Astronomy
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Astrophysics

The XMM-Ω project

II. Cosmological implications from the high redshift *L − T* relation of X-ray clusters

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Abstract. The evolution with redshift of the temperature-luminosity relation of X-ray galaxy clusters is a key ingredient to break degeneracies in the interpretation of X-ray clusters redshift number counts. We therefore take advantage of the recent measurements of the temperature-luminosity relation of distant clusters observed with XMM-Newton and Chandra satellites to examine theoretical number counts expected for different available X-rays cluster samples, namely the RDCS, EMSS, SHARC, 160 deg^2 and the MACS at redshift greater than 0.3. We derive these counts without any adjustment, using models previously normalized to the local ($z \sim 0.05$) temperature distribution function (TDF) and to the high-z ($z \sim 0.33$) TDF. We find that these models having Ω_M in the range [0.85–1.] predict counts in remarkable agreement with the observed counts in the different samples. We illustrate that this conclusion is weakly sensitive to the various ingredients of the modeling. Therefore number counts provide a robust evidence of an evolving population. A realistic flat low density model ($\Omega_M = 0.3$), normalized to the local abundance of clusters is found to overproduce cluster abundance at high redshift (above $z \sim 0.5$) by nearly an order of magnitude. This result is in conflict with the popular concordance model. The conflict could indicate a deviation from the expected scaling of the $M − T$ relation with redshift.

Key words. cosmology – cosmological parameters – dark matter – galaxies: clusters : general

1. Introduction

The evolution of the temperature distribution function (TDF) of X-ray clusters is known to be a powerful cosmological test of the density parameter of the Universe (Oukbir & Blanchard 1992). Indeed, the evolution with redshift of the mass function, on cluster scales, once normalized to present day, appears to be a robust cosmological test, with an exponential sensitivity to Ω_M through the gravitational growth rate of perturbations (Blanchard & Bartlett 1998). The high sensitivity of this test has allowed its first direct application from a sample of ten (revised to 9) clusters at redshift 0.3 with measured temperature (Henry 1997). However, several authors have inferred somewhat different values from this single sample (Eke et al. 1998; Viana & Liddle 1999; Blanchard et al. 2000, hereafter B00).

This might not be so surprising given the small size of the sample as well as the limited range of redshift. An alternative approach to track the evolution of the abundance of clusters is from their redshift distribution in X-ray samples for which the selection function is known. This procedure, reducing the time telescope investment, has been applied to the EMSS sample (Oukbir & Blanchard 1997; Reichart et al. 1999) and to the RDCS sample (Borgani et al. 1999, 2001) but the conclusion on Ω_M depends on the possible evolution of the $L − T$ relation (Sadat et al. 1998, hereafter SBO98; Borgani et al. 1999; Novicki et al. 2002). The various ingredients used in this modeling were not necessary accurately known, most noticeably the temperature mass ($T − M$) relation, and the luminosity-temperature ($L−T$) relation and its possible evolution with redshift. Therefore doubts have been raised up on the applicability of this test given these uncertainties (Colafrancesco et al. 1997; Rosati et al. 2002).

The XMM-Ω project was conducted in order to provide an accurate estimation of the possible evolution of the luminosity temperature relation at high redshift for clusters of medium luminosity which constitute the bulk of X-ray selected samples, allowing to remove a major source of degeneracy in the determination of Ω_M (Bartlett et al. 2001). To maintain a better control on the resulting $L - T$ it is clearly preferable to use clusters homogeneously obtained from X-ray selected samples. Therefore, the choice of the SHARC surveys in the XMM-Ω project provides several advantages: large angular coverage with the Bright SHARC (Nichol et al. 1999; Romer et al. 2000), deepness of the sample with the South SHARC (Burke et al. 1997), still keeping the number of clusters to a realistic size for comprehensive X-ray investigations.

The purpose of this letter is to examine the expected number counts in comparison with the observed counts in two different cosmological models, namely a concordance model and a high matter density flat universe, and to examine the amplitude of the major sources of uncertainties: the statistical dispersion on the value of σ_8 from the finite local sample, the systematic uncertainties in the $M - T$ and the $L - T$ relations at high redshift. In this modeling we take advantage of the accurate knowledge of the $L - T$ relation provided by the first results from the XMM-Ω project (Lumb et al. 2003, hereafter L03) and from recent Chandra measurements of distant clusters (Vikhlinin et al. 2002).

2. Modeling the temperature distribution function and number counts

Although a full likelihood is possible in order to determine the best parameters and their final uncertainty taking into account all the possible sources of uncertainties, we find enlightening to illustrate the differences in the counts predicted in the two following specific models: the first model (hereafter model A) is the best flat model obtained as in B00 by fitting the local TDF and the high redshift TDF from the Henry (1997) sample, assuming a Γ CDM–like spectrum. The second model (hereafter model B) we use is the so-called concordance model i.e. a flat Λ CDM model with $\Omega_M = 0.3$, in agreement with the recent WMAP results (Spergel et al. 2003). In this model, only the local TDF was then fitted. The parameters used are summarized in Table 1. The samples we used for comparison are EMSS (Gioia et al. 1990; Henry et al. 1992), RDCS (Rosati et al. 1995, 1998), 160 deg^2 (Vikhlinin et al. 1998, 2002), Bright SHARC (Nichol et al. 1999; Romer et al. 2000) and MACS (Ebeling et al. 2001) for which the selection criteria are believed to be well known, generally given as sky coverage versus flux limit. These catalogs provide us with a sample of 274 (non necessarily independent) clusters with redshift between 0.3 and up to more than 1 and luminosities between 10^{43} and 10^{45} erg/s.

In our modeling we follow a procedure close to the one used by Oukbir & Blanchard (1997), Reichart et al. (1999) and Borgani et al. (1999). In the first step, models are normalized using the local TDF, which request two fundamental ingredients: the mass function and the $M - T$ relation, assumed to follow a standard scaling law (Kaiser 1986). Intensive numerical simulations have allowed to provide accurate analytical fits to

Table 1. Models and parameters used in the number counts calculations.

T_{15} (keV)	Ω_M	σ_8	Γ	Cosmological model and ingredients
4	1.	0.55	0.12	A: best model+BN98+SMT
6.5	0.85	0.455	0.1	A: best model+M98+SMT
4	0.3	1.	0.2	B: Low Ω_M+BN98+SMT
6.5	0.3	0.725	0.2	B: Low Ω_M+M98+SMT

the mass function (Sheth et al. 2001, hereafter SMT; Jenkins et al. 2001; White 2002). Here we use the expression from SMT:

$$\frac{dN}{dm} = \sqrt{\frac{2a}{\pi}}\, c\, \frac{\bar{\rho}}{m} \frac{d\nu}{dm} \left(1 + \frac{1}{(a\nu^2)^p}\right) \exp\left(-\frac{a\nu^2}{2}\right) \tag{1}$$

with $a = 0.707$, $c = 0.3222$ and $p = 0.3$ and $\nu = \frac{\delta}{\sigma(m)}$.

2.1. The M − T relation

It has been shown that the normalization of the $M - T$ relation based on numerical simulations is significantly different from the normalization inferred from hydrostatic equation (Roussel et al. 2000). In this work we use two different normalizations so as to cover the whole range of possibilities: we use on one side the calibration based on the numerical simulations of Bryan & Norman (1998, BN98 hereafter) and on the other side we use a $M - T$ relation derived from the hydrostatic equation (Markevitch 1998, M98 hereafter) which produces a lower normalization of the matter power spectrum σ_8 (Seljak 2002; Reiprich & Böhringer 2002). The $M - T$ relation is written to be:

$$T = T_{15}(\Omega_M \Delta(z, \Omega_M)/178)^{1/3} M_{15}^{2/3}(1 + z) \tag{2}$$

where $\Delta(z, \Omega_M)$ is the contrast density with respect to the density of the Universe for virialized objects (hereafter $h = 0.5$). The subscript 15 means that masses are taken in unit of 10^{15} solar masses. BN98 found $T_{15} \sim 3.8$ keV, while M98 concluded to a higher normalization : $T_{15} \sim 6.5$ keV.

The mass function can then be normalized from the observed TDF (a possible dispersion of 15% is included as done in B00). The availability of bright ROSAT clusters samples has allowed reasonably accurate estimations of the local TDF (M98; B00; Pierpaoli et al. 2001; Ikebe et al. 2002), even if the agreement is partly due to the fact that the samples used in these previous works contain nearly the same clusters.

In the present work, we use the local TDF based on an updated version of the local X-ray clusters sample used in B00 in which clusters were selected with fluxes $f_x > 2.2 \times 10^{-11}$ erg/s/cm^2 in the ROSAT [0.1-2.4] keV and galactic coordinates $|b_{II}| > 20^\circ$. This revised TDF is essentially identical to B00 and other recent measurements.

2.2. Evolution of the L − T relation

In a second step we use the $L - T$ relation and its evolution to compute the luminosity function at different redshifts. Using
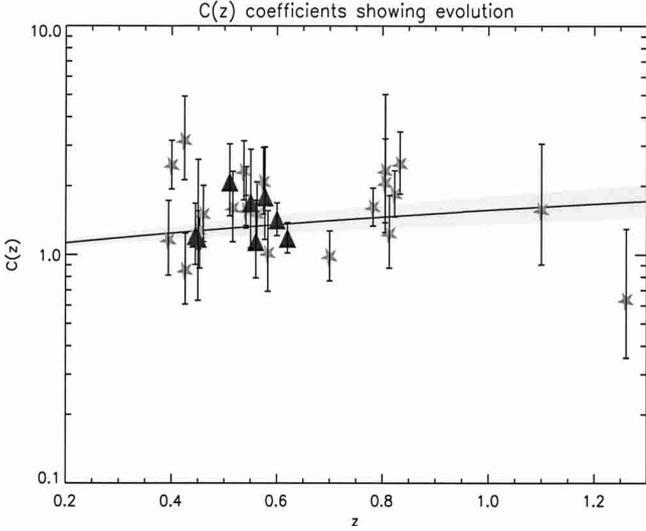
Fig. 1. XMM measurements of the evolution of clusters $L - T$ relation expressed by the $C(z)$ coefficient (Eq. (3)). Triangles are our XMM data and error bars are derived from the 1σ error on the temperature measurement. Grey (yellow) area represents the 1σ error on the $C(z)$ fit and stars are the Chandra data.

the observed local $L - T$ relation, models fitting the observed local TDF automatically provide a luminosity function matching the data (Oukbir et al. 1997). The local $L - T$ relation $L_{\text{bol}} = A(T/1\text{keV})^B$ is estimated from the sample described above (Vauclair et al. 2003, in preparation). We obtained $A = 0.0625 \times 10^{44}$ erg/s assuming $B = 3$. We then estimated the evolution of this relation using our XMM data of high-z clusters obtained in the XMM-Ω project (L03). Following SBO98 we compute for each cluster:

$$C(z) = \frac{L}{AT^B} \frac{D_l(\Omega_M = 1, z)^2}{D_l(\Omega_M, z)^2} \qquad (3)$$

and fit these $C(z)$ by a power-law evolution law:

$$C(z) = (1 + z)^\beta \qquad (4)$$

the best-fit parameter $\beta = 0.65 \pm 0.21$ was obtained by a standard χ^2 fitting (see Fig. 1) in good agreement with what was found previously (SBO98) and fully consistent with the Chandra results (Vikhlinin et al. 2002).

2.3. Number counts

In order to compute number counts, one can notice that the observations actually provide z and f_x (rather than the actual L_x and T_x). For a flux limited sample with a sky coverage area Ω and a flux limit f_x one has therefore to compute the following:

$$
\begin{aligned}
N(>f_x, z, \Delta z) &= \Omega \int_{z-\Delta z}^{z+\Delta z} \frac{\partial N}{\partial z}(L_x > 4\pi D_l^2 f_x) \mathrm{d}z \\
&= \Omega \int_{z-\Delta z}^{z+\Delta z} N(> T(z)) \mathrm{d}V(z) \\
&= \Omega \int_{z-\Delta z}^{z+\Delta z} \int_{M(z)}^{+\infty} N(M, z) \mathrm{d}M \mathrm{d}V(z) \qquad (5)
\end{aligned}
$$

where $T(z)$ is the temperature threshold corresponding to the flux f_x as given by the observations, being therefore independent of the cosmological model. We then compute the theoretical number counts in redshift bins $\Delta z = 0.1$ for the various clusters samples mentioned above accordingly to their respective selection function. In order to compare the same cluster population at different redshifts, we have excluded from the faint ROSAT samples number counts at redshift smaller than $z = 0.3$ for which clusters have too low luminosity compared to those used to measure the $L - T$ evolution in this project. In addition at $z < 0.3$ clusters become significantly more extended than the detection cell in the EMSS sample, and are not considered as reliable in MACS, a further reason for restricting our comparison to higher redshifts.

2.4. Comparison with observations

The final number counts for the different samples are presented in Fig. 2 for models A and B. As one can see the predicted counts in model A are in remarkable agreement with the observed number counts given the fact that no adjustment was performed, while the predicted number counts in the concordance model reveals a strong disagreement with the data. The overproduction of clusters at high redshift is impressively large, reaching a factor of nearly ten at redshift greater than 0.5. Two factors are responsible for this difference: the primary effect comes from the evolution in the number of clusters which is quite different in the two models and the second effect comes from the increase of the volume element in the Λ dominated universe. The uncertainties in the value of σ_8, in the $L - T$ relation and in the $M - T$ relation represent similar uncertainties in the predicted counts, in the range of 30% to 70%, but are far below the difference between the two models which is between 5 and 10. We also checked that changing the slope and the normalization of the local $L - T$ does not affect our results. One may worry whether the selection procedure of the samples has introduced more bias than usually assumed. A systematic bias in the flux of the order of 2 to 3 for the different surveys would eliminate most of the discrepancy between the predictions of concordance model and the observed counts. Such a possibility seems very unlikely: different flux inter-comparisons exist, including those of L03 between ROSAT SHARC and XMM fluxes and those of Vikhlinin et al. (2003) between ROSAT and Chandra fluxes, and do not provide any evidence for such a large bias.

3. Discussion

As we have seen a model which is normalized to the local as well as to the high redshift TDF, reproduces impressively well the redshift distribution of all the surveys we have investigated, without any adjustment and with little uncertainties arising from the modeling. In contrast, we have checked that relaxing the request of matching the local abundance a concordance model fitting the redshift distribution leads to a local abundance of X-ray clusters $N(>4$ keV, $z = 0.05)$ nearly 5 times lower than actually observed. This is a strong indication that existing samples of clusters (namely the Henry sample, the RDCS, the
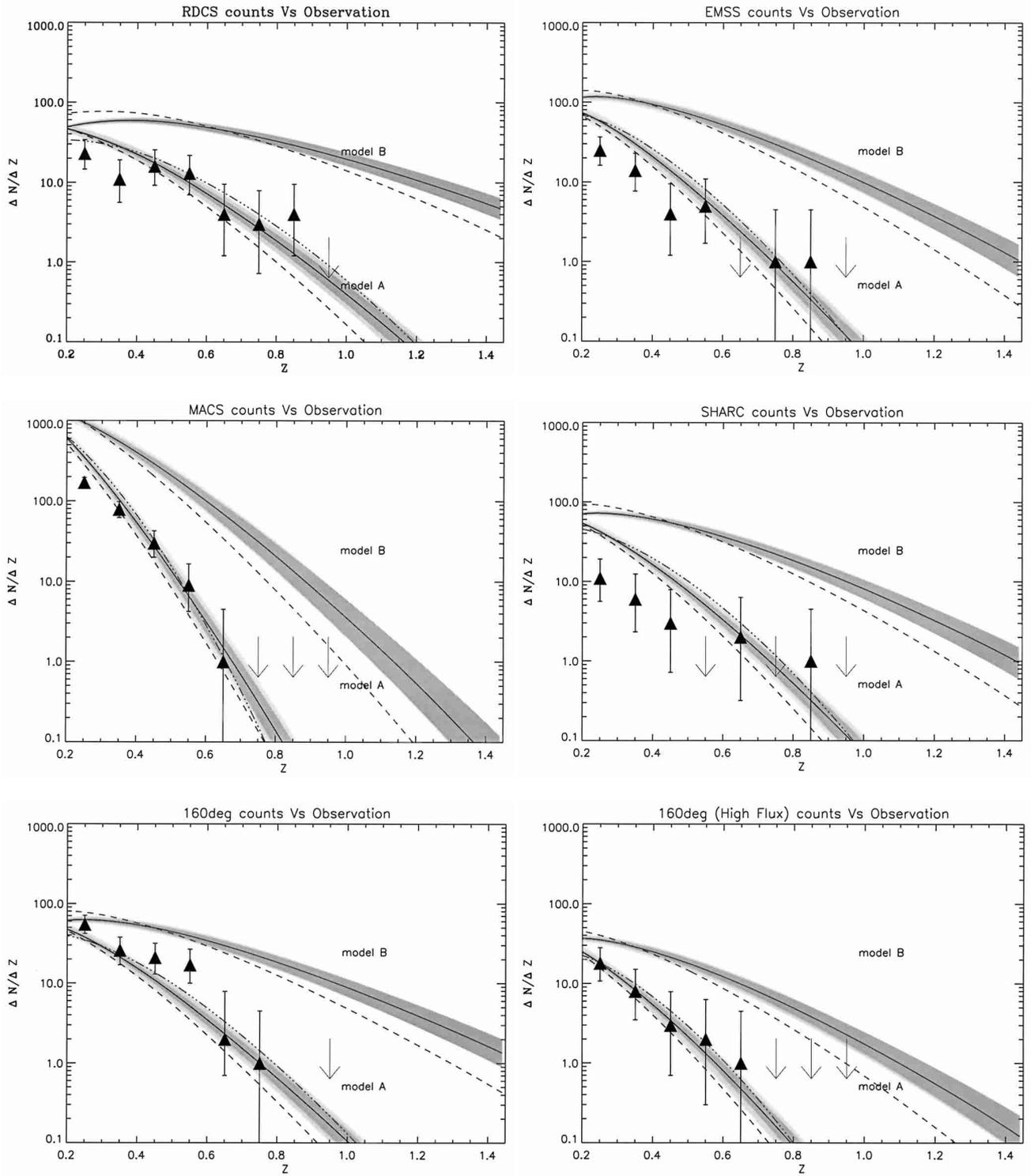
Fig. 2. Theoretical number counts in bins of redshift ($\Delta z = 0.1$) for the different surveys: RDCS, EMSS, SHARC, MACS and 160 deg^2. Observed numbers are triangles with 95% confidence interval on the density assuming Poissonian statistics (arrows are 95% upper limits). For the 160 deg^2 survey we have also examined the counts for the brightest part (160 deg^2(high flux) corresponding to fluxes $f_x > 2 \times 10^{-13}$ erg/s/cm^2), in order to show that the excess seen at $z \sim 0.5$ is not due to luminous clusters. The upper (red) curves are the predictions in the concordance model (model B). The lower (blue) curves are for model A (see Table 1). Different $M - T$ are figured: the dashed lines correspond to $T_{15} = 6.5$ keV (M98 $M - T$) while the continuous lines are for $T_{15} = 4$. keV, corresponding to virial mass nearly twice larger, close to BN98 normalization. The dark grey (green) area is the uncertainty range from our estimates on the uncertainty in the evolution of the $L - T$ relation while the light grey area is the uncertainty on number counts due to the dispersion on σ_8. The 3-dotted-dashed lines show the predicted counts in the concordance model using $M - T$ relation from Eq. (6) violating the standard scaling with redshift.

EMSS, the Bright SHARC, the 160 deg^2 and the MACS sample) draw the same picture, consistently pointing out toward the fact that the cluster abundance is significantly evolving with redshift, perhaps closing a long term controversy on this question (Henry et al. 1992). Furthermore, in standard hierarchical picture of structure formation such evolution points toward a high matter density universe with Ω_M in the range [0.85–1.], the precise value depending on the $M - T$ normalization. This conclusion is clearly conflicting with the currently popular concordance model. However, it should be emphasized that this is entirely consistent with *all previous existing analyzes* performed on the redshift distribution of X-ray selected samples of clusters performed with the same methodology: our conclusion corroborates previous analyzes of the EMSS clusters redshift distribution: SBO98 found $\Omega_M = 0.85 \pm .2$, Reichart et al. (1999) found $\Omega_M = 0.96 \pm .3$ as well as the RDCS redshift distribution for models normalized to the present-day X-ray clusters abundance. Indeed, from Eq. (14) in Borgani et al. (1999), $\Omega_M = (\beta + 2)/3 \pm 1/3$ we derive $\Omega_M \sim 0.88 \pm .34$ from our $\beta \sim 0.65 \pm .21$. Note that high Ω_M models are also consistent with WMAP (Blanchard et al. 2003). A possible loophole could be a large systematic bias flux, but we have argued that this seems very unlikely. An other possibility would be that the scaling in the redshift of the $M - T$ relation (Eq. (1)) is completely wrong, violating the basic scaling scheme. Voit (2000) has investigated such a possibility, but concluded to a moderate effect. In Fig. 2, we have plotted the predicted counts in a concordance model, assuming

$$T = T_{15}(\Omega_M \Delta(z, \Omega_M)/178)^{1/3} M_{15}^{2/3} \qquad (6)$$

instead of Eq. (2). As one can see, such a modification reestablishes agreement of the concordance model with observations. It is well known that the $L - T$ relation cannot be explained from simple scaling arguments. One may therefore argue that the redshift evolution of the $M - T$ relation may suffer from more dramatic effect than usually assumed, although – to our knowledge – such a possibility has never been advocated and it is probably not obvious to find physical motivation leading to gas thermal energy in distant clusters ($z \sim 1$) to be reduced by a factor of two compared to clusters in the local universe. We therefore conclude that the redshift distributions of present–day available X-ray clusters surveys, as well as the recent results on the $L - T$ relation of high redshift clusters, favor a high matter density universe unless the standard paradigm on clusters gas physics has to be deeply revised.

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