XMM-NEWTON OBSERVATIONS OF EVOLUTION OF CLUSTER X-RAY SCALING RELATIONS AT $z = 0.4–0.7$

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ABSTRACT

We present a spatially resolved analysis of the temperature and gas density profiles of galaxy clusters at $z = 0.4–0.7$ observed with XMM-Newton. These data are used to derive the total cluster mass within the radius $r_{500}$ without assuming isothermality and also to measure the average temperature and total X-ray luminosity, excluding the cooling cores. We derive the high-redshift $M$-$T$ and $L$-$T$ relations and compare them with the local measurements. The high-redshift $L$-$T$ relation has low scatter and evolves as $L \propto (1 + z)^{1.8 \pm 0.3}$ for a fixed $T$, in agreement with several previous Chandra and XMM-Newton studies (Vikhlinin et al., Lumb et al., and Maughan et al.). The observed evolution of the $M$-$T$ relation follows $M_{500} \propto E(z)^{-\alpha}$, where we measure $\alpha = 0.88 \pm 0.23$. This is in agreement with predictions of the self-similar theory, $\alpha = 1$.

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

1. INTRODUCTION

Scaling relations between the global cluster parameters such as total mass, X-ray luminosity, and average temperature are important tools for studies of galaxy clusters and their cosmological applications. Simple self-similar theory predicts that these relations have a power-law form, $M \propto T^{3/2}$, and $L_{\text{bol}} \propto T^2$ (e.g., Kaiser 1991). Deviations of the observed relations from these theoretical expectations have been used to assess the role of nongravitational processes in the cluster formation (see Voit 2005 for a recent review).

Of prime interest are relations between the total cluster mass and easily observed quantities such as the average temperature of the intracluster medium (ICM) or X-ray luminosity. Such relations allow one to estimate mass functions for large samples of poorly observed clusters and use them for cosmological constraints. To derive the mass-observable relation requires accurate mass measurements in a representative sample of clusters. Establishing an accurate normalization of the $M$-$T$ and $M$-$L$ relations has been a focus of many recent observational and theoretical studies (Nevalainen et al. 2000; Evrard et al. 1996; Finoguenov et al. 2001; Reiprich & Bohringer 2002; Mathiesen & Evrard 2001; Sanderson & Ponman 2003; Borgani et al. 2004; Arnaud et al. 2005; Vikhlinin et al. 2005a; A. V. Kravtsov et al. 2005, in preparation).

X-ray observations of dynamically relaxed clusters can be used to infer the total mass via the hydrostatic equilibrium equation (e.g., Sarazin 1988). However, these are technically challenging observations that require accurate determinations of the cluster temperature profiles. X-ray mass measurements at radius $r$ are only as accurate as $T$ and $dT/dr$ at that $r$. Simplifying assumptions, such as that the temperature is constant and gas density follows a $\beta$-model, lead to large biases in the mass determination (Markevitch & Vikhlinin 1997). Therefore, it is essential to have direct measurements of the ICM density and temperature distributions at large radii. Long-exposure Chandra X-Ray Observatory and XMM-Newton observations now provide such measurements for samples of low-redshift clusters (Vikhlinin et al. 2005b; Arnaud et al. 2005), and the resulting $M$-$T$ relations are in very good agreement with the state-of-the-art cosmological simulations (Borgani et al. 2004; A. V. Kravtsov et al. 2005, in preparation).

In addition to normalization of the local scaling relations, cosmological applications require experimental constraints on their evolution at high redshifts. Several studies over the past few years have used Chandra and XMM-Newton observations of small samples of distant clusters to study evolution of the $M$-$T$ relation (Ettori et al. 2004; Maughan et al. 2005). However, these works have used an isothermal $\beta$-model to infer cluster masses, which can bias results on evolution of the scaling relations.

In this paper we present a spatially resolved analysis of XMM-Newton observations of a sample of 10 distant clusters spanning a range of temperatures and redshifts, $2.5 \text{ keV} < T < 9 \text{ keV}, 0.4 < z < 0.7$. The large effective area of XMM-Newton provides good statistical quality for most of the distant cluster data. The finite angular resolution of the XMM-Newton mirrors ($\sim 4''$ FWHM or 24 kpc at $z = 0.5$) is the main technical challenge in this analysis. However, this problem can be solved and deconvolved ICM temperature and density profiles can be restored for our distant clusters. We use these measurements to infer the total cluster mass, as well as the X-ray luminosity and temperature, excluding the central cool regions, and thus study the evolution of cluster scaling relations at $z > 0.4$.

All distance-dependent quantities are derived assuming the $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ cosmology with the Hubble constant $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Statistical uncertainties are quoted at 68% CL.

2. OBSERVATIONS AND DATA REDUCTION

Our sample was selected from publicly available XMM-Newton observations of distant clusters. The final goal was to measure the cluster scaling relations at high redshift, and we restricted our sample to objects with $z \geq 0.4$. The selected clusters are listed in Table 1.

We used the data from all EPIC cameras (MOS1, MOS2, and pn). For data reduction, we used the XMM-Newton Science Analysis System (SAS) version 6.0.0 and the calibration database with all updates available prior to 2004 November. All data

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TABLE 1

Summary of XMM-Newton Observations

| Name                  | \(t_{\text{ex}}^a\) | \(\delta_{\text{pn}}^b\) | \(\delta_{\text{MOS}1}^a\) | \(\delta_{\text{MOS}2}^b\) | \(\delta_{\text{MOS}3}^b\) |
|-----------------------|---------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| CL 0016+16............. | 20.5               | 0.86                    | 25.3                     | 0.94                    | 22.2                     | 0.90                    |
| CL 0024+17............. | 31.7               | 0.92                    | 43.6                     | 0.89                    | 42.4                     | 0.88                    |
| MS 0302.5+1717.......... | 5.7                | 1.20                    | 1.00                     | 9.9                     | 9.6                     |
| MS 1054.4–0321.......... | 12.5               | 1.07                    | 19.8                     | 0.97                    | 15.8                     | 0.97                    |
| RX J1120.1+4318.......... | 11.6               | 0.96                    | 16.1                     | 0.99                    | 14.6                     | 0.96                    |
| RX J1334.3+5030.......... | 20.0               | 1.01                    | 26.5                     | 0.99                    | 26.5                     | 0.97                    |
| WJ 1342.8+4028.......... | 17.8               | 1.07                    | 27.6                     | 1.02                    | 25.3                     | 1.01                    |
| WARP J0152.7–1357........ | 33.4               | 0.98                    | 44.7                     | 0.94                    | 46.8                     | 0.90                    |
| RX J0505.3+2849.......... | 12.2               | 0.99                    | 21.5                     | 0.93                    | 20.8                     | 0.90                    |
| CL 0939+472................ | 20.7               | 0.91                    | 30.5                     | 0.85                    | 30.5                     | 0.82                    |

a Clean exposure times, in kiloseconds.

b Ratio of observed 10–15 keV flux outside the field of view to that in the “closed data set.”

3. IMAGE ANALYSIS

We excluded all detectable point sources from the data in our spectral and spatial analysis. The sources were detected separately in the “optimal” 0.3–3 keV, “soft” 0.3–0.8 keV, and “hard” 2.0–6.0 keV energy bands. Detected point sources were masked with circles of 80% point-spread function (PSF) power radii.

Spatial analysis of the cluster emission was performed in the 0.5–2.0 keV energy band. The images for each camera were corrected for vignetting and out-of-time events, with the particle background component subtracted as described in § 2, and analysis independently. We extracted the azimuthally averaged surface brightness profiles centered on the X-ray surface brightness peak, even for clusters with irregular morphology (see below), excluding the CCD gaps and circles around the point sources. The obtained profiles were used to derive the parameters of the spatial distribution of the ICM, the cluster fluxes, and the background levels.

The cluster surface brightness profiles are often modeled with the so-called \(\beta\)-model, \(n^2 \propto (1 + r^2/r_0^2)^{-\beta}\), or \(S_c \propto (1 + r^2/r_0^2)^{-\beta} \propto r^{-\beta} \propto r^{-\beta + 1}\) (Cavaliere & Fusco-Femiano 1976). However, this model poorly describes clusters with sharply peaked surface brightness profiles related to the radiative cooling of the ICM in the cluster centers. The simple modification of the \(\beta\)-model (Pratt & Arnaud 2002)

\[
n_e^{-\alpha} = \frac{(r/r_c)^{-\alpha}}{(1 + r^2/r_c^2)^{3\alpha/2}} \quad (1)
\]

allows adequately describing these cooling regions in the low-redshift clusters. For \(\alpha = 0\), this \(\alpha-\beta\) model is identical to the usual \(\beta\)-model.

The model for the observed surface brightness profiles can be obtained by numerical integration of equation (1) along the line of sight and convolution of the result with the XMM-Newton PSF. To represent the uniform sky X-ray background, we added a constant component to the model and treated it as a free parameter. The values of \(\alpha\), \(\beta\), and \(r_c\) were derived from the joint fit to the observed profiles in the MOS1, MOS2, and pn cameras, with the overall normalizations and background levels fitted independently for each camera. For comparison, we also fitted the standard \(\beta\)-model by setting \(\alpha = 0\). The obtained parameters for the \(\alpha-\beta\) model and the standard \(\beta\) model fits are summarized in Table 2.

The best-fit ICM model was used to derive the total flux and the total mass from the hydrostatic equilibrium equation (see § 6 below). Strictly speaking, equation (1) cannot be applied to the ICM distribution in clusters with irregular morphology. In these cases, the model fit was used only to measure the image background, and we do not list the values of \(\alpha\), \(\beta\), and \(r_c\) in Table 2.

4. SPECTRAL ANALYSIS

The cluster spectra were extracted in annuli and circles within radii listed in Table 3. The response matrices and effective area files were generated by the standard SAS tasks. Because the data were previously vignetting corrected, the effective area files were created for the on-axis position using the

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3 We used the latest available values of the King function parameterization of the MOS1, MOS2, and pn PSFs, see M. Kirsch, EPIC Status of Calibration and Data Analysis, at http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0018-2-4.pdf.
TABLE 2
RESULTS OF IMAGE ANALYSIS

| Name          | $z$ | $\beta$ | $r_c$ (kpc) | $\chi^2/\nu$ | $\alpha$ | $\beta$ | $r_c$ (kpc) | $\chi^2/\nu$ |
|---------------|-----|---------|-------------|--------------|----------|---------|-------------|--------------|
| CL 0016+16    | 0.54| 0.76±0.01| 267.8±7.5  | 176.4±128    | 0.64±0.11| 0.84±0.03| 372.7±12.1  | 158.1±127    |
| CL 0024+17    | 0.59| 0.80±0.01| 89.0±3.0   | 98.7±65      | 1.56±1.12| 0.72±0.07| 254.5±58.8  | 78.3±64      |
| MS 0302.5+1717| 0.42| 0.65±0.03| 118.7±16.2 | 74.9±83      | 1.63±0.36| 1.03±0.28| 456.0±196.6 | 69.0±82      |
| MS 1054.4-0321| 0.82|          |            |              |          |         |             |              |
| RX J1120.1+4318| 0.60| 0.87±0.04| 203.8±14.2 | 77.6±83      | 0.29±0.26| 0.84±0.08| 231.0±60.1  | 77.4±82      |
| RX J1334.3+5030| 0.62| 0.61±0.02| 127.7±3.4  | 94.5±77      | 1.57±0.17| 0.95±0.21| 502.0±203.5 | 87.2±76      |
| WJ 1348.8+4028| 0.70| 0.49±0.02| 56.3±10.4  | 40.7±56      | 2.03±0.42| 0.78±0.21| 579.1±393.4 | 35.1±55      |
| WARP J0152.7−1357| 0.83|          |            |              |          |         |             |              |
| RX J0505.3+2849| 0.51| 0.69±0.14| 162.8±36.4 | 103.1±96     | 1.07±0.41| 0.92±0.26| 353.2±167.6 | 101.6±95     |
| CL 0939+472   | 0.41|          |            |              |          |         |             |              |

* Profile fitting was not performed for irregular clusters.

5. THE CROSS-CALIBRATION BETWEEN XMM-NEWTON AND CHANDRA

To compare our results with the low-redshift scaling relations, we need to correct for any systematic differences between the ASCA (Advanced Satellite for Cosmology and Astrophysics), Chandra, and XMM-Newton measurements. Vikhlinin et al. (2002) verified that there is no systematic difference between the Chandra and the ASCA temperature measurements. Therefore, we need to cross-calibrate only XMM-Newton and Chandra. Several of our clusters were in the Vikhlinin et al. (2002) sample. The comparison of XMM-Newton and Chandra temperatures for these clusters is shown in Figure 1. There is a good overall agreement, although the Chandra temperature for the hottest cluster, CL 0016+16, is marginally higher than our value. The linear fit gives $T_{\text{chandra}} = (0.92 ± 0.08)T_{\text{chandra}}$. A similar systematic difference is found in the comparison of the Chandra and XMM-Newton temperature profiles of nearby clusters (Vikhlinin et al. 2005b). We applied this correction factor to all temperature values because we use the ASCA $L-T$ relation as low-redshift reference. For the $M-T$ relation, this correction is unimportant (see § 7). Comparison of the cluster luminosities shows a good agreement, within ±5%, between Chandra and XMM-Newton.

6. TEMPERATURE PROFILES AND MASS MODELING

The statistical quality of XMM-Newton data allows us to reconstruct the temperature profiles from all our clusters. The main complication is that the XMM-Newton PSF size is nonnegligible compared with the angular size of distant clusters. For example, 50% of the flux from the central 100 kpc region (15") at $z = 0.6$.

TABLE 3
RESULTS OF SPECTRAL AND MASS DETERMINATION

| Name          | $T^a$ (keV) | $Z^b$ (Z$_{\odot}$) | $r^c$ (Mpc) | $T_{\text{speed}}$ (keV) | $T_{\text{em}}$ (keV) | $T_{500}$ (keV) | $T_{500}^{\text{low}}$ (keV) | $r_{500}$ (Mpc) | $M_{500}$ (10$^{14}$ M$_{\odot}$) | $L_{\text{bol}}$ (ergs s$^{-1}$) |
|---------------|-------------|----------------------|-------------|--------------------------|----------------------|------------------|-----------------------------|----------------|--------------------------------|----------------------|
| CL 0016+16    | 8.9±0.3     | 0.17±0.04            | 1.0         | 9.3±0.9                 | 4.9±0.4              | 1.19±0.03        | 8.83±1.08                   | 50.79×10$^{44}$ |                                |                      |
| CL 0024+17    | 3.5±0.5     | 0.29±0.06            | 0.5         | 3.6±0.2                 | 2.7±0.2              | 0.74±0.02        | 1.77±0.10                   | 3.98×10$^{44}$  |                                |                      |
| MS 0302.5+1717| 4.5±0.3     | 0.61±0.31            | 0.5         | 4.1±0.8                 | 2.3±0.3              | 0.78±0.07        | 2.15±0.35                   | 4.29×10$^{44}$  |                                |                      |
| MS 1054.4-0321| 7.5±0.7     | 0.35±0.09            | 0.7         |                        |                      |                  |                            | 30.49×10$^{44}$ |                                |                      |
| RX J1120.1+4318| 4.9±0.3     | 0.41±0.11            | 1.0         | 5.0±0.3                 | 2.0±0.1              | 0.94±0.07        | 4.64±1.14                   | 13.04×10$^{44}$ |                                |                      |
| RX J1334.3+5030| 4.6±0.4     | 0.22±0.11            | 0.8         | 4.6±0.4                 | 2.4±0.4              | 0.78±0.04        | 2.73±0.48                   | 7.48×10$^{44}$  |                                |                      |
| WJ 1348.8+4028| 3.5±0.3     | 0.56±0.21            | 0.6         | 3.1±0.3                 | 1.5±0.3              | 0.59±0.01        | 1.29±0.17                   | 3.66×10$^{44}$  |                                |                      |
| WARP J0152.7−1357| 6.2±0.4     | 0.33±0.08            | 0.8         |                        |                      |                  |                            | 21.71×10$^{44}$ |                                |                      |
| RX J0505.3+2849| 2.5±0.3     | 0.61±0.42            | 1.0         | 2.8±0.3                 | 3.2±0.4              | 0.65±0.03        | 1.37±0.21                   | 1.58×10$^{44}$  |                                |                      |
| CL 0939+472   | 5.3±0.2     | 0.22±0.06            | 1.0         |                        |                      |                  |                            | 10.05×10$^{44}$ |                                |                      |

* Best-fit temperature to the integral cluster spectrum.

* Best-fit metallicity to the integral cluster spectrum.

* Spectral extraction radius.

* Spectroscopic temperature within 70 kpc < $r$ < $r_{500}$. Note that $T_{\text{em}}$ was renormalized by +8% to account for Chandra vs. XMM-Newton cross-calibration.

* Emission-weighted temperature within 70 kpc < $r$ < $r_{500}$. $T_{500}^{\text{low}}$ was renormalized by +8% to account for Chandra vs. XMM-Newton cross-calibration.

* The central region was not excluded for clusters with irregular morphology. MS 1054.4−0321, WARP J0152.7−1357, and CL 0939+472. Emission-weighted temperature, $T_{500}^{\text{low}}$, was used to compute $L_{\text{bol}}$ for all clusters except MS 1054.4−0321, WARP J0152.7−1357, and CL 0939+472.
is scattered to larger radii (≈90% of the flux stays within 260 kpc regions). The temperature in these regions is often lower than the cluster average because of radiative cooling, and hence this scattered flux can significantly bias the temperature measurements at large radii.

We corrected for the XMM-Newton PSF using an approach used for XMM-Newton data analysis by Pointecouteau et al. (2004). Using the best-fit α-β models of the cluster brightness and the XMM-Newton PSF calibration, we calculated the redistribution matrix, $R_{ij}$, of each contribution of emission from annulus $i$ to the observed flux in annulus $j$. The model spectrum, $S_j$, is then given by

$$S_j = \sum R_{ij} S(T_i),$$

where $T_i$ is the temperature in annulus $i$ and $S(T_i)$ is the MEKAL spectrum for this temperature. Fitting this model to the observed spectra in all annuli simultaneously and treating all $T_i$ as free parameters gives the deconvolved temperature profile. The raw and deconvolved temperature profiles are shown in Figures 2–8. The deconvolved temperature profiles are within 1σ of the raw measurements in all cases. However, the PSF correction is systematic and results in stronger temperature gradients. Thus, neglecting this effect can slightly biases the mass measurements. In many cases, we observe a decrease of temperature at large radii, which is qualitatively consistent with the results for low-redshift clusters (Markevitch et al. 1998; De Grandi & Molendi 2002; Vikhlinin et al. 2005b). The only cluster that appears approximately isothermal is RX J1120.1; our results for this cluster are fully consistent with the analysis by Arnaud et al. (2002). We fitted the observed temperature profiles by the function

$$T(r) = T_0 \frac{1}{\left[1 + (r/r_0)^2\right]^{\alpha}}.$$  

A similar model describes the temperature profiles for low-redshift clusters (Vikhlinin et al. 2005b). For local clusters,

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**Fig. 1.**—Comparison of XMM-Newton and Chandra temperatures. The dashed line corresponds to $T_{\text{XMM}} = T_{\text{Chandra}}$, and the solid line shows the best-fit relation, $T_{\text{XMM}} = 0.92 T_{\text{Chandra}}$.

**Fig. 2.**—Left: Observed X-ray surface brightness profile (pn, MOS1, and MOS2 combined) of CL 0016+16. The solid line shows the best-fit α-β model convolved with the PSF. For comparison, the dashed line shows the same model without the PSF degradation. Right: Filled circles show the deconvolved projected temperature profile. For comparison, open circles show the raw measurements from the X-ray fit in the same annuli. The solid line shows the best-fit projected temperature profile, and the dashed lines correspond to its 68% CL uncertainties.

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4 The prime motivation for temperature profile analysis is to derive the total masses from the hydrostatic equilibrium equation. This cannot be done for irregular clusters, e.g., MS 1054.4–0321, WARP J0152.7–1357, and CL 0939+472, so we have not analyzed the temperature profiles in these cases.
$r_0$ scales with the average temperature as $r_0 = 0.284(T/1\text{ keV})^{0.537}\text{ Mpc}$ (see Fig. 16 in Vikhlinin et al. 2005b). The statistical uncertainties in our temperature profiles are insufficient to fit $T_0$, $r_0$, and the outer slope $\alpha$. Therefore, we fixed $r_0$ at the value suggested by the low-redshift correlation, with an additional scaling, $r_0 \propto 1/E(z)$, to account for the redshift dependence of the virial radius for a fixed temperature (Bryan & Norman 1998).

To fit the observed profiles, we projected the three-dimensional model along the line of sight using the emission measure profile from the best-fit $\alpha$-$\beta$ model. Projection was based on a weighting method that correctly predicts the best-fit spectral $T$ for a mixture of different temperature components (Mazzotta et al. 2004; Vikhlinin 2005). For those clusters with the central temperature decrements we excluded the innermost bin from the fit. This procedure is correct because our temperature profiles were corrected for the XMM-Newton PSF. The obtained best-fit models are shown along with the deconvolved temperature profiles in Figures 2–8.

Assuming hydrostatic equilibrium for the ICM, we can use the best-fit temperature and density profiles to derive the total cluster masses:

$$M(r) = \frac{r T(r)}{G \mu m_p} \left[ \frac{d \log \rho(r)}{d \log r} + \frac{d \log T(r)}{d \log r} \right].$$

Fig. 3.—Same as Fig. 2, but for CL 0024+17.

Fig. 4.—Same as Fig. 2, but for RX J1120.1+4318.
The mass was calculated within the radius that corresponds to the mean overdensity $\Delta = 500$ relative to the critical density at the cluster redshift.

The uncertainties on the masses were calculated from Monte Carlo simulations. The mass uncertainties are dominated by statistical uncertainties of the temperature profiles, and we neglected all other sources of error. We used the best-fit temperature profile as a template, applied Gaussian scatter with the rms equal to the statistical uncertainties, and fitted the simulated profile and derived the mass. The mass uncertainty was estimated as an rms scatter in 1000 simulations.

For each cluster we calculated the following temperature averages:

1. $T_{\text{emw}}$, $T(r)$ weighted with $\rho_{\text{gas}}(r)^2$. $T_{\text{emw}}$ is needed to self-consistently compare the high-redshift $L-T$ relation of our sample with the low-redshift result of Markevitch (1998).
2. $T_{\text{spec}}$, $T_{\text{spec}}$ is obtained by integrating a combination of $T(r)$ and $\rho_{\text{gas}}(r)^2$ as described in Vikhlinin (2005). $T_{\text{spec}}$ is needed for comparison with the low-redshift $M-T$ relation from Vikhlinin et al. (2005a).
3. $T_{\text{spec}}$ and $T_{\text{emw}}$ were averaged in the radial range $70 \text{ kpc} < r < r_{500}$. The uncertainties on $T_{\text{emw}}$ and $T_{\text{spec}}$ were also calculated from Monte Carlo simulations. The obtained values of $T_{\text{emw}}, T_{\text{spec}}, M_{500}$, and the corresponding overdensity radius $r_{500}$ are listed in Table 3. The $r_{500}$ radii are also shown by vertical dotted lines in Figures 2–8.

Fig. 5.—Same as Fig. 2, but for RX J1334.3+5030.

Fig. 6.—Same as Fig. 2, but for RX J0505.3+2849.
To test how background subtraction can affect our mass result, we checked two sources of uncertainties. First, we varied normalization of the article-induced component by $\pm 10\%$. Normalization of CXB component was varied by $\pm 5\%$ (quoted XMM-Newton vignetting uncertainties). We refitted all spectra with renormalized background and repeated the mass analysis. The resulting variations in $M_{500}$ were well within our statistical uncertainties.

7. EVOLUTION OF $M$-$T$ RELATION

Self-similar theory (e.g., Bryan & Norman 1998) predicts that the relation between cluster mass and temperature is a power law that evolves as $M/T^{3/2} \propto E(z)^{-1}$, where $E(z) = H(z)/H_0 = [0.3(1 + z)^3 + 0.7]^{1/2}$ for the adopted cosmology. Our measurements for distant clusters can be used to test these predictions.

The reference low-redshift $M$-$T$ relation was adopted from a Chandra sample of Vikhlinin et al. (2005a), which is also close to the XMM-Newton results of Arnaud et al. (2005). The Chandra sample contains 11 nearby clusters with exposures sufficient to measure temperature profiles to $r/r_{500}$. The temperatures of these clusters, 2–10 keV, match well the temperature range in our distant sample. Vikhlinin et al. (2005a) derived the mass-temperature relation, $M_{500} = A_5(T_{\text{spec}}/5 \text{ keV})^{1.61 \pm 0.11}$, where $A_5 = (4.13 \pm 0.23) \times 10^{14} M_\odot$. The derived slope is consistent with the self-similar expectation, $M \propto T^{3/2}$.
Figure 9a shows the quantity $a = M_{500}/T_{\text{spec}}^{1.5}/A_5$ as a function of $z$ for our clusters. This quantity represents the normalization of the $M$-$T$ relation as constrained by each cluster. For non-evolving $M$-$T$ relation, all values of $a$ would be consistent with 1. However, the observed values of $a$ clearly indicate evolution. To quantify the observed evolution, we fitted the data from Figure 9a with a power law of $E(z)$, $a = E(z)^{-\alpha}$. The best-fit index is $\alpha = 0.88 \pm 0.23$, where the error bar includes the uncertainties in low-redshift normalization of the $M$-$T$ relation and our high-$z$ mass measurements. The derived rate of evolution is consistent with the theoretically expected one, $\alpha = 1$. Therefore, we can assume that the normalization of the $M$-$T$ relation evolves exactly as $A \propto E(z)^{-1}$.

Now we can derive slope and normalization of the $M$-$T$ relation defined by our distant clusters. For this, we corrected the mass measurements for evolution by multiplying them by $E(z)$. Figure 9b shows the corrected cluster masses as a function of temperature. The power-law fit, $E(z)M = A_5(T/5\text{ keV})^{\alpha}$, to distant clusters only gives $E(z)M_{500} = (3.21 \pm 0.31)(T_{\text{spec}}/5\text{ keV})^{1.79 \pm 0.19} \times 10^{14} h^{-1} M_\odot$. The obtained value of the slope, $\gamma = 1.79 \pm 0.19$, is statistically consistent with the value $\gamma = 1.5$ predicted by the self-similar theory.

Finally, we note that the results on $M$-$T$ relation are insensitive to the absolute calibration of the XMM-Newton effective area. The main effect of small calibration errors is to bias the derived temperatures by a constant factor. It follows from equation (4) that the normalization of the $M$-$T$ relation as given by individual clusters, $A = M_\Delta/(T)^{3/2}$, is

$$A = \left(\frac{4}{3} \pi \Delta \rho \right)^{-1/2} \left(\frac{T}{T_0}\right)^{3/2} \left(\frac{-d \log \rho}{d \log r} - \frac{d \log T}{d \log r}\right)^{-3/2}$$

where the last two terms are evaluated at the overdensity radius, $r_\Delta$. Small calibration errors lead to small changes in estimated $r_\Delta$ ($\Delta r_\Delta/r_\Delta \approx 0.5 \ell/\ell$), but the normalization of $M$-$T$ relation is not affected because both density and temperature are nearly power-law functions of $r$ in the interesting range of radii.

8. THE X-RAY TEMPERATURE-LUMINOSITY CORRELATION

Our results can also be used to test the evolution in the cluster X-ray luminosity versus temperature relation. We performed a spatially resolved analysis of the temperature and surface brightness profiles, including the PSF deconvolution. Therefore, we can directly exclude the contribution of the central cooling regions to both temperature and luminosity. This significantly reduces the scatter in the $L$-$T$ relation (Markevitch 1998) and thus makes any evolution more prominent.

The X-ray bolometric luminosities were calculated using the Mewe-Kaastra-Liedahl plasma emission model. We used the measured best-fit temperatures for three objects with irregular X-ray morphology (MS 1054.4–0321, WARP J0152.7–1357, and CL 0939+472) and the obtained emission-weighted temperatures for all other clusters. All temperatures were renormalized by $+8\%$ to account for Chandra versus XMM-Newton cross-calibration.$^6$ For the three objects with irregular X-ray morphology, we use the observed 0.5–2.0 keV count rates within $0 < r < 1.4$ Mpc as the normalizing fluxes. For all other clusters, the normalizing fluxes were calculated by subtracting from the observed 0.5–2.0 keV count rates within $0 < r < 1.4$ Mpc

$^6$ Vikhlinin et al. (2002) demonstrated that there is no bias between the Chandra and ASCA temperatures. Our XMM-Newton temperatures are on average 8% lower than the Chandra values; therefore, we need to apply temperature renormalization for a consistent comparison with the low-redshift ASCA measurements by Markevitch (1998).
the correlation corrected by the obtained best-fit evolution factor, \((1+z)^{-1.8}\).

Most of our clusters have nonconstant temperature profiles. We observe the central temperature decrements in clusters with the most peaked X-ray surface brightness profiles. There is a temperature decline at large radii in most objects, which is qualitatively consistent with the temperature profiles in low-redshift clusters (Markevitch et al. 1998; De Grandi & Molendi 2002; Vikhlinin et al. 2005b).

Using the derived temperature and density profiles, we determine the total cluster mass within the radius \(r_{500}\) without using the usual assumption of an isothermal \(\beta\)-model. This allows a direct comparison of the high-redshift M-T relation with the recent high-quality XMM-Newton measurements for low-redshift clusters (Arnaud et al. 2005; Vikhlinin 2005).

The observed M-T relation for distant clusters is \(E(z)M_{500} = (3.21 \pm 0.31)(T_{\text{spec}}/5 \text{ keV})^{0.31 \pm 0.19} \times 10^{14} \text{ h}^{-1} M_{\odot}\). The derived slope, \(\gamma = 1.79 \pm 0.19\), is statistically consistent with both \(\gamma = 1.61 \pm 0.11\) measured by Vikhlinin et al. (2005a) for low-redshift clusters and \(\gamma = 1.5\) predicted by the self-similar theory.

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FIG. 10.—Correlation of cluster cooling flow corrected bolometric luminosity and \(T_{\text{emw}}\). The data are corrected for the XMM-Newton–Chandra (ASCA) systematic discrepancies in the temperature and flux measurement. The solid line shows the \(L-T\) correlation for the low-redshift clusters (Markevitch 1998). Panel b shows the correlation corrected by the obtained best-fit evolution factor, \((1+z)^{-1.8}\).
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