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Scaling relations in LCDM from X-ray and Planck cluster data

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The abundance of clusters of galaxies is known to be a potential source of cosmological constraints through their mass function. In the present work, we examine the information that can be obtained from the temperature distribution function of clusters. For this purpose, the mass/temperature (M/T) relation and its statistical properties are critical ingredients. Using a combination of Cosmic Microwave Background (CMB) data from Planck and our estimations of X-ray cluster abundances, we use MCMC techniques to estimate simultaneously the ΛCDM cosmological parameters and the mass/X-ray temperature scaling relation. We determine the integrated X-ray temperature function of local clusters using flux-limited surveys. A local comprehensive sample was build from BAX – the X-ray cluster database – allowing us to estimate the local temperature distribution function above ∼1 keV. We model the expected temperature function from the mass function and the M/T scaling relation. We then estimate simultaneously the cosmological parameters and the calibration of the M/T relation. The measured temperature function of local clusters in the range ∼1-10 keV is well reproduced once the calibration of the M/T relation is treated as a free parameter, and is therefore self-consistent with respect to the ΛCDM cosmology. The best-fit values of the standard cosmological parameters as well as their uncertainties are unchanged by the addition of clusters data. The calibration of the mass temperature relation is determined with less than 10% statistical uncertainties. This calibration leads to masses that are ∼67% larger than X-ray masses used in Planck.

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1. Introduction

The quest for cosmological parameters has made dramatic progresses in recent years. The most spectacular progress has come from the evidence for accelerated expansion from the Hubble diagram of distant supernovae, while measurements of the angular power spectrum of the CMB fluctuations and of the power spectrum of galaxy distribution on large scale have allowed to confirm several predictions of the dark energy dominated, Cold Dark Matter picture. The parameters of this model have now been estimated with impressive precision [1], making alternative explanations rather contrived. The actual origin of the acceleration now appears as one of the most intriguing and challenging problem of modern cosmology and of fundamental physics. While the simplest explanation is an Einstein cosmological constant presently dominating the energy density of the Universe, various options have been investigated. The so-called “quintessence" models, the dark energy is due to the presence of a scalar field, the evolution of the potential of which determines its equation of state. Modifying the Lagrangian of the field opens an almost unlimited range of possibilities for the properties of the dark energy fluid. An other explanation for the origin of the cosmic acceleration comes from the modification of the law of gravitation at large scales, i.e. a deviation from general relativity at cosmological scales. In such a case the dynamics of the expansion could be identical to that of a concordant model and all geometrical tests will provide cosmological parameters identical to those inferred in a Friedman-Lemaître model, but the gravitational dynamics of matter fluctuations may differ, offering a possible signature of the modified gravity.

There is therefore a specific interest in measuring the gravitational growing rate of fluctuations. The evolution of the abundance of clusters with redshift is exponentially sensitive to the growing rate of linear fluctuations. This has motivated the use of cluster abundance evolution as a cosmological test. While the cluster observables are the X-ray temperature/luminosity, SZ, and lensing signal, the abundance of galaxy clusters however is conventionally predicted as a function of mass. Hence, the intrinsic scatter and the uncertainties in the scaling relations between mass and any observable lower the reliability of galaxy clusters to constrain cosmological parameters

We address here the problem of the calibration of the mass/temperature relation of X-ray clusters, using their distribution function at low redshift. We perform a Monte-Carlo Markov Chain (MCMC) analysis to constrain simultaneously the X-ray cluster scaling law and the standard cosmological parameters, with the help of the Planck CMB data. This allows us to derive the mass/temperature relation of clusters in the ΛCDM model, consistently with the Planck CMB data. We compare our result with the calibration derived from pure X-ray analysis, which was used as a prior in the Planck analysis of Sunyaev-Zel’dovich counts with Planck.

2. Mass function and abundances

The halo mass function, i.e. the distribution function of objects relative to their mass, is widely used for cosmological constraints. A theoretical formalism has been proposed by [2] which allows us to relate the non-linear mass function of cosmic structures to the linear amplitude of the fluctuations, usually specified by the power spectrum $P(k)$.

Using a limited set of generic assumptions, we obtain a universal self-similar form of the mass function which can be then computed for arbitrary models without requiring the systematic use of numerical simulations. The mass function can then be derived as :

$$\frac{dn}{dM} = -\frac{\rho_0}{M}\frac{1}{\sigma}f(\sigma)\frac{d\sigma}{dM} \tag{2.1}$$

where $f(\sigma)$ is a function that is usually fitted on numerical simulations, and ρ_0 is the mean matter density of the Universe.

Although the Press and Schechter approach was established in 1974, it is only after large N-body simulations were available that the validity of an universal self-similar mass function gained in strength. New versions of the mass function based on extensive numerical simulations have since been developed, improving greatly the accuracy of the description of the halo mass function. In the present work, we used two such descriptions of the mass function, and in particular of the fitting function f from Eq. (2.1). The first variant of the function f considered is the one obtained by [3] (SMT hereafter) while the second is from [4] (Tinker hereafter). The difference between these mass functions is appreciable but not critical given the statistical uncertainties in current samples of X-ray clusters; nevertheless, the difference could be as large as the (1 σ) errors on measured abundances.

The mass function is sensitive to the cosmological parameters, especially the matter density parameter Ω_m and the present-day amplitude of the fluctuations σ_8. In scenarios such as the Λ dominated cold dark matter (ΛCDM) paradigm, the power spectrum is well defined, and depends on a few parameters that can be constrained from the three standard cosmological data sets: the cosmic microwave background (CMB), the type Ia Supernovae and the galaxy power spectrum. In the following, the determination of the cosmological parameters as well as the parameters describing cluster physics is performed by combining the latest CMB data from Planck and cluster abundance data. The estimations of the parameters is done through a Monte-Carlo Markov chain (MCMC hereafter) using the COSMOMC package. Although we could in principle combine CMB data with other sets of data such as the SnIa Hubble diagram or the BAO signal, this leads to essentially identical cosmological parameters; we therefore choose to keep only Planck CMB data to allow a more direct comparison with Planck clusters results. We then estimate the range of predicted abundances for models which parameters fall within the 68% range. The results and the 68% errorbars on cosmological parameters are given in the first column of Table 1.

3. Determination of the temperature distribution function

Existing surveys of X-ray clusters provide comprehensive sets of clusters for which the selection function is reasonably well understood. When the temperature is known for every cluster of such a survey, we can estimate the temperature distribution function at the typical redshift of the survey. The matching between the mass function and these temperature distribution functions will provide self-consistent information on clusters for ΛCDM models. In this paper, we have built a new sample of X-ray selected clusters, complete and robust, extracted from the BAX database with a minimal flux threshold of $f_{min} = 1.810^{-11}$erg.s^{-1}.cm^{-2}. We get a sample of 73 clusters covering a temperature range of $[1.2-9]$ keV with a mean redshift of $z \sim 0.05$, making this sample the largest ever used for the determination of the local temperature distribution function (with actual temperature measurements).

Then, an ideal situation would be to have a direct estimation of the mass function to compare with theoretical expectations. However, a direct detection of DM halos based on their mass is not an easy task. We are therefore required to apply a relation between the observable and the mass of each cluster present in the survey. It is therefore necessary to have a good understanding of this mass/observable relation, in addition to a selection function that is well under control. In this work, we focus on X-ray clusters and start with the assumption that clusters are self-similar at some level, i.e. that their observable quantities (e.g. luminosity or temperature) can be related to their mass through a simple expression, generally a power law. Hereafter, such relation will be called a "scaling relation". Such relation on mass and redshift can be inferred from a simple collapse model; we will refer to these as "standard" scaling relations. Beyond these, it is important to take into account the effect of dispersion. In the following, we will work at the virial mass (unless specified otherwise), i.e. the mass inside the radius that corresponds to a contrast density equal to Δ_v in the standard spherical model. In order to derive the gas temperature, provided the gravitational collapse is the unique source of gas heating, we can assume that the average thermal energy of a particle is related to its average kinetic energy in the gravitational potential of the cluster (incomplete virialization is accommodated by such assumption). This allows us to derive the (theoretical) scaling law between temperature and mass:

$$T = A_{TM}(hM_v)^{2/3}\left(\frac{\Omega_{m0}\Delta(\Omega_m, z)}{178}\right)^{1/3}(1+z) \tag{3.1}$$

with A_{TM} the normalization constant, M_v the virial mass of the cluster expressed in unit of 10^{15} solar mass and $\Delta(\Omega_{m0}, z)$ the density contrast with respect to the total matter density of the Universe. For a given $T-M$ scaling relation assumed with no dispersion, the number of objects hotter than a temperature threshold is equivalent to the number of objects heavier than a corresponding mass threshold. The theoretical temperature function can be written:

$$n(>T) = \int_T^{+\infty}\frac{dn}{dt}(t)dt = \int_{M(T)}^{+\infty}\frac{dn}{dm}(m)dm \tag{3.2}$$

where $M(T)$ is given by the scaling relation (3.1). The last equation allows to compute the integrated temperature function from the mass function, i.e. the numerical density of clusters hotter than a given temperature.

All that remains now is to estimate this temperature distribution function from existing samples of X-ray clusters as well as the uncertainty on these estimations. Similarly to luminosity measurements of clusters, we can define a volume search $V(T)$ for an object with temperature T which will depend on the selection function. The temperature function will then be given by the following unbiased estimator:

$$n(>T) = \sum_{T_i>T}\frac{1}{V(T_i)} \tag{3.3}$$

4. Parameters determination

The use of the cluster population properties to constrain cosmological parameters has been widely used in the past. One fundamental limitation of this approach is that it usually relies on the knowledge of the scaling relations, including their calibration. For instance, the local abundance of clusters is a sensitive probe of the amplitude of matter fluctuations σ_8. However, it is well known that the amplitude of σ_8 is degenerated with the the normalization constant A_{TM}. In the present work we are following a different strategy: we perform a self-consistent analysis to constrain simultaneously both the cosmological parameters of the ΛCDM model and the parameters of the mass/temperature scaling law of X-ray clusters. In this analysis, we adopted the standard ΛCDM cosmology as our reference and performed a MCMC analysis using the COSMOMC package. We combined the constraining power of the CMB data from Planck, as well as our measured temperature function through the use of a separate COSMOMC module of our design. In practice, we do not use the measured temperature function as it is, i.e. as defined in Eqs. (3.2) ; instead, we binned the temperature range covered by our sample of clusters. In the present study, we used 10 distinct temperature bins for the likelihood analysis. We then need to estimate the likelihood of any given set of cosmological parameters given the measured temperature function. The details of this likelihood is hard to determine analytically. We circumvent this problem by performing a bootstrap analysis on our sample of clusters, in order to derive an approximation to the shape of the likelihood function corresponding to the real, underlying temperature function.

Parameter	Planck CMB T data			
	only	+X-ray (SMT)	+X-ray (Tinker vir.)	+X-ray (Tinker 500c)
Ω_Λ	$0.680^{+0.021}_{-0.013}$	$0.688^{+0.013}_{-0.020}$	$0.675^{+0.028}_{-0.0048}$	$0.681^{+0.022}_{-0.011}$
Ω_m	$0.320^{+0.013}_{-0.021}$	$0.312^{+0.020}_{-0.013}$	$0.325^{+0.0048}_{-0.028}$	$0.319^{+0.011}_{-0.022}$
n_s	$0.9595^{+0.0069}_{-0.0074}$	$0.9603^{+0.0065}_{-0.0081}$	$0.9608^{+0.0063}_{-0.0080}$	$0.9586^{+0.0087}_{-0.0058}$
σ_8	$0.826^{+0.015}_{-0.0096}$	$0.827^{+0.013}_{-0.012}$	$0.833^{+0.0062}_{-0.018}$	$0.831^{+0.0091}_{-0.016}$
h	$0.670^{+0.014}_{-0.0094}$	$0.674^{+0.011}_{-0.013}$	$0.666^{+0.019}_{-0.0049}$	$0.669^{+0.016}_{-0.0075}$
A_{TM}	-	$7.15^{+0.46}_{-0.54}$	$7.24^{+0.86}_{-0.23}$	$6.23^{+0.68}_{-0.26}$

Table 1: Column 1 gives results for the Planck temperature power spectrum data alone. Columns 2, 3 and 4 and 5 combine the Planck temperature data with X-ray cluster data. We give best fit parameters (i.e. the parameters that maximise the overall likelihood for each data combination) as well as 68% confidence limits for constrained parameters.

We performed our MCMC analysis in four different cases : the best-fit values and 68% confidence intervals of these parameters are summarized in Table 1 for all four scenarios. We chose to use both the SMT and Tinker mass function in order to quantify the difference in the resulting estimated parameters. As we can see, for all cases cosmological parameters are nearly identical since their strongest constraints come from the standard CMB data (and not from the cluster abundance). The limits on the values of A_{TM} reflect the uncertainty on the mass function. Its derived value when using either the SMT or the Tinker mass function lies within the 1σ interval of the other one, with the SMT function producing a lower value of A_{TM}. This was expected from the differences in the behaviour of the two mass functions. The comparison of the best-fit theoretical temperature function with the data shows a good agreement at all temperatures above 3 keV. At

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lower temperature there seems to be some deficit in the observed abundance of clusters (around 2 keV). The two mass functions produce nearly indistinguishable temperature distribution functions, reproducing equally well the local cluster data down to temperatures of the order of $T = 10$ keV. At high temperatures the difference between temperature distribution functions produced by the two mass function become more appreciable although still quite small.

4.1 Implication for the Planck SZ clusters results

We now check for consistency between our local sample of clusters selected in X-ray Flux and Temperature with the SZ cluster cosmological sample used by [5], selected in signal-to-noise ratio in the redshift range [0-1]. The Planck SZ cluster derived cosmology was shown to be in tension with the best CMB cosmology and depends highly on the assumption on the scaling relation between the SZ flux Y and the mass M [5]. In the latter, the scaling relation Y-M is derived from a sub-sample of 71 clusters for which the hydrostatic mass has been estimated from XMM observations and its normalization was calibrated on simulations [5]. The lack of knowledge of such normalization led to parametrize the scaling with a mass bias factor (1-b) such that: $Y \propto A[(1-b)M]^{\beta}$.

For each Planck cluster with redshift, the Planck catalogue of SZ sources provides an SZ mass estimate (calibrated on the Y-M scaling relation) assuming no bias (i.e. b=0). Knowing the T-M scaling relation for a Planck CMB cosmology allows us to compute a T_X based mass for each cluster with measured X-ray temperature. By comparing the two mass estimates we are thus able to compare the two samples based on different observables (X-ray and SZ). We thus proceed by computing the likelihood of the mass bias (1-b) given the likelihood of A_{TM}. For each value of A_{TM}, we derive T_X mass proxies for our entire X-ray sample, then fit for the best relation between these masses and the corresponding SZ masses provided by Planck. The best relation gives an estimate of the mass bias between the two samples. For the fitting procedure we use the BCES regression technique. For the best fit likelihood including Planck CMB and our X-ray cluster sample, we find (assuming Tinker mass function) $A_{TM} = 6.23 \pm 0.68$ leading to $(1-b) = 0.58 \pm 0.1$. This value is in perfect concordance with the value derived by PXX when fitting Planck CMB and the SZ cosmological sample (1-b=0.6), showing thus good, indirect agreement between our sample the Planck one. These results indicate that both SZ and X-ray clusters counts are completely consistent and lead to similar estimates of the standard cosmological parameters, once the issue of the mass/observable calibration is taken care of. This shows once again a lack of understanding of the intrinsic properties of clusters, more particularly in the context of estimating their masses with standard observables (temperature & luminosity), methods, and assumptions (hydrostatic equilibrium).

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