton flux light curve plotted for the same time span. Proton flux has been found to be correlated to SWCX. The elevated proton flux levels during the FGS24 observation may potentially cause significant SWCX contaminating emission.

$\beta$-model in some regions of the surface brightness profile with $p = 0.01$, the lowest $p$-value for our sample. The spectrum of this object is better fit by a power-law ($\chi^2 = 1.02$) than a thermal model ($\chi^2 = 1.17$), and no improvement in the fit occurs when a thermal component is added to the power-law model. Z14 find a velocity dispersion of $\sigma_v = 259$ km/s, the smallest dispersion of the S07 catalogue. Such a low velocity dispersion is typically associated with a cool IGM temperature, which would explain why there appears to be very little thermal emission when compared to a very bright AGN.

FGS04 is a fossil candidate and is has the coolest measured ICM of our sample ($T_X = 2.81$ keV). The BCG of this system contains the blazar NVSS J080730+340042 (Massaro et al. 2009) and in the radio, Hess et al. (2012) find bipolar jets originating from this source. We do not see evidence of contribution from this object in the imaging or spectral analyses. Furthermore the spectrum of FGS04 is fit significantly better by a thermal model than a power-law (compare a $\chi^2$ of 1.14 to 1.43).

FGS09 is a fossil candidate system at $z = 0.125$. A background $z = 0.73$ AGN (QSO B1040+0110; RA=10:43:03.84, DEC=+00:54:20.42) is located 15 arcsec from the peak X-ray coordinates of FGS09. This AGN is confirmed in the optical (Véron-Cetty & Véron 2010) and the radio (Hess et al. 2012) bands. Based on our surface brightness profile and spectral analyses, this AGN is significantly contributing to the observed projected X-ray emission of
FGS09. A Gaussian component with $p = 0.02$ is found in the observed surface brightness profile. A power-law model ($\chi^2 = 0.92$) fits the spectrum of FGS09 much better than the thermal model ($\chi^2 = 1.08$).

**FGS14** is a confirmed fossil system and is the largest, hottest, and most X-ray luminous cluster in our sample, with $r_{500} = 1$ Mpc, $T_X = 5.3$ keV, and $L_X = 3.8 \times 10^{44}$ ergs s$^{-1}$. Hess et al. (2012) detected radio loud emission from two central sources; however, we did not see evidence of X-ray bright non-thermal emission in our imaging or spectral tests.

**FGS15** is a rejected fossil candidate (Z14). There are a number of contaminating sources in the XIS FOV of this source. A radio loud AGN with an asymmetric jet is associated with the BCG of this system (Hess et al. 2012). Within 40 arcsec of the peak system X-ray, the background ($z = 0.45$) quasar [VV2010] J114803.2+565411 has been identified optically and in the radio (Véron-Cetty & Véron 2014; Hess et al. 2012). Of the two visually distinguishable point sources excluded in our analysis, the object closest to the centre of the system is spatially consistent with the QSO [VV2010] J114755.9+564948 at $z=4.32$ (Véron-Cetty & Véron 2014). The further south removed point source is located at (RA=11:48:08.38, DEC=+56:48:18.64). The closest known spatial match to this object is the radio source NVSS J114838+565327 located ~2 arcmin away. Our surface brightness profile analysis does not reveal contaminating point sources, but the best-fitting spectral model of FGS15 is a power-law. For this object, it is possible multiple AGN are contributing to the observed emission, which could explain the results of the surface brightness analysis. However, as noted by Z14, FGS15 could also be a filament due to its small number of constituent galaxies with large differences in velocity.

**FGS24** is a rejected fossil candidate. No associated AGN were identified in the literature. Our imaging analysis does not indicate a significant contributing point source; however, the spectrum of FGS24 is better fit by a power-law than a thermal model (compare a $\chi^2$ of 1.33 to 1.38). FGS24 was observed during a period of potentially strong SWCX emission. While we found the best-fitting spectral parameters of the full observation match those of the isolated time interval of low proton flux, it is possible SWCX contamination is occurring even during this interval, obscuring the observed emission from FGS24.

**FGS25** is a non-fossil galaxy cluster by the Z14 characterization. It is the second hottest cluster in our sample with $T_X = 3.92$ keV and a corresponding estimated mass of $M_{500} = 2.4 \times 10^{14}$ M$_\odot$. Hess et al. (2012) find a radio loud central point source in this cluster; however, our imaging analysis indicates no point source contribution and our spectral analysis shows the FGS25 spectrum is much better described by a thermal model ($\chi^2 = 0.96$) over a power-law model ($\chi^2 = 1.26$).

**FGS26** is a Z14 confirmed fossil with $T_X = 3.3$ keV and $L_X = 1.9 \times 10^{44}$ ergs s$^{-1}$. However, we find no associated significant non-thermal signatures in the spectrum or surface brightness profile.

**FGS27** is a confirmed fossil with measured global properties of $T_X = 3.3$ keV and $L_X = 3 \times 10^{44}$ ergs s$^{-1}$. Our imaging and spectral analyses do not indicate contribution of significant non-thermal emission.

**FGS30** is a confirmed fossil with with measured global properties of $T_X = 3.4$ keV and $L_X = 2.8 \times 10^{44}$ ergs s$^{-1}$. A radio loud AGN (2MASX J17181198+5639563) is associated with its bright central galaxy (Hess et al. 2012). Interestingly we find find some evidence of a point source in the surface brightness profile with $p \leq 0.05$; however the spectrum of FGS30 is better described by the thermal model ($\chi^2 = 1.05$) in comparison to the power-law model ($\chi^2 = 1.41$). The ratio of the strength of the Gaussian and the $\beta$-model in the brightness profile reveals FGS30 has a much weaker point source than FGS09 and FGS03, and it may not be contributing significantly enough in the X-ray to influence the fit of the spectrum.