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Ω_0 from Clusters of Galaxies

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Abstract. Clusters constitute a very rich source of information for cosmology. Their present day abundance can be used to found the normalization and the shape of the power spectrum. Clusters can also be used to determine the parameter density of the universe $\Omega - 0$. The evolution of their number density is a powerful cosmological global *test* of the mean density of the Universe. It is fashionable to claim that the abundance of clusters does not change very much with clusters redshift and therefore favor a low density universe. This is an overstatement and analyses based on the most recent data rather favor a high density universe. The baryon fraction in clusters is an alternative method to derive the mean density of the Universe. Here again, taking into account several biases in the baryon fraction is derived from data, the actual baryon fraction seen in clusters can be reconciled with a high density universe.

1. Introduction

Clusters provide a fascinating laboratory for cosmological studies: their stellar, baryonic and dark matter content can be accurately estimated, their spatial distribution can be measured on very large scale, and their evolution can be estimated up to high redshift (~ 1).

2. Mass estimates

Velocity dispersions can be determined quite accurately, which in principle can be related to their mass. However, this can be done safely possible only when hundred redshifts in each clusters are available, and the interpretation is delicate because the dynamical state of the galaxy population may not be well understood, needing some simplifying hypothesis. Lensing mass estimates are the most promising alternative, as lensing measurement provides a direct mass measurement of the projected mass without any assumption (but the validity of general relativity). Although present day measurements are claimed to be consistent with other mass estimates, they provide masses which are generally higher than other mass estimates, but with large error bars. The standard way

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to express the dynamical mass estimates for clusters is through the M/L ratio, that is the ratio of mass to light in unit of the same quantity for the sun. Dynamical mass estimates usually lead to :

$$M/L \sim 300h \tag{1}$$

Mass estimates of X-ray clusters can be obtained from the hydrostatic equation. This technique has been widely used in the past, however, it can lead to uncertainties which are larger than naively expected (Balland & Blanchard 1997; Hughes 1997). An other technique is to use the mass temperature relation derived from numerical simulations. There is a rather good convergence between different sets of numerical simulations which show that the virial mass (i.e. the mass enclosed in a region of fixed contrast density relative the critical density) is well correlated with the temperature:

$$T_x = 3.8 - 4.75\, M^{2/3}(1+z)\,\mathrm{keV} \tag{2}$$

the above range in the normalization represents the extreme values which have been published by different groups: the lower one corresponds to Bryan & Norman (1998), the higher one to Evrard, Maetzler, & Navarro (1996). These normalizations lead to mass estimates which are larger than the typical dynamical ones, or those derived from the hydro-static equilibrium method (Roussel, Sadat , & Blanchard 2000):

$$M/L \sim 640 - 800h \tag{3}$$

In order to infer the mass density of the universe, one has to make the assumption that the ratio of dark matter to light is the same everywhere in the universe. This is far from being obvious, and evidences for the presence of a such large quantity of dark matter are probably reasonable but far from being as robust as in clusters. A dramatic possibility would be that dark matter is present in large quantity only in clusters... (the amount of dark matter directly "seen" in galaxies from rotation curves is much smaller than in clusters). However, there are a couple of evidences that dark matter around galaxies extends up to few 100 kpc from the pair wise velocity distribution (Bartlett & Blanchard 1997) and up to a couple of Megaparsecs from weak lensing measurements (Van Waerbeke et al. 2000). The M/L ratio is related to Ω_0 by assuming that the ratio of matter to light is universal:

$$\rho_m = M/L \times \rho_l \tag{4}$$

where ρ_l is the light density of the universe (this quantity however may not be so well known, underestimated if galaxies are missed in present day survey). Then:

$$\Omega_0 = M/L \frac{8\pi G\rho_l}{3H_0^2} = \frac{M/L}{M/L|_c} \tag{5}$$

Using a recent determination of the luminosity function by Zucca et al. (1997), one finds $M/L|_c \sim 1250h$, the above M/L leading to $\Omega_0 \sim 0.5 - 0.65$, higher than values based on standard dynamical estimates. The main uncertainty on this method is due to the possibility that the distribution of light is not a fair

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representation of the dark matter distribution. For this reason, other methods of determination of the density parameter of the Universe are requested. Methods which do not rely on the assumption of the fairness of the light distribution can be qualified as global methods. Such global methods are rare. Clusters provide us with the two cases of such global methods for which small errors bars have been obtained.

3. Clusters abundance evolution.

The evolution of the abundance of clusters relative to the present day value is a direct test of Ω_0 which can be demonstrated like a mathematical theorem – see Blanchard & Bartlett (1998). As X-ray clusters can be detected at high redshifts, they provide us with a global test of Ω_0 (Oukbir & Blanchard, 1992). In principle, it is relatively easy to apply, because the change in the abundance at redshift $\sim 1.$ is more than an order of magnitude in a critical universe, while it is almost constant in a low density universe. Therefore the measurement of the temperature distribution function (TDF) at $z = 0.5$ should provide a robust answer. Actually, this is part of the XMM program during the guaranty time phase. 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 (~ 0.5) are overestimated by 30%, the difference between low and high density universe is cancelled.

3.1. 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 & 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 plotted in figure 1. As one can see there is in very good agreement with the TDF derived from the BCS luminosity function. The abundance of clusters is higher than thge one derived from the Henry & 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 $\Omega_0 = 1$ and to $\sigma_c = 0.7$ for $\Omega_0 = 0.3$ corresponding to $\sigma_8 = 0.96$ for a $n = -1.5$ power spectrum index

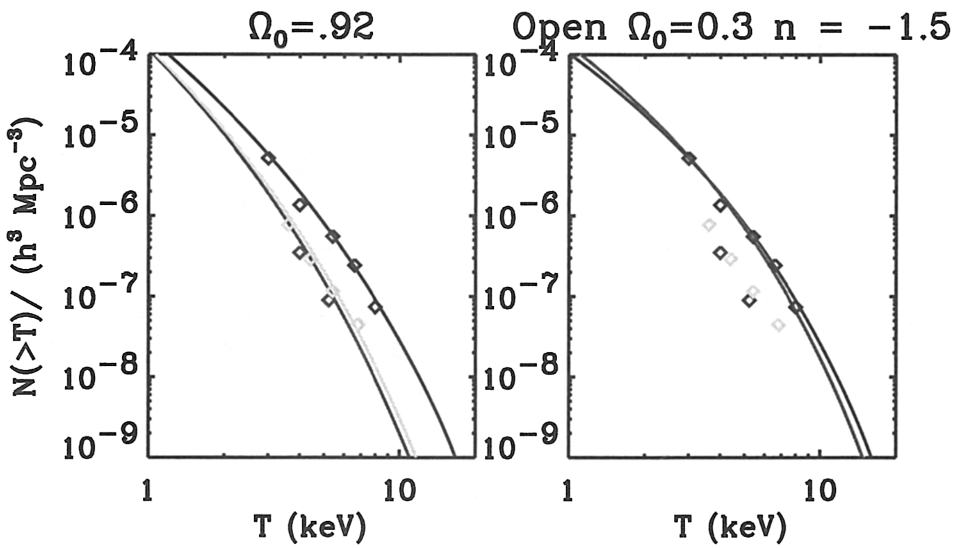

Figure 1. These plots illustrate the power of this cosmological test: the TDF normalized to present day abundances (dark lines) evolve much faster in a high density universe (left panel, $\Omega_0 = 0.92$) than in a low density universe (right panel, $\Omega_0 = 0.3$): $z = 0.33$ (yellow – light grey – lines) the difference is already of the order of 3 or larger. We also give our estimate of the local TDF (blue – black– symbols) as well as our estimate of the TDF at $z = 0.33$ (yellow – light grey – symbols). Also are given for comparison data (Henry 2000) and model 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 Ω_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.

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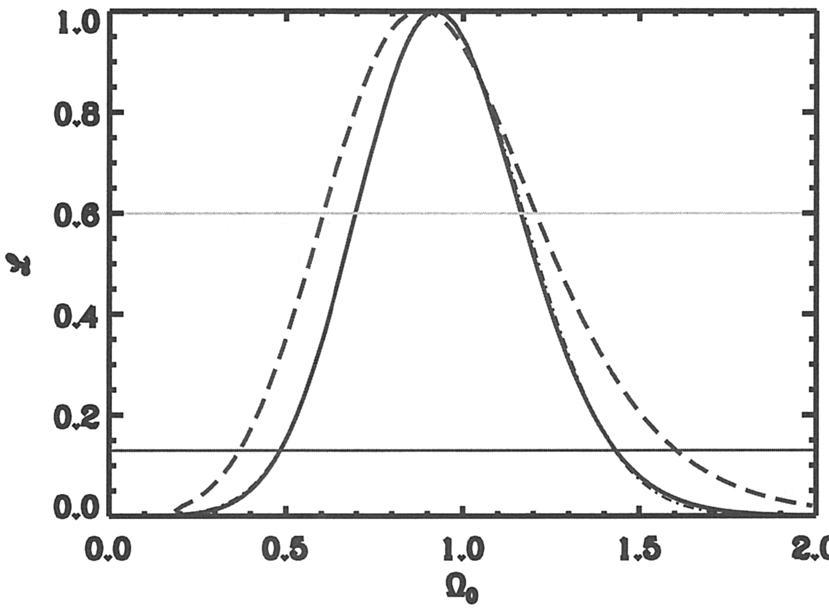

Figure 2. The comparison of the abundance of clusters at $z = 0.05$ with the abundance at $z = 0.33$ allows one to determine the likelihood of the mean density parameter of the universe. The continuous line corresponds to the open case, the dashed line corresponds to the flat case. In both cases a high value is preferred. The two horizontal lines allow to determine the 1 and 2 σ ranges for the parameter if the errors on the measured quantities are gaussian distributed.

(the cluster abundance does not provide an unique normalization for σ_8 in low density models).

3.2. Application to the determination of Ω_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 because of our better quality sample at $z = 0$. 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 terms of the parameters entering in the problem, including the power spectrum index and the amplitude of the fluctuations. The best parameters are estimated as those which maximize the likelihood function. The results show that for the open and flat cases, one obtains a high value for the preferred Ω_0 with a rather low error bars :

$$\Omega_0 = \quad 0.92^{+0.26}_{-0.22} \quad \text{(open case)} \tag{6}$$

$$\Omega_0 = \quad 0.79^{+0.35}_{-0.25} \quad \text{(flat case)} \tag{7}$$

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 $n \sim 1.7$, while high density universe prefers lower value $n \sim 1.9$, but with large uncertainties. The normalization is slightly higher than previously estimated: for $\Omega_0 = 1$, we found $\sigma_8 = 0.6$, consistent with recent estimates based on optical analysis of galaxy clusters (Girardi et al. 1998) and in remarkable agreement with weak lensing measurments (Maoli et al. 2000) .

4. The baryon fraction

This method is based on the measurement of the baryonic fraction in clusters, consisting mainly of the hot gas seen in X-rays. The X-ray image of a cluster allows one to measure the mass of the hot gas. The knowledge of the X-ray temperature allows one to estimate the total mass M_t. It is possible therefore to estimate the baryon fraction in clusters (the contribution of stars, around 1% is often neglected to first order) *assuming that the remaining dark matter is non-baryonic*, which can be related to Ω_0:

$$f_b = \frac{M_b}{M_t} = \Gamma \frac{\Omega_b}{\Omega_0}$$

the numerical factor Γ is introduced in order to correct for possible differences arising during cluster formation. Numerical simulations from various groups have shown that this factor is of the order of 0.90 in the outer part of clusters. Primordial nucleosynthesis allows the estimate of Ω_b, therefore the knowledge of f_b allows to infer Ω_0. This method has been widely used since the pioneering work of White et al. (1993). Typical baryon fraction at the virial radius have been found in the range 15 to 25 % (for a Hubble constant of 50 km/Mpc/s). Detailed studies of the baryon fraction in clusters have been conducted in recent years. There are some controversies about whether the baryon fraction varies with temperature is constant or not. Roussel et al (2000) found that the baryon fraction in clusters follows a scaling law and found that the baryon fraction seems not to vary significantly with temperature in the range 1 to 15 keV (see Fig. 3). The mean baryon fraction (including stars) they obtained is typically 16%, when the EMN mass estimator is used (higher baryons fraction can be found with the hydrostatic equation). An interesting consequence is about the baryon content of the universe which can be inferred from the same argument than for the total density of the universe.

$$\Omega_b = \frac{M_b/L}{M/L|_c} \tag{8}$$

Roussel et al (2000) found $M_b/L \approx 35h^{-1/2}$ leading to $\Omega_b \sim 0.027h^{-3/2}$. There has been some debates about on the primordial abundance of Deuterium and,

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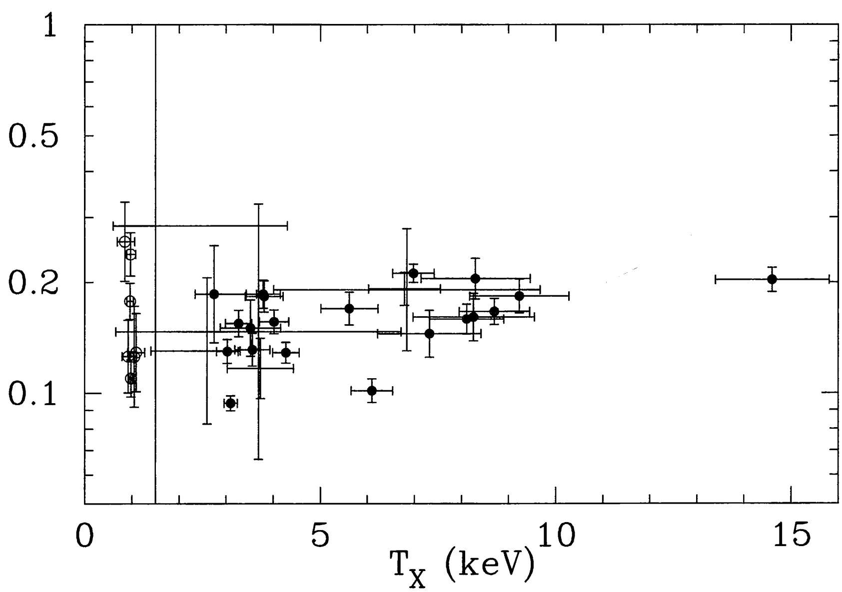

Figure 3. The baryon fraction at the virial radius versus temperature as derived by Roussel et al. (2000). No sign of a dependence with temperature is found.

consequently, on the preferred value for Ω_b, but there is now some convergence towards a high baryon content : $\Omega_b \sim 0.02h^{-2}$ (Tytler et al., 2000), well consistent with the above value. Using the above baryon fraction, one infers a value of Ω_0 in the range $0.3 - 0.5$. It is of course vital to have a reliable estimates of f_b to apply this test. Recently, Sadat & Blanchard (2000, hereafter sb2000) have challenged this question. They first noticed that Γ is a function of radius which behaves with a specific pattern in numerical simulations: in the inner part of clusters first raises up and then tends to flatten in the outer parts. On the contrary, the apparent baryon fraction profile as inferred by observations does not behave like this, it rather raises up continuously from the central part to the outer one. If this trend is real it would mean that our understanding of cluster formation is very poor and probably very dramatic heating processes took place during the cluster formation. However, this is probably not the case because one would expect that the gas distribution in clusters would not exhibit any regularity in their shapes, while such regularity seems to be observed (Neumann & Arnaud, 1999; Ponman, Cannon, & Navarro 1999; Roussel et al., 2000). Different conclusions on the baryon fraction have been reached by sb2000 : a) by using the most recent measurements o ga smass in clusters in the outer part (Vikhlinin et al., 1999) b) by applying a correction factor for the clumping of the gas (accordingly to Mathiesen et al. (1999), the numerical valueof this factor of the order of 1.16, probably an uncertain number), c) by using mass estimator from recent numerical simulations. By taking these effects into account, they showed that the baryon fraction shape in cluster is in reasonable agreement with what is seen in numerical simulations. The value they obtained for the primordial gas fraction is of the order of 10% ($h = 0.5$) and even smaller values were acceptable. In terms of Ω_0 this corresponds to values of the order of 0.8, consistent with what has been derived from clusters abundance evolution.

5. Conclusion

The different observed properties of clusters which can be used to constraint the cosmological density of the Universe do not necessarly favor a low Ω. The local TDF using an updated sample of fifty clusters lead to a slightly higher abundance of local clusters. The comparison between this sample 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 Ω_0 consistent with what Sadat et al. (1998) and Reichart et al. (1999) inferred from modeling the full EMSS sample. Low density universes with $\Omega_0 \leq 0.35$ are excluded at the two-sigma level. 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 30% to 50% or the primordial fluctuations are not gaussian. The baryon fraction in clusters is an other global test of Ω_0, provided that a reliable value of Ω_b is obtained. We have shown that the actual mean baryon fraction could have been overestimated in previous analyses, being closer to 10% rather than to 15%-25% as previously found. Given that the high baryon value seems to be preferred

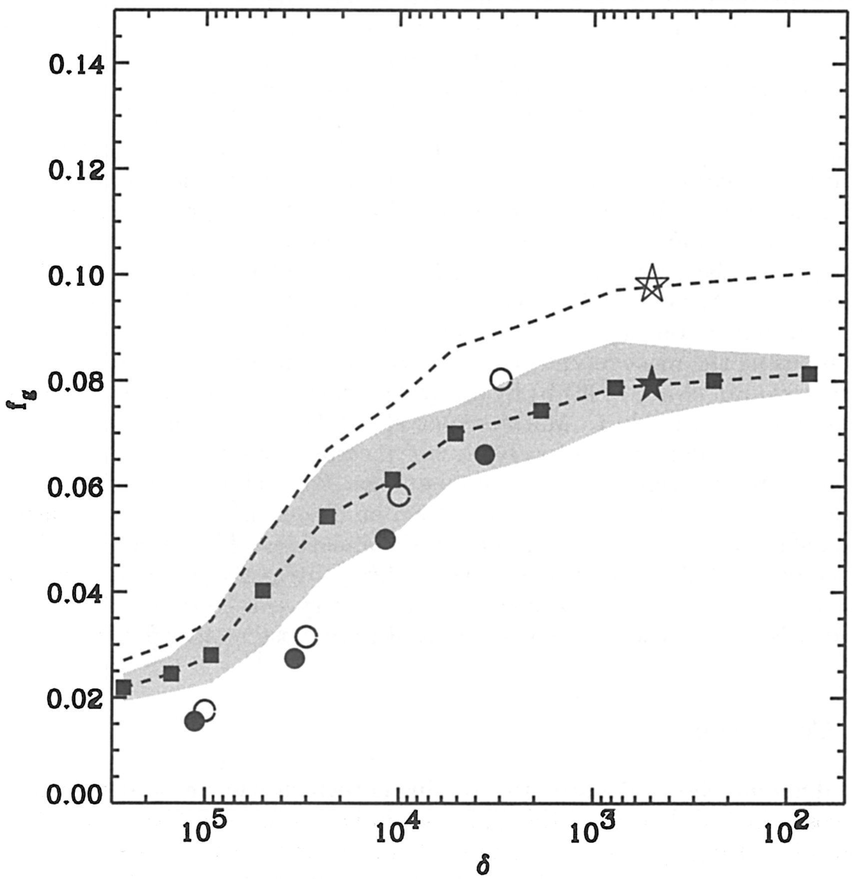

Figure 4. Comparison (Sadat & Blanchard 2000) of the theoretical baryon fraction, as derived from numerical simulations, for two primordial gas fraction, $f_g = 0.11$ and $f_g = 0.09$ (dotted lines), with the gas fraction inferred from observations at different density contrasts with two different mass estimators inferred from numerical simulations: filled symbols are values obtained with Bryan and Norman (1998) mass estimator, open symbols are obtained using Evrard et al (1996). Stars correspond to the gas fraction inferred the data on gas mass by Vikhlinin, Forman, W., & Jones (1999) after correction for the clumping effect (Mathiesen, Evrard, & Mohr 1999).

from primordial nucleosynthesis, this also leads to a high density for the universe as high as 0.8.

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