# THE EVOLUTION OF THE ABUNDANCE OF CLUSTERS AS A COSMOLOGICAL TEST

A. BLANCHARD
*Laboratoire d'astrophysique de l'O.M.P., U.P.S., 14, Ave E. Belin*
*31 400 Toulouse, France*

The evolution of cluster abundance with redshift has been recognized as one of the most powerful test of the mean density of the Universe. Heroic first applications of this test based on a sample of nine EMSS clusters at $z \sim 0.33$ for which temperature has been measured lead to somewhat discordant values ranging between between 0.45 and 0.9. In this talk I discuss the method to derive the mean density of the universe as well as the differences between the various analyses which are more systematical in nature than statistical. Using complete x-ray selected sample, with clusters ranging from 0.3 to 0.6, taking into account the various possible systematics, our lattest analysis leads to high values for the density parameter of the Universe, between 0.6 and 1.

## 1 Introduction

The determination of cosmological parameters is a central question in modern cosmology. The detection by COBE of the CMB fluctuations has opened a new area with the perspective of reaching high "precision cosmology". Indeed the detection of fluctuations on small angular scale more than 5 years ago provides a first convincing piece of evidence for a nearly flat universe (Linewaever et al, 1997; Lineweaver and Barbosa, 1998). The possible detection of a cosmological constant from distant supernovae has bring a further essential piece of evidence largely conforting the so-called concordance model. Indeed a CDM model in a flat universe dominated by a cosmological constant is in impressive agreement with most of existing data. Iit i stherefore obvious that the point of view that I will defend, that is that we may after all live in an Einstein-de Sitter Universe, is widely unorthodox. However, if one keeps an open mind one should realize that: 1) SNIa measurements provide the **single** direct evidence for a cosmological constant 2) measurements of $\Omega_m$ are most of the time local, inferred from clusters, objects representing $10^{-5}$ of the total volume of the universe. It is therefore reasonable to doubt that the extrapolation of the $M/L$ over 5 order of magnitudes is actually completely unbiased. In such a situation, it is vital to look for **global tests** of $\Omega_m$. An example is given by the baryon fraction in clusters. This was probably the most serious evidence in favor of a low density universe, given the primordial nucleosynthesis constraint. I refer to Sadat's contribution on this issue who shows that this constraint is actually not secure and might actually favors high $\Omega_m$, being consistent with values as high as 0.8. A second constraint on cosmological parameters comes from gravitational lensing statistics with JVAS and CLASS survey. Again the small number of detected lenses favors a high density universe (and obviously any good student in astrophysics is able to find good reasons why this should not be trusted...). Finally, the amplitude of bulk flows, which has been alternatively advocate in favor of a high and low density parameter, does not

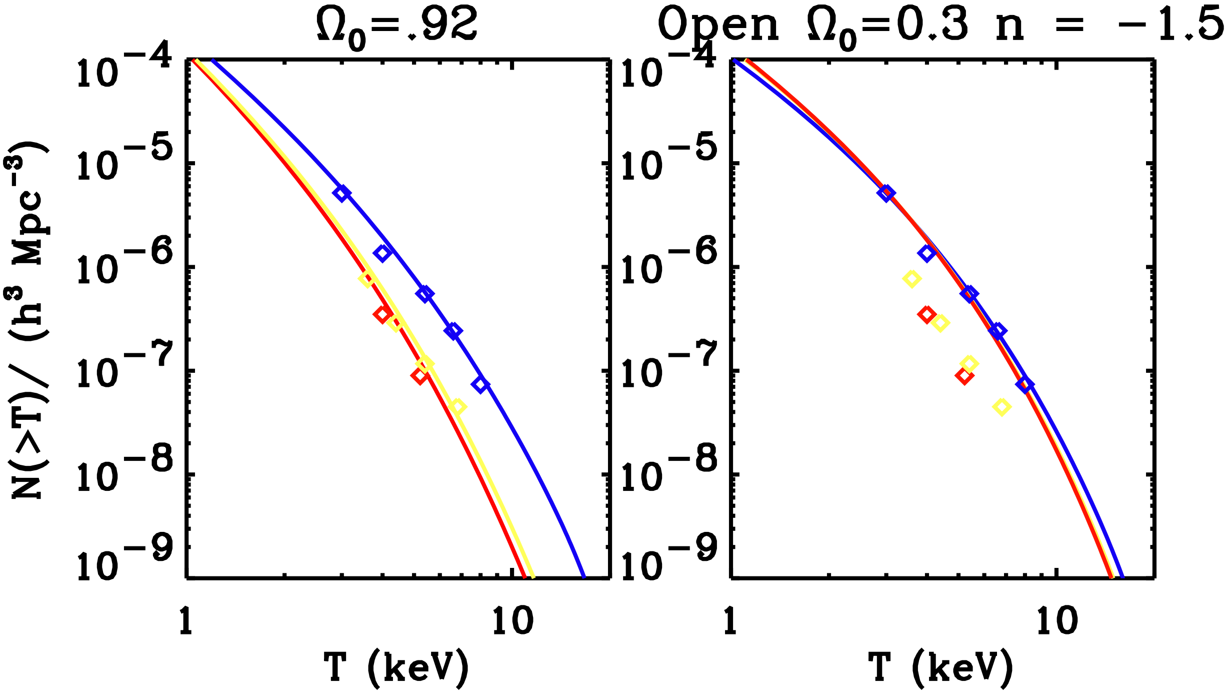


Figure 1: These plots illustrate the power of the cosmological test of the evolution of the abundance of x-ray clusters: the TDF has been normalized to present day abundance (blue lines). The abundance of local clusters is given by th eblue symbols (Blanchard et al., 2000). Present abundance allows one to set the normalization and the slope of the spectrum of primordial fluctuations on clusters scale (which is $\Omega_m$ dependant). The evolution with redshift is much faster in a high matter density universe (left panel, $\Omega_0 = 0.92$) than in a low density universe (right panel, $\Omega_0 = 0.3$): $z = 0.33$ (yellow – light) the difference is already of the order of 3 or larger. It is relatively insensitive to the cosmological constant. We also give our estimate of the local TDF (blue symbols) derived by Blanchard et al. (2000), as well as our estimate of the TDF at $z = 0.33$ (yellow symbols). Also are given for comparison data (Henry 2000) and models predictions at $z = 0.38$ (red – dark grey – symbols and lines). On the left panel, the best model is obtained by fitting simultaneously local clusters and clusters at $z = 0.33$ leading to a best value of $\Omega_0$ of 0.92. The right panel illustrates the fact that an open low density universe $\Omega_0 = 0.3$ which fits well local data does not fit the high redshift data properly at all.

provide a measurement of $\Omega_m$, but of a combination of $\Omega_m$ and of the bias parameter, leading to a degeneray, which is nearly the same than the information given by the local abundance of clusters.

## 2 A new cosmological test

The abundance of clusters at high redshift has been used as a cosmological contraint more than ten years ago by Peebles et al. (1989). The purpose was to show that the standard cold dark matter picture could not reproduce their overall properties. In 1992, Oukbir and Blanchard emphasize that the evolution of the abundance of clusters with redshift was rather different in low and high density universe, offering a possible cosmological test. The interest of this test is that it is global, not local, and therefore actually allows to constraint $\Omega_m$. It is relatively insensitive to the cosmological constant. Since that time this test has received considerable attention (Eke et al., 1998; Henry, 1997; Henry, 2000; Sadat et al., 1998; Viana  Liddle, 1996,

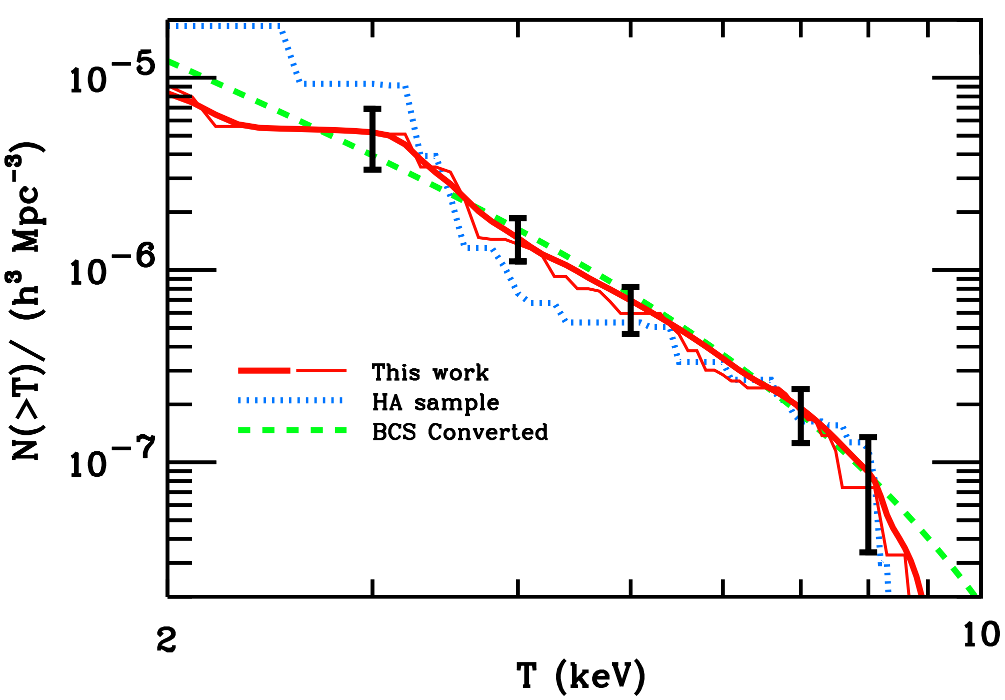


Figure 2: The integrated temperature distribution function inferred from our sample is given by the continuous (red) thin line. A smoothed version is also given (thick line). The dotted line is the same quantity for the original HA91 sample. The dashed (green) line is derived from the BCS luminosity function. The error bars represents the 68% interval for the distribution of the estimator from the bootstrap.

among others). The first practical application of it was by Donahue (1996) who emphasized that the properties of MS0451, with a temperature of around 10 keV at a redshift of 0.55, was already a serious piece of evidence in favor of a low density universe. In the mean time, however, the redshift distribution of EMSS clusters was found to be well fitted by a high density universe under the assumption of a non evolving luminosity-temperature relation (Oukbir and Blanchard, 1997; Reichert et al., 1999). The discovery of a high temperature cluster at redshift $z \sim 0.8$ MS1054, which has a measured temperature of $\sim 12$ keV (Donahue et al, 1999)

In principle, this test is relatively easy to apply, because the abundance at redshift $\sim 1.$ is more than an order of magnitude less in a critical universe, while it is almost constant in a low density universe. Therefore the measurement of the temperature distribution function (TDF) at $z \sim 0.5$ should provide a robust answer. Actually, this is part of the XMM program during the guaranty time phase lead by Jim Bartlett. In principle, this test can be applied by using other mass estimates, like velocity dispersion, Sunyaev-Zeldovich, or weak lensing. However, mass estimations based on X-ray temperatures is up to now the only method which can be applied at low and high redshift with relatively low systematic uncertainty. For instance, if velocity dispersions at high redshift ($\sim 0.5$) are overestimated by 30%, the difference between low and high density universe is cancelled. Weak lensing and SZ surveys of clusters remains to be done.

### *2.1 The local temperature distribution function*

The estimation of the local temperature distribution function of X-ray clusters can be achieved from a sample of X-ray selected clusters for which the selection function is known, and for which temperatures are available. Until recently, the standard reference sample was the Henry

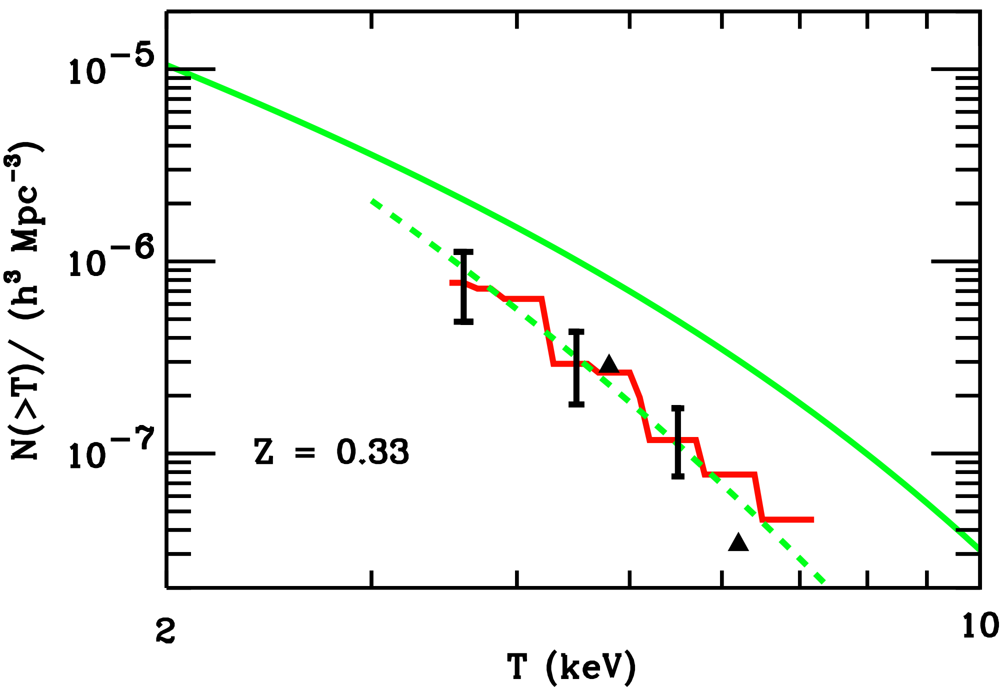


Figure 3: The integrated temperature distribution function at $z = 0.33$ inferred from Henry's sample is given by the continuous red line (corresponding to the case $\Omega_0 = 0.5$). The two triangles are the estimation from Viana & Liddle (1999a, 1999b) from the original H97 sample. The green line is the fit to our local temperature distribution function. The dashed green line is our best model at $z = 0.33$.

and Arnaud sample (1991), based on 25 clusters selected in the $2-10$keV band. The ROSAT satellite has since provided better quality samples of X-ray clusters, like the RASS and the BCS sample, containing several hundred of clusters. Temperature information is still lacking for most of clusters in these samples and therefore do not yet allow to estimate the TDF in practice. We have therefore constructed a sample of X-ray clusters, by selecting all X-ray clusters with a flux above $2.210^{-11}$ erg/s/cm$^2$ with $|b| > 20$. Most of the clusters come from the Abell XBACS sample, to which few non-Abell clusters were added. The completeness was estimated by comparison with the RASS and the BCS and is of the order of 85%. This sample comprises 50 clusters, which makes it the largest one available for measuring the TDF. The TDF is given in figure 1. This is in very good agreement with the TDF derived from the BCS luminosity function. The abundance of clusters is higher than derived from the Henry and Arnaud sample as given by Eke et al. (1998) for instance. It is in good agreement with Markevitch (1998) for clusters with $T > 4$ keV, but is slightly higher for clusters with $T \sim 3$ keV. The power spectrum of fluctuations can be normalized from the abundance of clusters, leading to $\sigma_8 = \sigma_c = 0.6$ for $\Omega = 1$ and to $\sigma_c = 0.7$ For $\Omega = 1$ corresponding to $\sigma_8 = 0.96$ for a $n = -1.5$ power spectrum index (contrary to a common mistake the cluster abundance does not provide an unique normalization for $\sigma_8$ in low density models).

### *2.2 Application to the determination of* $\Omega_0$

The abundance of X-ray clusters at $z = 0.33$ can be determined from Henry' sample (1997) containing 9 clusters. Despite the limited number of clusters and the limited range of redshift for which the above cosmological test can be applied, interesting answer can already be obtained, demonstrating the power of this test. Comparison of the local TDF and the high redshift TDF clearly show that there is a significant evolution in the abundance of X-ray clusters (see figure 1), such an evolution is unambiguously detected in our analysis. This evolution is consistent with the recent study of Donahue et al. (2000). We have performed a likelihood analysis to estimate the mean density of the universe from the detected evolution between $z = 0.05$ and $z = 0.33$. The likelihood function is written in term of all the parameters entering in the problem: the power spectrum index and the amplitude of the fluctuations. The best parameters are estimated as those which maximized the likelihood function. The results show that for the open and flat case, one obtains a high value for the preferred $\Omega_0$ with a rather low error bar :

$$\Omega_0 = 0.92^{+0.26}_{-0.22} \quad \text{(open case)} \tag{1}$$

$$\Omega_0 = 0.79^{+0.35}_{-0.25} \quad \text{(flat case)} \tag{2}$$

Interestingly, the best fitting model also reproduces the abundance of clusters (with $T \sim 6$ keV) at $z = 0.55$. The preferred spectrum is slightly different in each model: low density universe prefers $n \sim -1.5$, while high density universe prefers lower value $n \sim_1 .8$, but with large uncertainties. The normalization is slightly higher than previously estimated: for $\Omega = 1$, we found $\sigma_8 = 0.6$, consistent with recent estimates based on optical analysis of galaxy clusters (Girardi et al., 1998).

### *2.3 Systematic uncertainties in the determination of* $\Omega_0$

The above values differ sensitively from several recent analyses on the same test and using the same high redshift sample. It is therefore important to identify the possible source of systematic uncertainty whether may explain these differences. The test is based on the evolution of the mass function (Blanchard & Bartlett, 1998). The mass function has to be related to the primordial fluctuations. The Press and Schechter formalism is generally used for this, and this is what we did here. However, this may be slighly uncertain. Using the more recent form proposed by Governato et al. (1999) we found value 10% higher. A second problem lies in the mass temperature relation whixh is necessary to go from the mass function to the temperature distribution function. The mass can be estimated either from the hydrostatic equatio or from numerical simulations. In general hydrostatic equation leads to mass smaller than numerical simulations (Roussel et al., 2000). Using the two most extreme mass–temperature relations inferred from numerical simulations, we found a 10% difference. We concluded that such uncertainties are not critical. A more critical issue is the local sample used: using HA sample we found a value smaller by 40%. Identically, if we postutaled that the high redshift abundance has been underestimated by a factor of two, $\Omega_m$ is reduced by 40%. The determination of the selection function of EMSS is therefore critical. An evolution in the morphology of clusters with redshift results in a dramatic change in the inferred abundance (See Adami's contribution in this volume). This is the most serious uncertainty in this analysis.

## 3 Conclusion

The local TDF has been revisited using an updated sample of fifty clusters. We have used this sample to show that the comparison with Henry's sample at $z = 0.33$ clearly indicates that the TDF, inferred from EMSS, is evolving. This evolution is consistent with the evolution detected up to redshift $z = 0.55$ by Donahue et al. (1999). This indicates converging evidences for a high density universe, with a value of $\Omega_0$ consistent with what Sadat et al. (1998) inferred previously from the full EMSS sample taking into account the observed evolution in the $L_x - T_x$ relation (which is moderately positive and consistent with no evolution). Low density universes with $\Omega \leq 0.35$ are excluded at the two-sigma level. This conflicts with some of the previous analyses on the same high redshift sample. Actually, lower values obtained from statistical analysis of X-ray samples were primarily affected by the biases introduced by the local reference sample, which lead to a lower local abundance and a flatter spectrum for primordial fluctuations (Henry, 1997, 2000; Eke et al., 1998; Donahue & Voit, 1999). Our result is consistent with the conclusion of Viana and Liddle (1999) and Sadat et al (1988). The possible existence of high temperature clusters at high redshift, MS0451 (10 keV) and MS1054 (12 keV), cannot however be made consistent with this picture of a high density universe, unless their temperatures are overestimated by at least 50% or the primordial fluctuations are not gaussian. The baryon fraction in clusters is an other global test of $\Omega$, provided that a reliable value for $\Omega_b$ is obtained. However, it seems that the mean baryon fraction could have been overestimated in previous analysis, being closer to 10% rather than to 15%-25%. this is again consistent with a high density universe.

Clusters provide us with the most important tests for the determination of the mean density of the Universe, which allows to suppress the degeneracies existing in the method based on CMB anisotropies. As we have seen, the cluster number evolution may indicate a rather high value, of the order of 0.8 and this value could be consistent with the baryon fraction. This contradicts the result from high redshift Supernovae. Better understanding of systematic uncertainties in these methods will be critical.


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