

How Evolution Can Affect the Use of Clusters as Cosmological Probes. *XMM-Newton* Observations of Distant Galaxy Clusters

M. Arnaud

CEA/DSM/DAPNIA/Service d'Astrophysique, CE Saclay, 91191 Gif sur Yvette Cedex, France

Several independent methods can be used to constrain the cosmological parameters from cluster X-ray observations. These observations include the baryon fraction in clusters, non-evolving properties used as distance indicator and cluster abundance. All three methods rely on specific assumptions on the scaling and structural properties of clusters. I discuss some caveats, with a particular focus on those related to cluster evolution, and present new insight from *XMM-Newton* observations of distant galaxy clusters.

1. Introduction: X-ray Clusters as Cosmological Probes

In the standard hierarchical formation scenario, clusters of galaxies, the most massive collapsed objects in the Universe, are forming in the recent cosmological epoch ($z \sim 2$ to the present time). In theory, X-ray cluster evolution is simple and driven by the collisionless gravitational collapse of the main dark matter (DM) component, whereas the hot intra Cluster Medium (ICM) “follows” the DM gravitational potential. The mass distribution function of clusters can be computed at any redshift from the power spectrum of the primordial fluctuations, the value of Ω_m determining their growth-rate. Furthermore, analytical models of dark matter collapse, supported by numerical simulations, predict that galaxy clusters constitute a homologous population (e.g., Eke et al. 1998). Clusters are self-similar in shape and scaling laws relate each physical property to the cluster total mass M (or temperature T) and redshift z , in the form $Q \propto A(z)T^\alpha$.

In the framework of the self-similar model, several *independent* methods can be used to put stringent constraints on cosmological parameters, such as the matter density of the Universe (Ω_m), the cosmological constant (Λ) and the normalization of the power spectrum (σ_8). These methods include:

- *The baryon fraction in clusters*

In the simple model, the content of clusters provides a fair sample of the Universe as a whole (e.g., White et al. 1993). The baryon mass fraction in clusters is thus $f_b = \Omega_b/\Omega_m$, where Ω_b is the mean baryon density of the Universe. Combined with the Ω_b value allowed by nucleosynthesis, f_b in clusters can be used to measure Ω_m . The baryonic mass in rich clusters is dominated by the X-ray gas and the gas mass fraction (which is a constant) sets a firm upper limit on Ω_m .

- *Clusters as standard candles*

Non evolving properties can be used as distance indicators, providing further constraints in the (Ω_m ,

Λ) plane. This includes the gas mass fraction (e.g., Allen et al. 2002; Ettori et al. 2003), the isophotal radius (Mohr et al. 2000), or properties corrected for evolution, like the scaled emission measure profiles (Arnaud et al. 2002a).

- *Cluster abundance*

This method is extensively discussed by S. Borgani in these proceedings. The cluster mass function and its evolution depends very sensitively on Ω_m and σ_8 . In the simple self-similar model the mass is directly related to observable quantities like the X-ray luminosity and temperature. Strong constraints can thus be derived from the cluster luminosity (XLF) or temperature (XTF) function and their evolution derived from X-ray cluster surveys. A key ingredient is also the selection function of various surveys, which for flux-limited samples depends on cluster morphology and scaling laws.

However, real clusters deviate from the simplest model, which may limit the ability of clusters to provide constraints on the cosmological parameters. In this paper I discuss some caveats, with a particular focus on those related to cluster evolution.

2. Structural and Scaling Properties of the Local Cluster Population

2.1. Departures From the Standard Self-Similar Model

From new *XMM-Newton* and *Chandra* observations, as well as recent statistical analysis of large samples with previous satellites, we have now a clearer view of the local cluster population (see Arnaud, Pratt, & Pointecouteau 2003 for a more detailed review and bibliography).

The emerging picture is that local clusters do form a self-similar population, down to relatively low temperature (or mass):

- The shape of the gas density and temperature profiles of hot clusters is remarkably similar, outside the cooling core region (Neuman & Arnaud 1999; Allen et al. 2001; Fig 5 in Arnaud, Pratt, & Pointecouteau 2003). Furthermore the shape of the gas

TABLE 1. LOGARITHMIC SLOPE OF LOCAL SCALING LAWS FROM THE LITERATURE (NOT EXHAUSTIVE).

Relation	Slope [†]	Reference	Note
L_X-T	2.64 ± 0.27	Markevitch (1998)	a
	2.88 ± 0.15	Arnaud & Evrard (1999)	b
$M_{\text{gas}}-T$	1.98 ± 0.18	Mohr et al. (1999)	c
	1.71 ± 0.13	Vikhlinin et al. (1999)	
	1.89 ± 0.20	Ettori et al. (2002)	c
	1.80 ± 0.16	Castillo-Morales & Schindler (2003)	c
$EM-T$	1.38	Neuman & Arnaud (2001)	d
$S-T$	0.65 ± 0.05	Ponman et al. (2003)	d,e
$f_{\text{gas}}-T$	0.34 ± 0.22	Mohr et al. (1999)	c
	0.66 ± 0.34	Ettori et al. (2002)	f

NOTE. — a: Corrected for cooling flow contribution; b: non-cooling-flow clusters; c: Gas mass integrated within r_{500} (density contrast $\delta = 500$); d: see also Pratt & Arnaud (2003); e: entropy estimated at $0.1R_{200}$; f: f_{gas} integrated within r_{1000} .

[†]The slope α given in column 2 is obtained by fitting the data with power laws: $Q \propto T^\alpha$. In the standard self-similar model: $L_X \propto T^2$, $M_{\text{gas}} \propto T^{1.5}$, $EM \propto T^{0.5}$ and $S \propto T$.

density and entropy profiles of cool clusters (down to $kT \sim 2/\text{keV}$) appear similar to that of hotter systems (Ponman et al. 2003; Pratt & Arnaud 2003). We also begin to have evidence that numerical simulations predict the correct shape for the DM distribution (Pratt & Arnaud 2002 and reference therein).

- Scaling laws do relate various physical properties with T (Table 1). This includes global properties like the X-ray luminosity L_X , the gas mass M_{gas} or the total mass M . This also consistently includes the normalization of various profiles, e.g., the emission measure EM or the entropy, $S = kT/n_e^{2/3}$, at a given scaled radius. While various *ROSAT/ASCA* studies of the slope of the $M-T$ relation gave some contradictory results, higher precision *Chandra* and *XMM-Newton* results are consistent with the expected $M \propto T^{1.5}$ scaling (see Arnaud, Pratt, & Pointecouteau 2003 and Allen et al. 2001).

On the other hand, the *gas* scaling properties differ significantly from expectation in the simple model:

- The observed L_X-T , $M_{\text{gas}}-T$, $EM-T$ relations are steeper than expected, while the $S-T$ relation is shallower (see Table 1). If the total mass scales as $T^{1.5}$, and taking into account the self-similarity of form, these are converging evidence that the gas mass fraction increases with T (or mass). Such a variation is also indicated by direct studies of the $f_{\text{gas}}-T$ relation (Table 1, see also Sanderson et al. 2003).
- Furthermore, current adiabatic numerical simulations over-estimate the normalization of the local $M-T$ relation (e.g., Allen et al. 2001; Pratt & Arnaud 2002) and fail to account for the observed gas distribution (see, e.g., Borgani, these proceedings).

These departures from the simplest model clearly indicate that the ICM properties are not governed by gravitation alone. Various non-gravitational processes have been proposed, like heating before or after collapse (from SNs or AGNs), radiative cooling ... and it is now clear that a single process cannot alone explain the data (Voit et al. 2002; Borgani et al. 2002 and references therein).

2.2. Relative Gas and Dark Matter Distribution

There is converging evidence that the gas distribution in clusters is more inflated than the dark matter distribution. The integrated gas mass fraction increases with scaled radius (see, e.g., Fig. 6 in Sanderson et al. 2003). The increase, measured with *Beppo-SAX* is about 25% between a density contrast of $\delta = 2500$ (about 1/3 of the virial radius) and $\delta = 500$ (Fig 2 in Ettori et al. 2003). These results at $\delta = 500$ were largely based on extrapolations and could be biased. However, recent *XMM-Newton* and *Chandra* results seem to confirm this trend. From a sample of six massive clusters observed by *Chandra*, Allen et al. (2002) derived an average f_{gas} value of 0.113 ± 0.013 at $\delta = 2500$. At this density contrast, the value derived from the *XMM-Newton* analysis of A1413 by Pratt & Arnaud (2002) is $f_{\text{gas}} = 0.11$ (perfectly consistent with *Chandra* results). The *XMM-Newton* data extends up to $\delta = 500$ and show that f_{gas} keeps increasing with radius to reach $f_{\text{gas}} \sim 0.14$ at $\delta = 500$ (25% increase)¹.

2.3. Real Clusters as Cosmological Probes: Some Caveats

2.3.1. The Baryon Fraction in Clusters

The variation of f_{gas} both with radius and system mass is the main concern. Although the effect is not dramatic (typically 25%) this is a major source of systematic uncertainties for high precision cosmology. For instance Ω_m

¹ The published values have been scaled to the cosmology adopted by Allen et al. (2002)

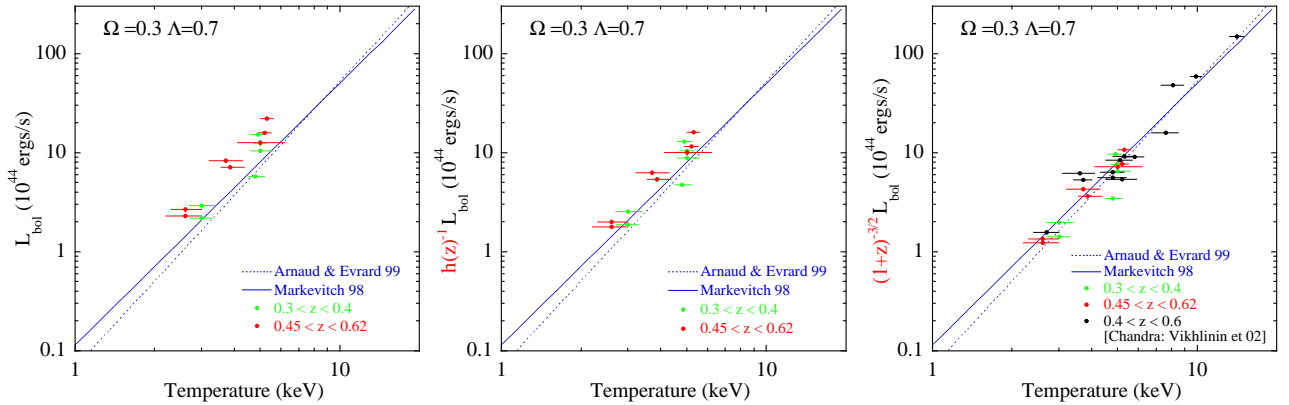


FIG. 1.— Correlation between bolometric luminosity and temperature ($\Omega_m = 0.3, \Lambda = 0.7$). Blue lines: local relations from Arnaud & Evrard (1999) and Markevitch (1998) for comparison. Left panel: Data points for the medium z (green points) and high z (red points) SHARC sample observed with *XMM-Newton* (Lumb et al. 2003; Majerowicz 2003 and Arnaud et al., in prep). All the data points stand significantly above the local relation, indicating evolution. Middle panel: Luminosities scaled by $h(z)^{-1}$, removing the evolution expected in the standard self-similar model. There is a slight indication that the evolution is actually stronger. Right panel: Luminosities have been scaled by $(1+z)^{-3/2}$, according to the best fit evolution found by Lumb et al. (2003). Black points: *Chandra* data from Vikhlinin et al. (2002). Note the excellent agreement between *Chandra* and *XMM-Newton*.

estimates are biased high if the gas mass fraction is estimated at too low radii and not corrected for this effect. Note also that corrections estimated from numerical simulations may not be adequate in view of their failure to account for the observed ICM structure. The variation of f_{gas} with system mass must also be understood, to firmly establish if (and in what mass range) clusters are fair samples of the Universe.

2.3.2. Clusters as Standard Candles

Due to the radial variation of f_{gas} , one must be careful when using f_{gas} as a distance indicator. It is mandatory to compare the gas mass fractions at similar density contrast, or fraction of the virial radius (as indeed done by Allen et al. (2002) and Ettori et al. (2003)). However, this assumes that cluster profiles are similar at all redshifts. This last assumption must be verified from detailed observations at high z .

In general, the main concern is the actual evolution of the X-ray properties of clusters. For instance one can wonder if f_{gas} varies with redshift as it varies with the system mass. Scaled quantities can be biased distance indicator, if an improper evolution of the scaling laws is used. The extra-physics, responsible for the observed departures from the standard self-similar model in the local Universe, is likely to affect also the ICM evolution. This may not only affect the normalization of the scaling laws, but also their slope, which might not be constant.

2.3.3. Cluster Abundance

This is extensively discussed by S. Borgani in these proceedings. The issue is the same than for the previous methods. We need to relate X-ray observable quantities to the cluster mass. This requires robust estimates of the corresponding scaling laws, and their evolution and thus to understand the ICM physics.

In conclusion, the evolution of cluster structure and scaling laws is a key information. Using empirical laws, whenever available, should minimize systematic biases

in cosmological parameter estimates. Furthermore, the evolution of cluster properties should help disentangle the respective role of gravitational and various non-gravitational processes in cluster evolution. A good understanding of cluster formation and evolution is required to assess the validity and robustness of the various methods. It is obviously needed, whenever one has to rely on theoretical estimates (e.g., the $M-T$ relation at high redshift).

3. Evolution of Clusters: Some Insight from XMM Observations

The standard self-similar model makes definitive predictions on the evolution of cluster properties. While they should keep the same internal structure as nearby clusters, more distant clusters should be denser, smaller and more luminous. For instance, the total and gas mass scales as $M_{\text{gas}} \propto M_{200} \propto h^{-1}(z)T^{3/2}$, and the X-ray luminosity as $L_X \propto h(z)T^2$. Here $h(z)$ is the Hubble constant normalized to its local value.

ROSAT/ASCA observations gave the first indication that the self-similarity does hold at $z > 0$. The universal EM profile appears to extend to $z \sim 0.8$, with a redshift scaling consistent with the expectation for a Λ CDM cosmology (Arnaud et al. 2002a). These authors found significant evolution in the normalization of the L_X-T relation, consistent with the self-similar model (as have other studies considering this cosmology; Reichart et al. 1999, Novicki et al. 2002). However these observations were highly biased towards massive systems, mostly clusters discovered by the EMSS, and their statistical quality was poor.

Several X-ray samples of distant clusters have been assembled using *ROSAT* observations. They are much larger and cover a much wider mass range than the EMSS. With *XMM-Newton* it is now possible to make detailed studies of these clusters. We present here results from a follow-up of the clusters detected in the Bright and South SHARC survey (Romer et al. 2000; Burke

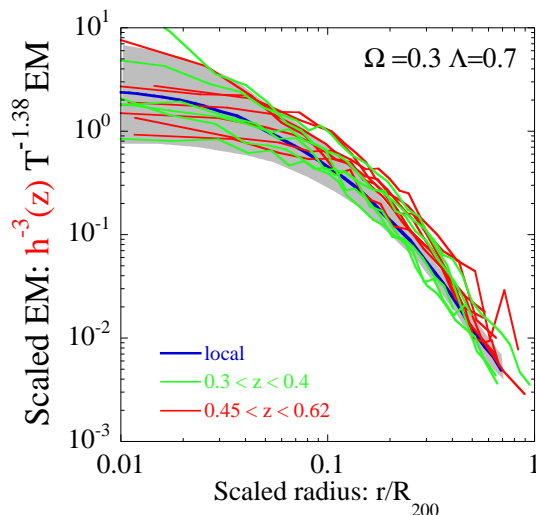


FIG. 2.— The scaled EM profiles of medium and high redshift SHARC clusters (green and red lines) observed with *XMM-Newton*, compared to the mean scaled profile of nearby hot clusters (full line, the grey area is the scatter around the mean).

et al. 2003). Eight high z ($0.45 < z < 0.62$) clusters were observed in Guaranteed Time (Lumb et al. 2003, Arnaud et al. 2002b) and six medium redshift ($0.3 < z < 0.4$) clusters in Open Time. A combined analysis of the whole sample is in progress (Arnaud et al., in prep.; see also Majerowicz 2003).

These data definitively confirm a positive evolution in the normalization of the L_X-T relation (Lumb et al. 2003, Fig. 1). In the left panel of Fig. 1, we show the luminosities for the combined SHARC sample versus temperature. The cooling core contribution, when present, have been removed from the data. All the data points stand significantly above the local relation. Lumb et al. (2003) found that the normalization of the L_X-T relation for the high z sample scales as $(1+z)^{1.54 \pm 0.26}$, consistent with the evolution found by Vikhlinin et al. (2002) from *Chandra* data ($(1+z)^{1.5 \pm 0.3}$). The right panel illustrates this evolution: when each luminosity is scaled by $(1+z)^{-1.5}$, the data points of the whole *XMM-Newton* and *Chandra* samples become consistent with the local relation. Note that this best fit evolution is stronger than the $h(z)$ evolution predicted by the standard self-similar model (see middle panel), although the effect is probably not very significant (work in progress).

We show in Fig. 2 the corresponding EM profiles, scaled according to the standard evolution: $EM_{sc} =$

$h(z)^{-3} T^{-1.38} EM$ (the empirical slope of the $EM-T$ relation derived by Neuman & Arnaud (2001), is assumed not to evolve). The profiles are traced up to similar, or even larger, radii than the mean profile of nearby clusters observed with *ROSAT*. There is good agreement between individual profiles and the local mean profile (taking into account the local dispersion and errors); the self-similarity of form up to high z is confirmed. However there is a hint of a systematic discrepancy: most high z profiles lie above the above local curve (the effect is stronger for the highest z sample). This is again an indication for stronger evolution, as found from the L_X-T relation.

4. Conclusion

Clusters of galaxies are powerful cosmological tools. Several *independent* methods can be used to constrain the cosmological parameters from cluster X-ray observations. All of them rely on specific assumptions on the scaling and structural properties of clusters.

Recent observations indicate that clusters form a self-similar population, down to surprisingly low temperature and up to high redshift. However, the ICM scaling properties for local clusters differ significantly from expectation in the simplest self-similar model. Furthermore, the ICM evolution may also differ from the expectation. These observations confirm that the specific physics of the gas component is still insufficiently understood.

High precision cosmology with clusters is a priori possible. However, the key issue is to decrease the systematic uncertainties due to our imperfect knowledge of the physics that govern cluster formation and evolution. A combined observational and theoretical effort is required. Observations of larger samples, with unbiased mass and redshift sampling, is essential. In particular we need i) to fully assess evolution, including possible evolution of the scaling law slopes ii) to better calibrate the $M-T$ relation iii) to estimate the intrinsic scatter in cluster properties. The statistical precision required is now achievable with *XMM-Newton* and *Chandra*. Confrontation with numerical simulations is essential to disentangle the roles of the various physical processes.

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