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DETERMINATION OF Ω_0 FROM X-RAY GALAXY CLUSTERS

 

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Clusters constitute one major source of information for cosmology. In the present paper we discuss their implication for the determination of the density parameter of Universe Ω_0. We concentrate on two global tests, which are expected to provide robust estimates, contrary to the local, possibly biased, classical dynamical argument. The first method uses the evolution of the abundance of clusters with redshift (Oukbir and Blanchard 1992), the second one make use of the baryon fraction in clusters (white et al. 1993). The former method needs reliable estimates of the local temperature distribution function as well as at high redshift ($z \geq 0.3$). The latter can provide a direct estimate of Ω_0 provided that we have a reliable estimate of the baryon content of clusters and a good estimate of Ω_b from primordial nucleosynthesis. Although it has become fashionable to claim that these tests lead to low values for the density parameter of universe, our most recent analyses lead to rather convergent values $\Omega_0 \sim 0.8-0.9$, and are nicely consistent with what can be inferred from CMB data.

1 Introduction

The first evidence for the existence of dark matter has been provided by dynamical measures performed on the Coma cluster, in ~ 1930 by F.Zwicky. Since that time, our understanding of clusters has greatly increased. There is 100 times more mass in clusters than in the stars that can be seen within them. However, there is much more baryons seen in X-ray clusters in form of hot gas. The discovery of this hot gas has revolutionized the study of clusters. Indeed X-ray temperatures can be measured with a high accuracy and they are likely to provide accurate mass measurements. Velocity dispersions can be determined quite accurately, but this is possible only with hundred redshifts in each clusters, and the interpretation is delicate because the dynamical state of the galaxy population may not be well understood. Lensing mass estimates are the most promising alternative, although present day measurements which are claimed to be consistent with other mass estimates, provide masses which are generally rather high, but with large error bars. The standard way 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 :

$$M/L \sim 300h$$

Mass estimates of X-ray clusters can be obtained from numerical simulations. There is a rather good convergence between different numerical simulations. They shows 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:

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

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

$$M/L \sim 640 - 800h$$

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 tranformed in term of Ω by assuming that the ratio of matter to light is universal:

$$\rho_m = M/L \times \rho_l$$

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:

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

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 $\Omega \sim 0.5 - 0.65$, 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 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 only cases of such global methods for which small errors bars have been obtained. These two methods are discussed in the two following sections.

2 Clusters abundance evolution.

The evolution of the abundance of clusters relative to the present day value is a direct test of Ω which can be demonstrated like a mathematical theorem – see Blanchard and Bartlett (1998). As X-ray clusters can be detected at high redshifts, they provide us with a global test of Ω (Oukbir and 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

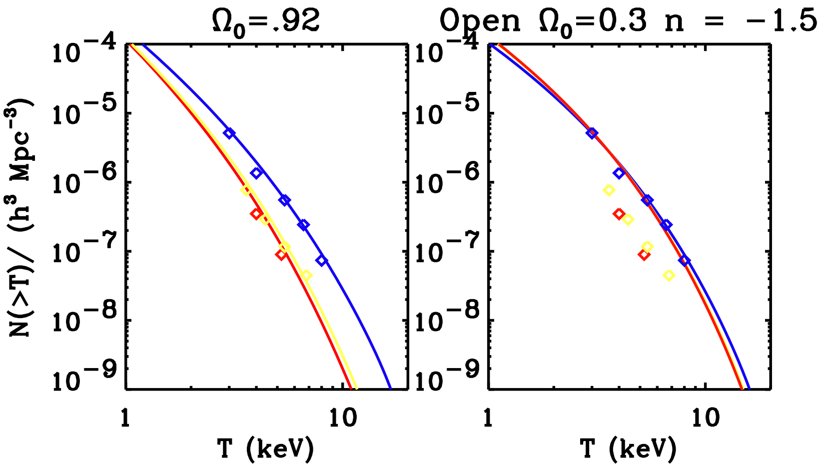

Figure 1: On these plots, we illustrate the power of this cosmological test : the TDF normalized to present day abundances (dark lines) evolve much faster in a high density universe (left panel, $\Omega_0 = 0.92$) than in a low density universe (right panel, $\Omega_0 = 0.3$): $z = 0.33$ (yellow – light 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.

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.

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 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 $2.2 10^{-11}$ 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

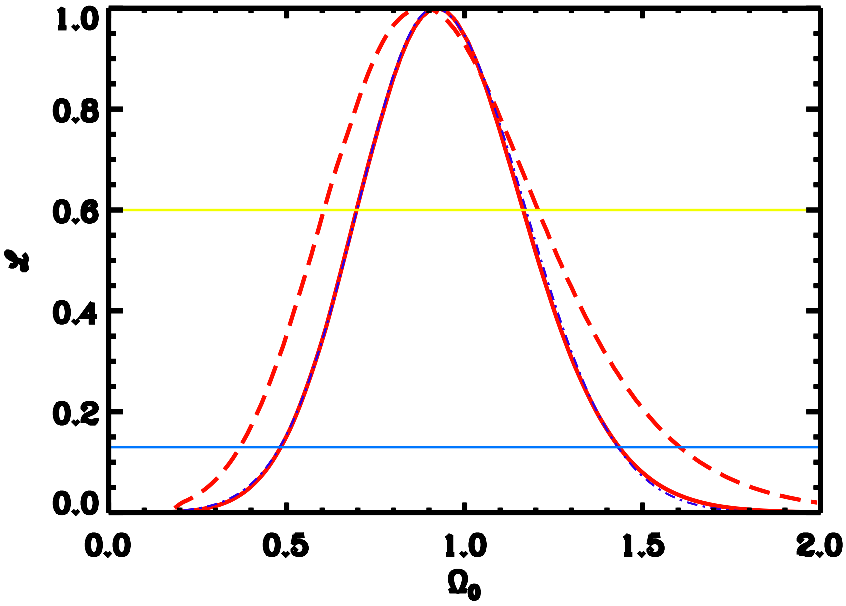

Figure 2: The comparison of the abundance of clusters at $z = 0.05$ with the abundance at $z = 0.33$ allows one to determine the likelihood of the mean density parameter of the universe. The continuous line corresponds to the open case, the dashed line corresponds to the flat case. In both cases a high 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.

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 σ_8 in low density models).

2.2 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 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 Ω_0 with a rather low error bars :

$$\Omega_0 = 0.92^{+0.26}_{-0.22} \quad \text{(open case)} \tag{1}$$
$$\Omega_0 = 0.79^{+0.35}_{-0.25} \quad \text{(flat case)} \tag{2}$$

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

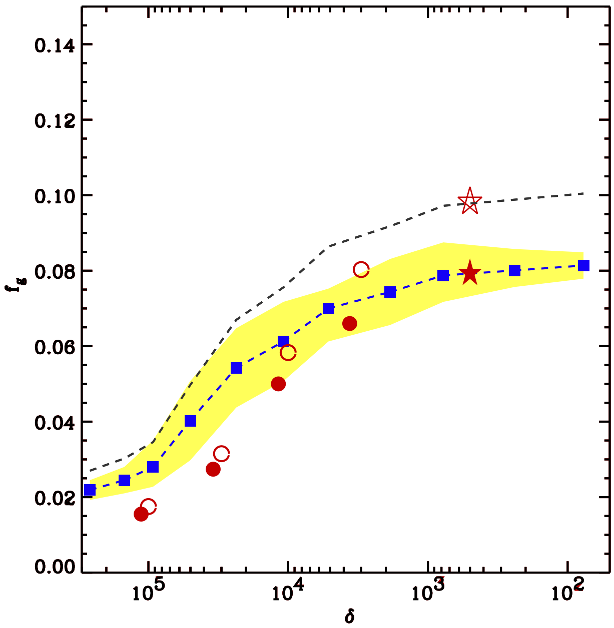

Figure 3: The comparison of the theoretical baryon fraction, as derived from numerical simulations, for two primordial gas fraction, $f_b = 0.11$ and $f_b = 0.09$ (dotted lines) with the observed gas fraction at different density contrast and using two different mass estimators inferred from numerical simulations: filled symbols are obtained with Bryan and Norman (1998) mass estimator, open symbols are from Evrard et al (1996). Stars are derived from the data of Viklinin et al. (1999), corrected for the clumping factor ().

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 $\Omega = 1$, we found $\sigma_8 = 0.6$, consistent with recent estimates based on optical analysis of galaxy clusters (Girardi et al., 1998).

3 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 this X-ray gas. The knowledge of the X-ray temperature allows one to estimate the total mass M_t. It 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:

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

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). There has been some debate about the preferred value for nucleosynthesis, but there is now some convergence towards a high baryon content : $\Omega \sim 0.02h^{-2}$ (Tytler et al., 2000), significantly different from the standard value in 1993. With the above baryon fraction, this leads to $\Omega_0 \sim 0.3 - 0.5$. It is of course vital to have a reliable estimates of f_b to apply this test. Recently, Sadat and Blanchard (2000, sb2000) have challenged this question. They first noticed that Γ is a function of radius which behaves in numerical simulations with a specific pattern: from the very central part of clusters to the outer the baryon fraction first raises up and then tends to flatten in the outer part. However 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 distributions in cluster would not exhibit any regularity in their shapes, while such regularity seems to be observed (Neumann & Arnaud, 1999; Ponman, 1999; Roussel et al., 2000). Different conclusions on the baryon fraction have been reached by sb2000 : a) by using the most recent measurements of clusters properties in the outer part (Vikhlinin et al., 1999) b) by applying a correction for the clumping of the gas (accordingly to Mathiesen et al. (1999) the correction factor of the order of 1.16, probably an uncertain number), c) by using mass estimator from recent numerical simulations. They showed that the baryon fraction shape in cluster is in reasonable agreement with what is seen in numerical simulations and that the numerical value could be of the order of 10% ($h = 0.5$) or even smaller. In terms of Ω this corresponds to values of the order of 0.8, consistent with what has been derived from clusters abundance evolution.

4 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 Ω_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 Ω, provided that a reliable value for Ω_b is obtained. However, the mean baryon fraction could have been overestimated in previous analysis, being closer to 10% rather than to 15%-25%.

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 method based in CMB anisotropies. As we have seen, the cluster number evolution and the baryon fraction may indicate a rather high value, of the order of 0.8. which contradicts the result from high redshift Supernovae. Better understanding of systematic uncertainties in these methods will be critical.

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