Cluster abundance normalization from observed mass-temperature relation

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ABSTRACT

Abundance of rich clusters in local universe is currently believed to provide the most robust normalization of power spectrum at a scale of 10 Mpc. This normalization depends very sensitively on the calibration between virial mass $M$ and temperature $T$, which is usually taken from simulations. Uncertainties in the modelling, such as gas cooling and heating, can lead to a factor of two variations in the normalization and are thus not very reliable. Here we use instead an empirical $M_{500} - T$ relation derived from X-ray mass determinations to calibrate the method. We use results from dark matter simulations to relate the virial mass function to the mass function at observed $M_{500}$. We find that the best fitted value in flat models is $\sigma_8 = (0.7 \pm 0.06)(\Omega_m/0.35)^{-0.44}(\Gamma/0.2)^{0.08}$, where only the statistical error is quoted. This is significantly lower than previously obtained values from the local cluster abundance. This lower value for $\sigma_8$ is in a better agreement with cosmic microwave background and large scale structure constraints and helps alleviate small scale problems of CDM models. Presently the systematic uncertainties in the mass determination are still large, but ultimately this method should provide a more reliable way to normalize the $M - T$ relation. This can be achieved by obtaining a larger sample of well measured cluster masses out to a significant fraction of virial radius with BeppoSAX, Chandra and XMM-Newton.

Key words: cosmology: theory – dark matter – galaxies: haloes – galaxies: clusters: general – X-rays: galaxies.

1 INTRODUCTION

Abundance of clusters in the local universe provides one of the strongest constraints on the matter power spectrum amplitude on scales of order 10Mpc. The main power of this method is that the abundance depends very sensitively on the amplitude of linear power spectrum on this scale. Numerous studies over the past decade have investigated this constraint, obtaining more or less consistent results (White, Efstathiou & Frenk 1993; Bond & Myers 1995; Viana & Liddle 1998; Kitayama & Suto 1998; Eke et al. 1998; Pen 1998; Wang & Steinhardt 1998, Blanchard et al. 2000; Henry 2000). Two most recent studies are those by Pierpaoli, Scott & White (2001) using a local sample of clusters and Borgani et al. (2001) using a higher redshift sample, both of which find a relative error of 5 – 10% on the density dependent normalization (but which are inconsistent with each other at a more than 3-σ level, see discussion below).

While cluster abundance normalization is usually assumed to be the most reliable on a scale of 10Mpc, other data sets also provide some more model dependent constraints on the same scale. Recent determinations of the best fitted model from CMB combined with large scale structure (Wang, Tegmark, & Zaldarriaga 2001; Efstathiou et al. 2001) and from Ly-α forest (Croft et al. 1999; McDonald et al. 2000) both give $\sigma_8$ values more than 30% lower than those from the latest local cluster abundance determinations for the favored $\Omega_m = 0.3 - 0.4$ case. A lower normalization also helps significantly with the problems that CDM has on small scales (Alam, Bullock, & Weinberg 2001). This tension between the cluster abundance normalization and other data sets, which is formally at more than 3-σ level, could indicate there are still some unrecognized systematic uncertainties present in the cluster abundance normalization.

An implicit assumption in all of the studies above is to assume a relation between halo mass $M$ and observed gas temperature $T$, $M/(10^{15} h^{-1} M_{\odot}) = (T/\beta)^{3/2} \Delta_c^{-1/2} E^{-1}$, where $\Delta_c$ is the mean overdensity inside the virial radius defined using spherical collapse model, $T$ is gas temperature in keV, $E^2 = \Omega_m (1+z)^3 + \Omega_{\Lambda}$ for the zero-curvature case and the constant $\beta$ is determined from the hydrodynamical simulations. The problem with this approach is that the simulations may not capture all of the physics occurring in the real
world. For example, most simulations only include adiabatic hydrodynamics, while it was recently shown that including gas cooling (which must be present at some level) can lead to a factor of two change in the normalization constant of the mass temperature relation (Muanwong et al. 2001). Other potentially important effects, such as heating of the gas with stars, supernovae or AGN, could further change the relation. Resolution issues could also be affecting the results: there is quite a lot of scatter in the relation between different groups even when all the physical ingredients are identical (see Komatsu, Seljak 2001 and Pierpaoli et al. 2001 for a recent comparison between different groups). Yet another possible complication is the observer’s definition of temperature, which depends on the spectral bandpass and other instrumental details. Mathiesen & Evard (2001) explore several different possibilities and find up to a 20% variation between them. Since all these effects are systematic it is difficult to place a reliable error estimate on them, except to argue that a factor of two changes are not excluded at this point. To put this into a context, such a change leads to a 30–40% change in the overall power spectrum normalization, much larger than the quoted error-bars. It seems therefore worthwhile to explore alternative methods to normalize the $M-T$ relation which do not rely exclusively on the simulations.

Over the past several years there has been a lot of progress in the direct determination of cluster masses using spatially resolved temperature and X-ray intensity information. Under the assumption of spherical symmetry and hydrostatic equilibrium with no non-thermal pressure support one can solve for the radial mass profile of the matter in the cluster. This approach consistently yields $M-T$ relation up to a factor of two lower than the average over simulations (Horner, Mushotzky, & Scharf 1999, Nevalainen, Markovich, Forman 2000, Finoguenov, Reiprich, & Böhringer 2001). Such a discrepancy could be explained if there was an additional non-thermal pressure support, which should be added to the equation of hydrostatic equilibrium (such as from turbulent motions or magnetic fields). However, recent comparison between X-ray mass measurements and weak lensing mass measurements for several clusters shows very good agreement between the two, excluding the possibility of a large non-thermal support, at least for relaxed clusters (Allen, Schmidt, & Fabian 2001). An alternative possibility is to assume that X-ray mass determinations are reliable and there is some systematic problem with the simulations.

The purpose of this paper is to use the empirical $M-T$ relation to derive the power spectrum normalization. An earlier attempt to do this based on one measured cluster mass has been made by Markovich (1998) and a lower value of $\sigma_{8}$ has been found than calibrating from simulations. Since then the observed $M-T$ relation and scatter around it has been established much more accurately. Since the measured masses are limited to the inner part of the cluster they cannot be extended to the virial mass, defined here as the mass that gives rise to the universal mass function, without additional modelling. Here we use CDM type mass profiles to make this connection. We find that the offset relative to the simulations persists and leads to a significantly lower power spectrum normalization than was found before. The implications of this result and future prospects for this approach are discussed in the conclusions.

2 THEORY

The halo mass function describes the number density of halos as a function of mass. It can be written as

$$\frac{dn}{d\ln M} = \frac{\bar{\rho}}{M} f(\sigma) \frac{d\ln \sigma^{-1}}{d\ln M},$$

(1)

where $\bar{\rho}$ is the mean matter density of the universe, $M$ is the virial mass of the halo and $n(M)$ is the spatial number density of halos of a given mass $M$. We introduced function $f(\sigma)$, which has a universal form independent of the power spectrum, matter density, normalization or redshift if written as a function of rms variance of linear density field $\sigma$,

$$\sigma^2(M) = 4\pi \int P(k)W_R(k)k^2 dk.$$

(2)

Here $W_R(k)$ is the Fourier transform of the spherical top hat window with radius $R$, chosen such that it encloses the mass $M = 4\pi R^3\bar{\rho}/3$ and $P(k)$ is the linear power spectrum.

The universality of the mass function has been recently investigated by a number of authors (Sheth & Tormen 1999, Jenkins et al. 2001, White 2001), where it has been shown that the mass function is indeed universal for a broad range of cosmological models. Jenkins et al. (2001) propose the form

$$f(\sigma) = 0.315 \exp[-|\ln \sigma^{-1} + 0.61|^{|3.8|}].$$

(3)

They find this equation works best if the cluster mass $M$ is defined as the mass within the radius where mean density in units of critical is 200$\rho_0$. Other authors (Sheth & Tormen 1999, White 2001) find that a similar mass function works if the mass is defined within the spherical overdensity defined by the spherical collapse model, which is 108 for $\Lambda$CDM model with $\Omega_m = 0.35$ that we adopt here as the reference model. We will adopt the Jenkins et al. (2001) value here and comment on the implications of other choices in the discussion section.

Given that the mass profiles at large radii are difficult to measure observers prefer to quote the masses $M_\Delta$ at smaller radii or higher $\Delta$ than virial values. Two often used values in the literature are $M_{2500}$ (Allen et al. 2001) and $M_{500}$ (e.g. Finoguenov et al. 2001). Since at the moment we do not have mass functions at $M_{500}$ or $M_{2500}$ directly from simulations we will construct them by relating $M_\Delta$ to $M_{500}$ adopting an average mass profile for the clusters. This is typically parametrized as

$$\rho(r) = \frac{\rho_\Delta}{(r/r_s)^{-\alpha}(1+r/r_s)^{3+\alpha}}.$$

(4)

This model assumes that the profile shape is universal in units of scale radius $r_s$, while its characteristic density $\rho_\Delta$ at $r_s$ or concentration $c_\Delta = r_{\Delta}/r_s$ may depend on the halo mass. The halo profile is assumed to scale as $r^{-3}$ in the outer parts and as $r^\alpha$ in the inner parts, with the transition between the two at $r_s$. We fix the inner slope to $\alpha = -1$ (Navarro et al. 1997), since we are not concerned about the shape of the halo profile in the center. The outer slope $r^{-3}$ is the most common value found in the $N$-body simulations, although scatter around this value can be quite significant (Thomas et al. 2001). Even if we adopt this value the profile is still not fixed and the remaining freedom can be parametrized with the concentration parameter $c_\Delta$. In
**3 RESULTS**

The observed $M - T$ relation for $T > 3$ keV clusters relevant for abundance studies as given by Finoguenov et al. (2001) is

$$M_{200\Omega_m} = 10^{15} h^{-1} (1 \pm 0.2) M_\odot \left( \frac{T}{\beta \Delta c^{3/2} \text{keV}} \right)^{1.5},$$

(5)

where $\beta = 1.75 \pm 0.25$ and we used the relation between $M_{200}$ and $M_{200\Omega_m}$ based on the adopted cluster profile (figure 1). The value of $\beta$ quoted above is for the fiducial model with $\Omega_m = 0.35$, but in fact it varies little with $\Omega_m$, increasing only by 5% for $\Omega_m = 1$. This is because while $\Delta c$ in equation 5 increases with $\Omega_m$, the mass $M_{200\Omega_m}$ extrapolated from $M_{200}$ decreases, compensating each other for a profile that is close to isothermal.

While the scaling in equation 5 is in agreement with the theoretical predictions the normalization of the $M - T$ relation is not. If we used $M_{2\Delta}$ as done in previous work we would find $\beta = 1.95 \pm 0.25$. This value should be compared to $\beta = 1.3 \pm 0.2$ as the average over the simulations (Pierpaoli et al. 2001). The two values are inconsistent with each other at a 3-$\sigma$ level, suggesting that there is a significant systematic error either in the observed mass estimates or in the simulations. Other data samples find similar discrepancies between simulated and observed relation. For example, Allen et al. (2001) find a 40% offset in $M_{200} - T_{200}$ relation relative to the simulations. It is unclear how $T_{200}$ obtained from Chandra relates to temperatures in cluster samples used to derive the power spectrum normalization, which are mostly obtained from ASCA. Moreover, $M_{200}$ to $M_{\Delta}$ conversion carries considerable uncertainty (figure 1). For these reasons we will not use this data set here.

For the cluster sample we use a recent compilation by Pierpaoli et al. (2001) based on the data from nearby clusters. Their adopted temperature measurements are taken mostly from White (2000), which are on average 15% higher than those derived by Markevitch (1998). This by itself can be a significant systematic effect. Since we wish to compare this data sample to the $M - T$ relation by Finoguenov et al. (2001) we must compare the temperatures of the two samples. We do this in two different ways. First, we compare the derived luminosity-temperature ($L - T$) relation for the two samples, which gives us the relative normalization between the adopted temperature values, since in both samples luminosities are obtained from ROSAT. Finoguenov et al. (2001) data combined with $L - M$ relation (Vikhlinin et al. 1999) gives $L = 1.15 \times 10^{43} M_\odot h^{-1} \text{ergs/s}$, which implies that temperature values used by Pierpaoli et al. (2001) are on average 5% higher than those used by Finoguenov et al. (2001). Second, 13 clusters are contained in both samples. Linear regression with zero offset gives again the same 5% deviation. The two methods give consistent results and we apply this small correction in the analysis below. Another small effect which goes in the same direction is to correct back the redshift dependence of $T$ which was applied by Finoguenov et al. (2001) in the $M - T$ fitting. Together these corrections make an effective $\beta = 1.9$ for the fiducial model.

We emphasize that $T$ is used here just as a label and does not necessarily need to be the correctly calibrated temperature of the cluster, as long as the mass assigned to this $T$ is correct and there is a monotonic relation between the two. For this method to be unbiased we must only address the bias in the mass determination. However, the masses are derived from the assumption of hydrostatic equilibrium combined with the measurements of the temperature and gas profile. For a polytropic profile $T \propto \rho_b^{-\gamma}$ and beta-model for X-ray intensity profile $I_X \propto \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-3/2}$ one finds

$$M(r) \propto T^{3} \beta X \rho_b^{1/2} \left[ 1 + \left( \frac{r_c}{r} \right)^2 \right].$$

(6)

Here $r_c$ is the core radius of the beta-model profile. We see that the derived mass is linear in $\beta_X$, $\gamma$ and $T$ (note that the $\beta_X$ here should not be confused with $\beta$ as a parametrization of $M - T$ relation), each of which has some uncertainty associated with it. Uncertainty in mass determination from surface brightness profile fitting is expected to be small. Somewhat more controversial are $T$ profiles derived.
from ASCA, which have been interpreted by some groups (e.g. Finoguenov et al. 2001, Markevitch 1998) to show a decline in $T$ at larger radii, in agreement with theoretical predictions, while others do not find this (e.g. White 2000). Such declines are not seen in general from Chandra (Allen et al. 2001), although the radii probed are smaller and this is not unexpected. BeppoSAX does see a decline in most of the clusters observed (De Grandi & Molendi 2001) and for the few clusters that overlap with the ASCA sample in Finoguenov et al. (2001), the drop in $T$ out to $r_{500}$ is in a reasonable agreement between the two. It is also in agreement with XMM-Newton for the clusters that have been observed by both satellites, although the XMM-Newton sample is still small (Arnaud et al. 2001). The measured average polytropic index $\gamma \sim 1.2$ (Finoguenov et al. 2001) is close to theoretical predictions (Komatsu & Seljak 2001) and we verified that this also provides a reasonable fit to the BeppoSAX data (De Grandi & Molendi 2001) in the outer parts of the cluster where most of the mass is (in the inner parts the polytropic assumption fails, since it cannot predict a sharp flattening of the temperature profile at a radius larger than the core radius, as seen with BeppoSAX data).

To derive the constraints on the power spectrum amplitude, we compute the cumulative $T$-function at an effective mean redshift of the sample $z \sim 0.05$. We compare it to the best fitted model of Pierpaoli et al. (2001) around $T = 6.5$ keV, which is the pivot point where most of the sensitivity is. The results are not very sensitive to this choice since the shapes of cumulative mass function are very similar. Our simplified approach, which avoids a proper likelihood evaluation, is reasonable as long as the estimated errors in the two methods are comparable. Large errors can introduce bias since for a steeply declining $T$ function low $T$ clusters can scatter into high $T$ and produce a cumulative $T$ function with a higher amplitude in this exponential regime (Pen 1998). The scatter in $M-T$ relation is comparable or perhaps somewhat larger than the estimated errors in Pierpaoli et al. (2001). In the latter case this would lead to a slight overestimate of $\sigma_s$. Here we will assume the errors are comparable and we do not correct for this effect, which would further reduce $\sigma_s$.

Figure 2 shows the comparison between the best fitted theoretical prediction for $\Omega_m = 0.35$, $\Omega_{\Lambda} = 0.65$, $\Gamma = 0.2$ model and the data sample of Pierpaoli et al. (2001). Here $\Gamma$ is the shape parameter of the power spectrum. The best fitted value for this model is $\sigma_s = 0.7$. A more general fit around this model is $\sigma_s = 0.7(\Omega_m/0.35)^{-0.44}(\Gamma/0.2)^{0.08}$, which is supposed to give a few percent accuracy over $0.2 < \Omega_m < 1$ and $0.1 < \Gamma < 0.3$. Note that the dependence on $\Omega_m$ is less steep than the usual $\Omega_m^{-0.6}$, a consequence of the different mass temperature relation and different mass function and mass definition. We estimate the error by varying $\beta$ by one standard deviation in both directions. This gives $\sigma_s = 0.7 \pm 0.06$ for the fiducial model. We emphasize that this is only the statistical error. The systematical error, which is much harder to estimate, is discussed below.

4 DISCUSSION AND CONCLUSIONS

The value for $\sigma_s \sim 0.7 \pm 0.06$ for $\Omega_m = 0.35$ is about 25% lower than the most recent value derived from the local cluster sample (Pierpaoli et al. 2001). While it is very close to the value obtained from high redshift cluster catalog (Borgani et al. 2001), it is important to note that they use $\beta = 1.2$ in their analysis and so if the actual value is $\beta = 2$ as suggested by the local $M_{500} - T$ observations then their value for $\sigma_s$ would be even lower. For the same value of $\beta$ the discrepancy in the normalization between the local and high redshift sample is at a more than 3-$\sigma$ level and difficult to explain as a statistical fluctuation. This points to perhaps additional systematic effects beyond the $M-T$ normalization discussed here that may be affecting either the local or the high redshift sample. We also note that our lower value for $\sigma_s$ agrees well with other recent attempts to circumvent the use of simulations by adopting the measured masses from weak lensing (Viana, Nichol, & Liddle 2001) and hydrostatic equilibrium (Reiprich & Boehringer 2001). The latter analysis in particular is very close in spirit to our approach.

Even though the method used here does not rely on simulations and so in principle should be more reliable, it still contains several possible systematic uncertainties. We mentioned some before: the mass determination from spatially resolved temperature maps has perhaps a 20% uncertainty. It is difficult, although perhaps not impossible, to invoke systematic errors in the mass determination to bring the observed $M-T$ relation in agreement with the adiabatic simulations results. We know however that additional processes must be included in simulations. Cooling, which is relatively well understood, although numerically challenging, makes a significant difference in the normalization of $M-T$ relation and its inclusion brings the predicted relation closer to the observations (Muwanng et al. 2001). Underestimation of errors in $M-T$ can also bias the results and if these are larger than assumed here then $\sigma_s$ will be reduced further, although probably by not more than a...
few percent unless the scatter in $M - T$ relation is seriously underestimated.

On the theoretical side the extrapolation from $M_{200}$ to $M_{\Delta}$ has roughly a 10% uncertainty in mass. The use of the mass function by Sheth & Tormen (1999) with $M_{\Delta}$, rather than Jenkins et al. (2001) mass function with $M_{200\Delta}$, would decrease the value of $\sigma_8$ by 7%. Rather than to construct mass function based on a spherical overdensity on a virial radius, which is not directly observable, it is more useful to focus on mass functions using masses defined within some smaller radius, such as $r_{500}$, where mass can be directly measured. A step in this direction has been undertaken recently by Evrard et al. (2001), who evaluate mass function at $M_{200}$, which is only 40% above $M_{500}$ for $c_{\Delta} = 5$. Unfortunately they do not provide a universal mass function valid for all models, but a fitting formula for the two cosmological models they simulate. We find that for flat $\Omega_m = 0.3$ model their mass function agrees with ours if the mass definition of Jenkins et al. (2001) is used together with $c_{\Delta} = 5$. Similarly, M. White (private communication) has evaluated mass functions using $M_{200}$ for several models and again we find the agreement with our mass function is very good. This can be further improved in the future by defining the mass as close as possible to the observational definition (e.g. in projection for the case of lensing and X-rays). The agreement between different groups gives us confidence that the mass function has converged to the form proposed by Jenkins et al. (2001), and this should not be a major source of uncertainty in the future.

On the other hand, use of different mass functions can explain up to 10% differences in derived $\sigma_8$ in the past work.

Our results are actually good news for CDM models, which are facing significant problems on small scales (see Alam et al. 2001 for an overview). The models predict too steep density profiles of halos and too many subhalos within halos, both of which are related to predicting too much small scale power. If the 10Mpc normalization can be significantly reduced this not only reduces the amplitude of the power spectrum, but also allows for a stronger tilt, which can further reduce the power on scales below 1Mpc where most of the problems are. Such tilted ACDM model was recently investigated by Alam et al. (2001). It was shown there that the halo structure problems with CDM are significantly alleviated and the tilted low $\sigma_8$ model gives halo concentrations in line with observations. Subhalos are reduced as well, but not to the point where there would be too few to match the observations once photoionization suppression is included (Bullock 2001).

Perhaps the most important message of the present paper is that the systematic errors associated with the cluster abundance normalization are still significantly larger than often assumed (see also Voit 2000) and so one should be cautious when ruling out cosmological models based on this constraint. Our results suggest that even models with $\sigma_8 \approx 0.6$ at $\Omega_m = 0.3$ are not excluded at this point. Although at present the cluster normalization may be less reliable than previously thought, the prospects for the future are more promising. Instead of concentrating on calibration of $M - T$ relation from the simulations, which may be uncertain for some time in the future, one should focus on obtaining better data to empirically calibrate the relation through the mass determinations from lensing, velocity dispersions and applications of hydrostatic equilibrium. The latter should be especially promising as well calibrated spatially resolved temperature profiles become available with Chandra, BeppoSAX and XMM-Newton. These mass measurements should be tied to the temperature determinations of clusters used in the construction of cluster sample and compared to mass functions constructed using masses which are observationally defined. As larger samples become available one will be able to construct mass selected samples directly without the need of using temperatures at all. Ultimately this approach should provide a reliable constraint on the cosmological models at 10Mpc scale.

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