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Cluster scaling and its redshift evolution from XMM-Newton ☆

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Abstract

We put together the results of XMM-Newton observations of a number of representative group and cluster samples at low and high redshifts. These results confirm the entropy ramp as an explanation of the observed scaling relations. We observe a mild evolution in the entropy of clusters. The observed degree of evolution is consistent with expectations of the shock heating at a fixed overdensity (500) with respect to the critical density in ΛCDM. The study of the evolution in the pressure scaling imposes strong requirements in the definition of the average temperature of the cluster. The scaling temperature should be consistent to better than the 10% level. Once such a consistency is achieved, no additional evolution in the pressure has been detected in addition to the prediction of the shock heating in the ΛCDM Universe.

Keywords: Galaxy groups; Clusters; Large scale structure of the Universe; Galaxy clusters; X-ray sources; Observational cosmology

1. Introduction

Comparative studies of the scaling relations in clusters of galaxies reveal strong deviations of the observed relations from predictions based on self-similar collapse, e.g., the observations show a steeper L_x–T relation than predicted by the self-similar laws (Kaiser, 1986). These deviations are thought to be best characterized by the injection of energy (preheating) into the gas before clusters collapse (Kaiser, 1991; Evrard and Henry, 1991). Recently, an analysis of a large compilation of entropy profiles on groups and clusters of galaxies also required at r_{500} much larger entropy levels than was thought before (Finoguenov et al., 2002) and modifying the concept of the entropy floor to the entropy ramp at $0.1r_{200}$ (Ponman et al., 2003). Reproduction of these results both analytically and numerically, strongly supports the scenario of Dos Santos and Doré (2002), where an initial adiabatic state of the infalling gas is further modified by the accretion shock (Voit and Ponman, 2003). As a supporting evidence to the latter, Ponman et al. (2003) noticed a self-similarity in the entropy profiles, once scaled to $T^{0.65}$. Some XMM-Newton observations are consistent with this result (Pratt and Arnaud, 2003). A major change introduced by these studies is that groups of galaxies can again be viewed as scaled-down versions of clusters, yet the scaling itself is modified. Other evidence for the departure of groups from the trends seen in clusters, such as the slope of the L–T relation, has been recently refuted by Osmond and Ponman (2004).

The idea of this *contribution* is to check the consistency between the data and both the concept and the level of the modified entropy scaling. While we give an

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overview of the results here, the details of the data analysis could be found in Zhang et al. (2004) and Finoguenov et al. (submitted-a).

For our study, we have selected 14 groups in Mulchaey et al. (2003) in the redshift range $0.012 < z < 0.024$ with publicly available XMM-Newton (Jansen et al., 2001) observations. Most of the groups in the Mulchaey et al. (2003) sample were found by cross-correlating the ROSAT observation log with the positions of optically selected groups. Their final group list contains 109 systems.

The REFLEX-DXL galaxy cluster sample, comprising distant X-ray luminous objects within REFLEX, was constructed from the REFLEX galaxy cluster survey covering the ROSAT detected galaxy clusters above a flux limit of 3×10^{-12} erg s^{-1} cm^{-2} in the 0.1–2.4 keV band in an 4.24 ster region of the southern sky (see Böhringer et al., 2004 for details). The REFLEX-DXL clusters form a volume limited subset of REFLEX in the redshift range 0.27–0.31 including 14 members. The properties of the REFLEX-DXL clusters are described in Zhang et al. (2004).

In addition to these two samples, we have added some of the published work on the nearby clusters, A754 (Henry et al., 2004), A3667 (Briel et al., 2004), A3562 (Finoguenov et al., 2004); A478 (Sanderson et al., submitted); A3558 (Rossetti et al., in preparation); A3266 (Finoguenov et al., submitted-b). Addition of these data allows us to demonstrate to which extent the scaling works at low redshift.

At the moment, a number of prescriptions exists on how to scale the cluster properties and look for their evolution (e.g., Voit, in press). We choose the following approach to scale the observables. The calculation of the r_{500} is the following: $r_{500} = 0.45\ \mathrm{Mpc}\times\sqrt{kT/\mathrm{keV}}h_{70}^{-1}h(z)^{-1}$, where the scaling in Finoguenov et al. (2001) for $h_{50}(r_{500}\approx 0.63\ \mathrm{Mpc}\sqrt{kT/\mathrm{keV}})$ is translated into our assumption for $h_{70}=1$. We use $h(z) = (\Omega_{\mathrm{M}}(1+z)^3+\Omega_\Lambda)^{1/2}$, suitable for our choice of cosmological model. In Finoguenov et al. (2001), it has been demonstrated that the cosmological corrections are negligible in deriving the scaling for r_{500} in their sample of local clusters. These corrections are, however, important for REFLEX-DXL.

The normalization of the empirical entropy scaling is taken from Ponman et al. (2003, hereafter PSF) and rescaled for the difference in the assumption for the Hubble constant.

A suggested modified entropy scaling of PSF reads $S\sim T^{0.65}h(z)^{-4/3}$. We also take into account that to fit the clusters hotter than 5 keV, the normalization of this relation should be 20% lower. In Fig. 1, we illustrate this issue by performing the locally weighted pseudo-non-parametric analysis (for further insights and references, see Sanderson et al., submitted). While this is done here to properly reproduce the mean entropy of

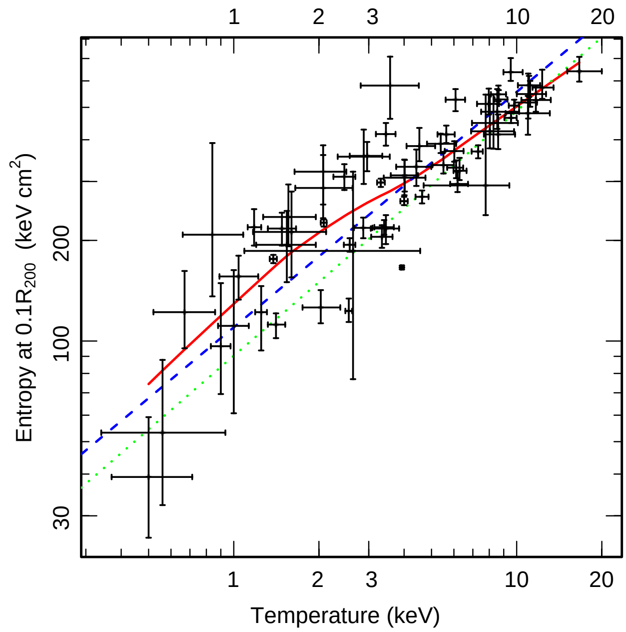

Fig. 1. Reanalysis of the entropy ramp data of Ponman et al. (2003). Blue dashed line represents the best-fit unweighted power law (slope is equal to 0.70 ± 0.05). The green dotted line stands for the weighted orthogonal regression (slope equals to 0.73 ± 0.07). The red solid line shows the results of the locally weighted pseudo-non-parametric analysis. This analysis reveals a glitch in the S–T behavior at 4 keV temperature.

the clusters, observed previously, a glitch in the S–T (and P–T) relation implied by such an approach, will be studied elsewhere. In the following, we will use the entropies measured at r_{500} for a 10 keV systems and apply scaling with $\left(\frac{kT}{10\ \mathrm{keV}}\right)^{0.65}$. In addition to the scaling of the entropy and a fixed fraction of virial radius, we adopt a radial behavior of the entropy as $r^{1.1}$, which for the local sample has been shown to work outside the $0.1r_{500}$ (Pratt and Arnaud, 2003).

In the analysis of clusters, we will also present the scaled pressure plots. As entropy, $Tn^{-2/3}$, scales as $T_{\mathrm{w}}^{2/3}$ (where T_{w} is the weighted temperature), the density scales as $T_{\mathrm{w}}^{1/2}$ and the pressure $Tn\sim T_{\mathrm{w}}^{3/2}$. For high-redshift clusters, we introduce a correction for the evolution of the critical density, which is proportional to $h(z)^2$. Introduction of the correction for the evolution of the critical density to either pressure or entropy is appropriate only if the shock heating of the accreted gas is the dominant mechanism defining the thermodynamics of the ICM and the resulting agreement of the data with the local scaling confirms the major role of the shock heating in establishing the entropy and pressure profiles for clusters. A sample of high-redshift groups would be needed to extend this conclusion to groups.

As we are not aware of any prescription for the pressure, in this *contribution*, we use the fit to A478 data and discuss whether it is representative. Including the prescription for the scaling of the pressure with the average