IS WMAP3 NORMALIZATION COMPATIBLE WITH THE X-RAY CLUSTER ABUNDANCE?

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ABSTRACT

We present the mass and X-ray temperature functions derived from a sample of more than 15,000 galaxy clusters of the MareNostrum Universe cosmological SPH simulations. In these simulations, we follow structure formation in a cubic volume of $500\, h^{-1}\text{Mpc}$ on a side assuming cosmological parameters consistent with either the first- or third-year WMAP data and Gaussian initial conditions. We compare our numerical predictions with the most recent observational estimates of the cluster X-ray temperature functions and find that the low-normalization cosmological model inferred from the 3 year WMAP data results is barely compatible with the present-epoch X-ray cluster abundances. We can only reconcile the simulations with the observational data if we assume a normalization of the mass-temperature relation, which is a factor of $\sim 2.5$–3 smaller than our nonradiative simulations predict. This deviation seems to be too large to be accounted by the effects of star formation or cooling in the ICM, which are not taken into account in these simulations.

Subject headings: cosmology: theory — galaxies: clusters: general — methods: numerical

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1. INTRODUCTION

Clusters of galaxies are strong X-ray emitters that can be observed at large distances using the XMM-Newton and Chandra X-ray telescopes. They are excellent cosmological probes that can be used to put strong constraints on the matter density of the universe, $(\Omega_m)$, the normalization of primordial density fluctuations $(\sigma_8)$, and the associated spectral index $(n)$. The number of massive clusters in cold dark matter–dominated cosmologies is known to be exponentially dependent on $\sigma_8$ (Seth & Tormen 2002), as has been extensively confirmed by simulations. Therefore, the determination of the abundance of massive clusters gives one of the best constraints on the normalization of the initial power spectrum of density fluctuations, provided we adopt Gaussian initial conditions. An independent measurement of the cosmological parameters comes from the study of CMB anisotropies. The most recent data from the 3 year WMAP results (Spergel et al. 2007; WMAP3) gives a value of $\sigma_8 \sim 0.76 \pm 0.05$ to within 1 $\sigma$ error. This is smaller than the previous value of $\sigma_8 = 0.84 \pm 0.04$ estimated from the first-year WMAP data (Spergel et al. 2003; WMAP1). This difference in the normalization and the matter content ($\Omega_m = 0.24$ vs. $\Omega_m = 0.3$) translates into large differences, up to an order of magnitude as we will show in this Letter, in the number density of the most massive objects formed at present in the universe. Other recent papers independently also argue against the low values of $\sigma_8$ obtained from WMAP3 (Evrard et al. 2007; Rozo et al. 2007).

In order to compare the theoretical cluster mass function for a particular cosmological model with the observed abundance of X-ray clusters as a function of the ICM gas temperature, one has to assume that the mass-temperature relation is sufficiently well known. The main obstacle is the accuracy in the determination of this relation. Small differences can lead to large changes in the determination of cluster mass (see, e.g., Henry 2004) from the X-ray temperature. Estimations of the $M-T$ relation from gas dynamical simulations show large discrepancies, mainly due to numerical resolution effects as well as to the physics involved (see Ascasibar et al. 2006 for a review). Most previous numerical studies on the comparison of cluster mass functions and X-ray temperature and/or luminosity functions have either high numerical resolution and a low number of objects or larger statistics but with very low resolution.

The aim of this Letter is to study the X-ray cluster temperature function (XTF) obtained from a set of large-scale nonradiative gas dynamical simulations with sufficient numerical resolution and statistics to cover the range of temperatures for which observational estimates of the cluster abundance are known. Our main goal is to test whether the observed number of X-ray-emitting galaxy clusters can be obtained in a cosmological model with parameters consistent with WMAP3 or WMAP1 data at the present time. For this purpose, we compute the XTF directly from simulations and compare them with the most recent observational estimates. At the same time, we derive the values for the normalization of the $M-T$ relation that best fit the simulation mass functions to the observed XTF and compare them with the $M-T$ resulting from the simulations.

2. SIMULATIONS

To study the X-ray cluster abundance, we have performed a series of nonradiative SPH simulations with the GADGET2 code (Springel 2005) at the Barcelona Supercomputer Center. Starting at redshift $z = 40$, we followed the nonlinear evolution of structures in gas and dark matter (DM) to the present epoch ($z = 0$) within a comoving cube of $500\, h^{-1}\text{Mpc}$ on a side. The so-called MareNostrum Universe is the SPH simulation with $2 \times 1024^3$ particles (MUC). We assumed a concordance cosmological model with the following parameters: total matter
density $\Omega_m = 0.3$, baryon density $\Omega_b = 0.045$, cosmological constant $\Omega_k = 0.7$, Hubble parameter $h = 0.7$, slope of the power spectrum $n = 1$, and normalization $\sigma_8 = 0.9$. We also ran the same simulation with exactly the same initial data but lower mass resolution ($2 \times 512^3$; MUCL), as described in Gottlöber & Yepes (2007).

After the release of the 3 year WMAP data, we complemented our numerical data set with new simulations of the same computational box but using WMAP3 cosmological parameters: $\Omega_m = 0.24$, $\Omega_b = 0.0418$, $\Omega_k = 0.76$, $h = 0.73$, $n = 0.95$, and $\sigma_8 = 0.75$. We have changed both $\Omega_m$ and $\Omega_b$ (rather than only $\sigma_8$) so as to remain on the WMAP degeneracy line for these two parameters. As in the concordance model, the power spectrum was kindly provided by Wayne Hu, who computed it by direct numerical integration of the Boltzmann code. We generated the initial conditions for the WMAP3-compatible simulations with $2 \times 512^3$ (MUW) particles in exactly the same way as for the MareNostrum Universe. In order to study the effects of cosmic variance, we have completed a second simulation with a different random realization (MU2W). Furthermore, and driven by the results obtained for the XTF from these simulations, we have also repeated the MareNostrum Universe realization of the WMAP3 cosmology, but with a higher normalization of the initial power spectrum ($\sigma_8 = 0.8$), consistent within 1 $\sigma$ with the WMAP3 best fit (MUWHS). In Table 1 we summarize the main characteristics of the simulations and the corresponding acronyms for reference in what follows. The best-fit values of the mass-temperature relations from clusters obtained in each simulation are also shown in the last two columns (see § 4).

The clusters have been identified in the simulations by means of a hierarchical friends-of-friends (FOF) halo finder, as described in Gottlöber & Yepes (2007). For comparison with observational data, we have estimated total masses (dark + gas) of clusters at different spherical overdensities (200, 500, 2500) with respect to the critical density. To this end, we started at the position of the most massive substructure of the clusters identified with FOF and used the “bound density maxima” algorithm (Klypin et al. 1999) to find the spherical overdensities.

### 3. Cluster Mass Functions

In Figure 1 we plot the resulting cumulative mass functions for all the simulations described in Table 1. In this figure, the total mass of objects corresponds to the region enclosing an overdensity of 200 around the center of mass found as described in the previous section. As can be deduced from this figure, there are no significant resolution effects on the number of objects as a function of mass. The mass functions for simulations MUC and MUCL nicely overlap each other despite the fact that they differ by a factor of 8 in mass resolution and a factor of ~3 in spatial resolution. On the other hand, there is a significant difference in the number of cluster-size objects depending on the cosmological model. The number density of clusters with masses $M_{200} \geq 5 \times 10^{14} h^{-1} M_{\odot}$ in both simulations with the low-normalization, best-fit WMAP3 cosmological parameters, MUW and MU2W, is ~10 times smaller than for the simulations of the concordance ΛCDM model. The MUWHS simulation with $\sigma_8 = 0.8$ has a number density ~2 higher than the simulations with $\sigma_8 = 0.75$, but still is a factor of ~5 smaller than in the concordance cosmology. Finally, Figure 1 also shows that the effects of cosmic variance are not important in determining the abundance of clusters at these scales. The agreement of the mass functions for the two different realizations of the WMAP3 cosmological model clearly confirms this. On the other hand, we have also checked for the possible effects of small-volume sampling in the determination of the mass function for the most massive objects. To this end, we have compared our mass function for the MUWHS simulation with the mass function obtained from a DM-only simulation of the same cosmological model as MUWHS and the same number of particles, but with a larger computational volume (1.5 Gpc). This simulation has been done also at MareNostrum with the GADGET2 code by P. Fosalba for the
Dark Energy Survey. The agreement between the two mass functions is remarkable for halos with masses $M_{200} > 5 \times 10^{14} \, h^{-1} \, M_\odot$.

Therefore, we conclude that the estimation of the cluster mass function from our simulations is robust and not likely to be affected by numerical effects. Now our purpose is to compare them with data coming from X-ray observations of clusters. As our simulations include gas dynamics, we can directly measure the X-ray temperature from the gas content of our halos. In DM-only simulations, one has to rely on the mass–X-ray temperature relation to transform mass into temperature or vice versa. Here we will do the same exercise and compare the calculated XTFs.

4. X-RAY TEMPERATURE FUNCTION

The most recent published data for the XTF of nearby clusters uses temperatures derived from X-ray observations mainly by the ASCA satellite (Ikebe et al. 2002; Henry 2004) as a measure of the mean temperature of the ICM. The differences shown in the temperatures of clusters from these two data sets reflect the systematic errors in the observed XTF. For our simulated clusters, we computed several temperature estimations. These include the emission-weighted temperature ($T_{ew}$), computed by weighting the temperature of each SPH particle within the cluster by its X-ray luminosity. We also computed the spectroscopic temperature ($T_s$), following the procedure described in Vikhlinin (2006), which is supposed to give a more accurate value of the observed temperature of an X-ray-emitting plasma. Therefore, in what follows we will use $T_s$ for the simulated clusters.

In Figure 2 we show the cumulative XTF as a function of the spectroscopic $T_s$ for the clusters found in simulations described in Table 1. We also represent the observational data as points with error bars as described in Henry (2004). The observational data were rescaled to units of $h = 1$.

The predicted number density of X-ray clusters above a given temperature for the MUC and MUCL simulations with $\sigma_8 = 0.9$ is in good agreement with the data. Again, as in the case of mass, the WMAP3 most-favored cosmological model underpredicts the density of X-ray clusters with respect to the observations by a factor of $\sim 10$ for clusters with $T_s > 4$ keV. The situation is slightly better for the higher normalization MUWHS simulation. But still, it predicts a factor of $\sim 6$ fewer density of clusters hotter than $T_s > 4$ keV than in reality.

We showed in Figure 1 that effects of resolution are negligible in the estimate of the cumulative mass function for massive clusters. This could not be the case for the temperature estimates from the gas particles. In order to check whether the XTF could be affected by resolution, we also show in Figure 2 a comparison of the XTF between MUC and MUCL simulations. As can be seen, the spectroscopic temperature estimate of clusters is biased high when low-mass resolution is used in a SPH simulation. Thus, we expect that the difference in XTF shown between the MUC concordance model simulation with 1024$^3$ particles and the WMAP3 lower resolution simulations (512$^3$) is in fact a lower limit. If we increased the mass resolution of the latter, we would obtain a larger difference with respect to the MUC and data.

5. DISCUSSION

We have shown in the previous sections that the low-normalized WMAP3 cosmological simulations underpredict the abundance of X-ray clusters by a factor that ranges between 6 and 10 with respect to estimates from ASCA observations. Now our estimates are based on the results from nonradiative gas dynamical simulations of the ICM. There is still no clear answer to what extent cooling and star formation are important in the thermodynamics of the ICM. The extreme complexity of the processes involved presents a serious challenge for simulating them accurately in a cosmological setting. Results from simulations that incorporate some modeling of these processes have shown that the $M$–$T$ relation is not strongly affected by non-gravitational heating (Borgani et al. 2004; Nagai et al. 2007). A rather more important ingredient in the determination of the XTF from mass functions is the intrinsic scatter of the $M$–$T$ relation. If the scatter is big, then a rather low normalization power spectrum can in principle give a high enough XTF to be compatible with observations. Given the very good statistical sample of objects in our simulations, we can reliably estimate not only the $M$–$T$ relation but also the intrinsic scatter due to the cluster dynamics. In Table 1 we report the least-squares fit values of the $M_{200}/M_\odot \, h^{-1} = (M_\odot / M_{200} \, h^{-1}) (T_s/3 \, \text{keV})^\alpha$ for the different simulations where errors in both the slope $\alpha$ and normalization $M_\odot$ correspond to 1 $\sigma$ in the fit. We can also make a reliable estimate of the intrinsic scatter in the $M_{200}$–$T_s$ relation. The linear fit of the log $M_{200}$ versus log $T_s$ has a Pearson’s correlation coefficient better than 0.99 for all simulations. The maximum intrinsic scatter, $\Delta \log M_\odot$, is also shown in Table 1. It is defined as the value for which 99% of all the clusters used in the fit have their spectroscopic temperature within the values $\log T_s = (\log M_{200}) / \alpha - \log M_\odot + \Delta \log M_\odot$. As can be seen, the values of the scatter are between 0.28 and 0.31 dex (factor $\sim 2$ with respect to $M_\odot$) for the WMAP3 simulations. But are the differences shown in Figure 2 between the simulated XTF and data compatible with this intrinsic scatter of the $M$–$T$ relation? In order to give a possible answer to this question, we have estimated the $M_\odot$ and $\alpha$ parameters of the $M_{200}$–$T_s$ relation.
needed to accommodate the mass functions shown in Figure 1 to the observational XTF data by a $\chi^2$ minimization. We show in Figure 3 the best-fit simulated XTF for the WMAP3 simulations to the observational data points, together with the simulation results for the high-normalization MUC simulation. The $\chi^2$ best-fit values found for the MUW+MU2W simulations are $\alpha_i^\text{fit} = 1.64$ and $\log M_{0500}^i = 14.09$ for the Ikebe et al. data and $\alpha_i^\text{fit} = 1.49$ and $\log M_{0500}^i = 14.17$ for the Henry data. When both observational data sets are taken together in the fit, we obtain $\alpha_i^\text{fit} = 1.64$, $\log M_{0500}^i = 14.10$. For the higher normalization WMAP3 simulation MUWHS, we find $\alpha_i^\text{fit} = 1.66$, $\log M_{0500}^i = 14.18$ for Ikebe; $\alpha_i^\text{fit} = 1.44$, $\log M_{0500}^i = 14.28$ for Henry; and $\alpha_i^\text{fit} = 1.67$, $\log M_{0500}^i = 14.18$ for the combined data sets. Now if we fix the slope $\alpha_i$ to the best-fit value obtained from each simulation (see Table 1), we find a value for the normalization parameter $\log M_{0500}^i = 14.10–14.13$ for WMAP3 simulations and $\log M_{0500}^i = 14.19–14.22$ for the WMAP3 simulation. Finally, if we assume a self-similar behavior of the $M$-$T$ scaling relation, $\alpha = 3/2$, then the best-fit values for $M_{0500}^i$ are quite similar: $\log M_{0500}^i = 14.20–14.26$ for the MUWHS simulation and $\log M_{0500}^i = 14.12–14.17$ for the MUW+MU2W simulations. Therefore, the normalization of the $M_{500}^\text{fit}$-$T_\text{X}$ relation needed to fit the observational XTF for the $\alpha_i = 0.75$ MUW and MU2W simulations is a factor of $0.40–0.45$ dex ($\sim 2.5–2.8$ times) smaller than the best-fit values shown in Table 1. For the $\alpha_i = 0.8$ WMAP3 simulation this factor is $0.36–0.39$ dex ($\sim 2.3–2.4$ times). As we have seen, the maximum scatter derived from our WMAP3 nonradiative gas dynamical simulations is $\pm 0.28–0.31$ dex (i.e., a factor of $\sim 2$). It is not clear that nongravitational heating could affect the thermodynamics of the IC in such a way that this could account for a factor of $\sim 2.5–2.8$ lower normalization with respect to the predictions of the simulations reported here. For instance, the normalization for the emission-weighted $M_{500}^\text{fit}$-$T_\text{X}$ from SPH simulations including cooling and star formation (Borgani et al. 2004) is a factor of 1.46 smaller than the value we obtained for our MUWHS simulation. If we compare the normalization of the spectroscopic $M_{500}^\text{fit}$-$T_\text{X}$ from the radiative cluster simulations of Nagai et al. (2007) with ours, the difference is within a factor of 1.5–1.6.

In conclusion, it seems unlikely that we can reproduce the observational estimates of abundance of X-ray clusters with a normalization of the power spectrum as low as the best-fit value given by WMAP3. A slightly higher normalization of $\alpha_i = 0.8$ alleviates the problem, although the cluster abundance still lies below the observational estimates. Considerably steeper slopes and lower normalization of the $M$-$T$ relation are needed to reconcile the predicted mass functions of clusters with the observed XTF in this case. Alternative explanations that retain a low normalization of $\alpha_i$ appeal to the effects of primordial non-Gaussianity (Sadeh et al. 2006) or to dynamical dark energy (Bartelmann et al. 2006). However, for the standard cosmological model, X-ray clusters of galaxies seem to prefer a higher $\alpha_i$ than predicted by the CMB anisotropies, in agreement with the abundance of optical clusters from SDSS (Rines et al. 2007; Rozo et al. 2007).

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