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Scaling laws in X-ray Galaxy Clusters at $z > 0.4$

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Abstract. We present a study of the integrated physical properties of a sample of 25 X-ray galaxy clusters observed with *Chandra* at redshift between 0.4 and 1.3. In particular, we have nine objects in the redshift range 0.4–0.6, five between 0.6 and 0.8, seven between 0.8 and 1 and four at z >1.0, compounding the largest sample available for such a study. We focus particularly on the properties and evolution of the X-ray scaling laws. We observe correlation steeper than what expected from self-similar model by a significant ($> 3\sigma$) amount in the $L - T$ and $M_{\rm gas} - T$ relations, by a marginal value in the $M_{\rm tot} - T$ and $L - M_{\rm tot}$ relations. We confirm at higher redshift the deficit by about 30 per cent in the normalization of the $M_{\rm tot} - T$ relation when compared with results in hydrodynamical simulations. We do not observe considerable ($\lesssim 2\sigma$) evolution in each of the investigated scaling laws, apart from some hints of *negative* evolution in the $L - T$ and $M_{\rm gas} - T$, suggesting that systems at higher redshift have lower X-ray luminosity and gas mass for fixed temperature. On the other hand, we find a significant ($\sim 4.2\sigma$) evidence of *positive* evolution in the entropy value estimated at 0.1 R_{200} for fixed temperature. This trend might indicate that we are observing at higher redshift regions where the entropy is larger due to shocks that propagate through the still-acreting material, as expected for clusters in formation. Moreover, higher values of entropy suppress the core emission, lowering the total luminosity and the gas mass estimates as mildly observed in our data.

Key words. galaxies: cluster: general – galaxies: fundamental parameters – intergalactic medium – X-ray: galaxies – cosmology: observations – dark matter.

1. Introduction

The physics of the intracluster medium (ICM) is mainly driven from the infall of the cosmic baryons trapped in the deep gravitational potential of the cluster dark matter halo. Through a hierarchical formation that from the primordial density fluctuations generates the largest virialized structures via gravitational collapse and merging, the galaxy clusters maintain similar properties when they are rescaled with respect to the gravitational mass and to the epoch of formation. The shock heated X-ray emitting ICM accounts for most of the baryons collapsed in the cluster potential and its physical properties, like density and temperature, relate in a predictable way in

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this simple self-similar scenario (e.g. Kaiser 1986). Under the assumptions that the smoothed and spherically symmetrically distributed X-ray ICM undergoes only to gravitational collapse, virialized by maintaining the hydrostatic equilibrium with the underlying dark matter potential and emits mainly through bremsstrahlung processes, one can write the following expected scaling relations between the observed (gas bolometric luminosity, $L_{\rm bol}$, temperature, $T_{\rm gas}$) and derived (gas entropy, S, mass, $M_{\rm gas}$, total gravitating mass, $M_{\rm tot}$) quantities in X-ray galaxy clusters:

- $E_z^{4/3} \; S \propto T_{\rm gas}$
- $E_z^{-1} \; L_{\rm bol} \; \propto \; \Delta^{1/2} \; T_{\rm gas}^2$
- $E_z \; M_{\rm tot} \; \propto \; \Delta^{-1/2} \; T_{\rm gas}^{3/2}$
- $E_z^{-1} \; L_{\rm bol} \; \propto \; \Delta^{7/6} \; (E_z M_{\rm tot})^{4/3}$
- $E_z \; M_{\rm gas} \; \propto \; \Delta^{-1/2} \; T_{\rm gas}^{3/2}$.

The factors that indicate the dependence on the evolution of the Hubble constant at redshift z, $H_z/H_0 = E_z = \left[\Omega_{\rm m}(1+z)^3 + 1 - \Omega_{\rm m}\right]^{1/2}$ (for a flat cosmology with matter density $\Omega_{\rm m}$), and on the overdensity Δ appear as consequence of the fact that all the quantities are generally estimated at a fixed value of Δ with respect to the critical density, $\rho_{\rm c,z} = 3H_z^2/(8\pi G)$, once the redshift of the observed structure and the cosmological parameters are given. Numerical simulations (e.g. Evrard et al. 1996, Borgani et al. 2002 and references therein) and observational analysis (e.g. Ettori et al. 2002 and references therein) support the overall validity of these simple relations in nearby samples, but with some level of disagreement on (i) the normalization of the $M_{\rm tot} - T_{\rm gas}$ relation as observed and estimated in numerical simulations, (ii) the slopes of all the relations, starting with the most widely studied case of the $L_{\rm bol} - T_{\rm gas}$ and $M_{\rm tot} - T_{\rm gas}$ relations, and their changes when low temperature ($T_{\rm gas} < 3$ keV) systems are considered. Moreover, due to the objective difficulties to ensemble a large dataset of high redshift objects, there has been very little work done until now on the observed evolution of these scaling laws, and with contradictory results. For example, while Holden et al. (2002) observe no evolution of the $L_{\rm bol} - T_{\rm gas}$ relation in a ΛCDM universe, Vikhlinin et al. (2002) claim to have evidence at 3σ level of a positive evolution, i.e. systems at higher redshift have higher luminosity for fixed temperature.

2. The scaling relations at $z > 0.4$

In this work, we focus on the general behaviour of the scaling laws for X-ray clusters at redshift larger than 0.4 and investigate the presence of any evolution with respect to what is observed locally. To do this, we consider *Chandra* observations of 25 galaxy clusters at redshift larger than 0.4 (median $z = 0.73$), with emission-weighted temperature in the range 3–11 keV (median value of 6.5 keV) and luminosity between 8×10^{43} erg s^{-1} and 5×10^{45} erg s^{-1} (median value: 6×10^{44} erg s^{-1}). Part of this sample has been already used to study the gas fraction as cosmological probe (Ettori et al. 2003a) and the metal content of clusters at high redshift (Tozzi et al. 2003). The use of *Chandra* data allows us to resolve on scales of few tens of kpc the gas density (once the surface brightness is deprojected through a $\beta-$model) of these systems, and to determine a single emission weighted temperature. To make a proper use of our single-temperature measurement, and considering that the temperature profile does not decline significantly ($\lesssim$ 20 per cent) up to an overdensity of ~ 500 (e.g. Evrard et al. 1996, De Grandi & Molendi 2002), we estimate all the observed quantities considered in this work, i.e. total mass, gas mass and luminosity to $R_\Delta = R_{500}$ (see details in Ettori et al., 2003b).

To constrain the evolution in the considered scaling law, we then fix (α, A) to the best-fit results obtained from a sample of objects observed at lower redshift, $(\overline{\alpha}, \overline{A})$ (see Figure 1), and evaluate the confidence

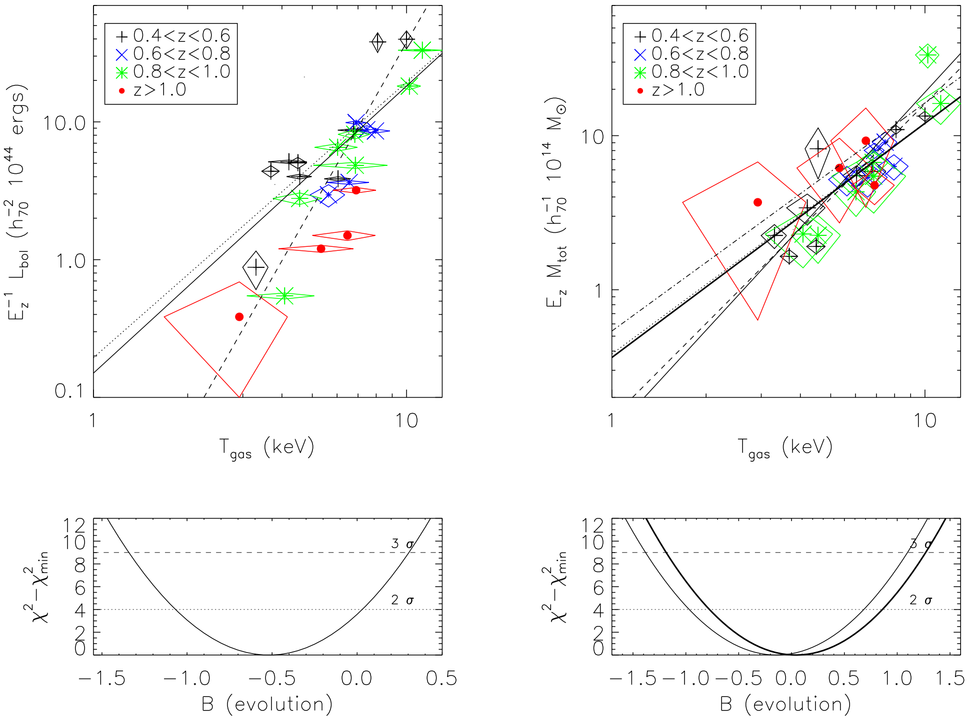

Fig. 1. Dotted line: slope fixed. Dashed line: slope free. (*Left*) $L-T$ relation after cosmological correction. Solid lines: Allen et al. (2001). (*Right*) $M-T$ relation after cosmological correction. Solid line: Ettori et al. (2002; thinest line), Allen et al. (2001). The dash-dot line indicates the best-fit result from hydrodynamical simulations in Mathiesen & Evrard (2001, Table 1, with temperatures from simulated spectral analysis in the band 0.5–9.5 keV), that is $\sim$ 30 per cent higher than what we measure.

interval through a least-square minimization on the parameter B in the relation

$$\log Y = \overline{\alpha} + \overline{A} \log X + B \log(1+z), \qquad (1)$$

where two sets of measured quantities $\{X_j\}$ and $\{Y_j\}$ are considered.

3. Conclusions

We do not observe any relevant evolution in the $M_{\rm tot}-T$ and $L-M_{\rm tot}$ relations. Also in the $L-T$ and $M_{\rm gas}-T$ we have not statistically significant deviation from $B=0$, where B is the slope of the $(1+z)$ dependence. However, in the latter two correlations we detect a mild ($< 2\sigma$) *negative* evolution, being clusters at higher redshift with estimated lower X-ray luminosities and gas masses (see Fig. 1). This trend appears more clearly (4.2σ detection) when the entropy of these systems evaluated at $0.1R_{200}$ is compared with local determinations (see Fig. 2).

Furthermore, we have indication that lower entropy values correspond to higher estimates of the metal content of our clusters. The Spearman's rank correlation is significant at about 95 per cent against the null-hypothesis that no-correlation is present. This result, with the evidence that systems at lower temperature stores lower amount of entropy at the same fraction of

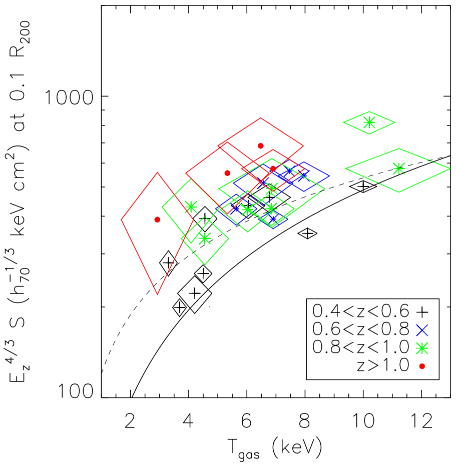

Fig. 2. Behavior of the Entropy measured at $0.1 \times R_{200}$ versus gas temperature and metallicity. A rescaling factor of $E_z^{4/3}$ is used to compare these values to what is expected from hydrodynamical simulations, $S \approx 50\ (f_{\rm gas}/0.106)^{-2/3}\ T_{\rm keV}\ h_{70}^{-4/3}$ kev cm^2 (solid line, from Ponman et al. 1999 and normalized to the median gas fraction measured in our sample; dashed line, $S \approx 120\ T_{\rm keV}^{0.65}$, from Ponman et al. 2003).

the virial radius (Spearman's rank correlation significant at 99.9 per cent), is an other way to show what we reported in a previous paper (Tozzi et al. 2003), that clusters at lower temperature appear to have higher Iron abundance. (We remind that in these high$-z$ systems Iron is the only element that we can sample in their metal budget.)

It is now well-established (e.g. Finoguenov et al. 2002) that most of the star formation (and Iron production) happened before ($z \gtrsim 2$) the final collapse of the acreting baryons into clusters, and preferentially in low-entropy structures like groups along the cosmic filaments. Considering that these groups are the main constituents of the richer virialized systems and that seem to maintain their structure and survive for a transit through the cluster environment (as the frequently observed *cool cores* in relaxed systems -e.g. Vikhlinin et al. 2001- suggest and recent hydrodynamical simulations -Motl et al. 2003- corroborate), less is the time elapsed from the aggregation of these clumps in a larger system, greater is the number of survival regions at low entropy and high metallicity. It is worth noticing that these stable subclusters should contribute significantly to all the X-ray emission-weighted observables because of their high gas density. Therefore, from an observational point of view, clusters with a larger number of similar subsclusters should present higher metallicity with corresponding lower gas temperature.

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