WMAP5 AND THE CLUSTER MASS FUNCTION

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ABSTRACT

The recently revised cosmological constraints from the 5 year WMAP data ameliorate previous tension between cosmological constraints from the microwave background and from cluster abundances. We demonstrate that the revised estimates of cosmological parameters are in excellent agreement with the mass function of X-ray clusters in the Sloan Digital Sky Survey. Velocity segregation between galaxies and the underlying dark matter could cause virial mass estimates to be biased, causing the mass scale of the mass function to be offset from the true value. Modest velocity segregation \((\sigma_{\text{gy}}/\sigma_{\text{DM}} = 1.13^{+0.06}_{-0.06})\) is sufficient to match the mass function to the 5 year WMAP results. However, when the new WMAP results are combined with constraints from supernovae and baryon acoustic oscillations, there is no need for velocity segregation \((\sigma_{\text{gy}}/\sigma_{\text{DM}} = 1.05 \pm 0.05)\). This result agrees with expectations for velocity segregation from state-of-the-art numerical simulations of clusters. Together with the improved agreement between the new WMAP results and recent cosmic shear measurements, this result demonstrates that the amplitude of large-scale structure in the nearby universe matches that predicted from the structure seen in the microwave background. The new constraint we place on velocity segregation in clusters indicates that virial mass estimates for clusters are reasonably accurate. This result suggests that future cluster surveys will be able to probe both cosmological parameters and fundamental cluster physics.

Subject headings: cosmology: observations — galaxies: clusters: general — galaxies: kinematics and dynamics

1. INTRODUCTION

The increased statistical power and sophistication of different cosmological probes enables new tests of long-standing astrophysical problems. We compare recent cosmological constraints from observations of the microwave background with those obtained from cluster abundance estimates. This analysis effectively compares the amplitude of large-scale structure at \(z \approx 1100\) with the large-scale structure in the local universe.

Clusters of galaxies are the most massive gravitationally relaxed systems in the universe, so the observed cluster mass function is a sensitive probe of cosmological parameters. Galaxy cluster abundances are most sensitive to the matter density of the universe \(\Omega_m\) and \(\sigma_8\), the rms fluctuations in spheres of radius 8 h\(^{-1}\) Mpc, and the normalization of the linear power spectrum (Henry & Arnaud 1991; Bahcall & Cen 1993). The estimated values of these two parameters underwent significant revisions between the 1 year and 3 year WMAP results (hereafter WMAP1 and WMAP3; Spergel et al. 2007). With the recent release of the 5 year WMAP results (hereafter WMAP5), the estimates of these two parameters shifted again, although this latest shift is smaller than the statistical uncertainties (Dunkley et al. 2008; see their Table 2 and Fig. 6).

The shift in these parameters between WMAP1 and WMAP3 significantly alters the expected abundance of massive clusters. Reiprich (2006) noted that this revision agrees well with the X-ray mass function of Reiprich & Böhringer (2002). However, other studies suggest that hydrostatic X-ray mass estimates such as those used in Reiprich & Böhringer (2002) underestimate true cluster masses because either the gas temperatures are underestimated (Rasia et al. 2005) or because turbulent flows and kinetic pressure in the intracluster medium (ICM) are a significant energy component (Vikhlinin et al. 2006; Nagai et al. 2007). The (poorly constrained) amount of energy in nonthermal pressure has a dramatic impact on estimates of \(\sigma_8\) inferred from X-ray observations (e.g., see Fig. 17 of Mantz et al. 2008).

We recently estimated the cluster mass function using ROSAT X-ray cluster surveys to determine the selection function and redshifts from the Sloan Digital Sky Survey (SDSS; Stoughton et al. 2002) to estimate virial masses (Rines et al. 2007). The cluster masses were computed as part of the Cluster Infall Regions in SDSS project (CIRS; Rines & Diaferio 2006). Our estimate of cluster abundance exceeded that expected for the best-fit WMAP3 parameters. We showed that this difference could be attributed to velocity segregation: if cluster galaxies have a significantly higher velocity dispersion than the underlying dark matter, then dynamical mass estimates based on the virial theorem overestimate cluster masses and thus overestimate the abundance of clusters at a given mass threshold. We argued that significant velocity segregation \((\sigma_{\text{gy}}/\sigma_{\text{DM}} \approx 1.28 \pm 0.06)\) is needed to produce agreement with the cosmological parameters of WMAP3 (Rines et al. 2007).

Numerical simulations including models of galaxy formation typically predict little velocity segregation (also called “velocity bias”) in clusters (Kauffmann et al. 1999a, 1999b; Gao et al. 2004; Diemand et al. 2004; Faltenbacher et al. 2005; Faltenbacher & Diemand 2006; Biviano et al. 2006; Benavides et al. 2006; Evrard et al. 2008). Evrard et al. (2008) showed that velocity dispersions of dark matter halos provide robust and accurate mass estimates over many orders of magnitude in halo mass; that is, dark matter particles obey virial scaling relations. Further, they confirmed that the CIRS velocity dispersion function requires significant velocity segregation in clusters to match the cosmological parameters estimated from a joint analysis of WMAP3 and SDSS data (Tegmark et al. 2006). In particular, they show that the parameter \(S_8 = \sigma_8(\Omega_m/0.3)^{0.35}\) has conflicting estimates of \(S_8 = 0.69\) from WMAP3+SDSS versus \(S_8 \approx 0.9\) from the CIRS velocity dispersion function. Evrard

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et al. (2008) also show that the WMAP3+SDSS cosmology requires excess specific energy in the ICM, again conflicting with expectations from numerical simulations. They propose that a plausible intermediate value of $S_\text{int} = 0.8$ would reconcile the estimates without requiring excess specific energy in galaxies or the ICM.

In this Letter, we show that the revised cosmological constraints from WMAP5 and other methods significantly alleviate the need for velocity segregation and excess ICM specific energy in galaxy clusters. We review the challenges of accurately determining the cluster mass function in § 2 and compare the WMAP5 results with the cluster mass function in § 3. We discuss the implications of these comparisons in § 4. We assume $H_0 = 100\ km\ s^{-1}\ Mpc^{-1}$ and a flat $\Lambda$CDM cosmology ($\Omega_m = 1 - \Omega_\Lambda$) throughout. Where not stated explicitly, we assume $\Omega_m = 0.3$ and $h = 0.7$ for initial calculations.

2. DETERMINING THE CLUSTER MASS FUNCTION

There are many challenges to accurately estimating the abundance of galaxy clusters. The first challenge is accurately measuring the survey volume. In particular, one must know the maximum volume $V_{\text{max}}$ in which a cluster with certain properties could be detected within a given survey. Most clusters exhibit X-ray emission from the ICM. As a result, X-ray surveys can be used to define flux-limited samples where $V_{\text{max}}$ can be computed directly. Optical surveys are excellent for detecting clusters, but they are more sensitive to projection effects than X-ray surveys. Our approach was therefore to combine the virtues of a well-defined selection function available from large-area X-ray surveys with the large redshift samples available from SDSS (Rines et al. 2007). This approach has the advantage that cluster selection and cluster mass estimates are decoupled.

Another significant challenge is sampling a large and representative volume. Clusters are extremely rare objects, so a large survey volume is required to fairly sample the cluster mass function. The cluster sample we use is the CIRS sample of Rines & Diaferio (2006) with some minor modifications described in Rines et al. (2007). The CIRS clusters are selected from X-ray cluster catalogs constructed from ROSAT All-Sky Survey data (Ebeling et al. 2000; Böhringer et al. 2000, 2001). We searched for all $\Delta z \leq 0.1$ X-ray clusters within the 4783 deg$^2$ of spectroscopic data available in the Fourth Data Release (DR4) of SDSS (Adelman-McCarthy et al. 2006). The volume contained in the CIRS mass function is $\sim 10^7\ h^{-3}\ Mpc^3$, the largest ever probed by virial mass estimates (Rines et al. 2007).

The CIRS clusters are an unbiased sample: the selection of the sample is based purely on X-ray flux and the footprint of the SDSS DR4 spectroscopic survey. We confirmed this claim with a $V/V_{\text{max}}$ test (Schmidt 1968): we find $V/V_{\text{max}} = 0.518 \pm 0.035$ compared to an expected value of 0.5 for a complete, uniform sample (Rines et al. 2007). The CIRS sample is essentially volume-limited for clusters with $L_X > 3 \times 10^{43}\ h^{-2}\ ergs\ s^{-1}$ and $z \leq 0.1$.

The greatest obstacle to measuring the cluster mass function is obtaining sufficiently accurate mass estimates. It is observationally challenging to obtain detailed mass estimates for large samples of clusters. One common approach to computing the cluster mass function is therefore to use relatively simple observables such as X-ray temperature or luminosity (e.g., Mantz et al. 2008) or optical luminosity or richness (e.g., Bahcall et al. 2003; Rozo et al. 2007) as proxies for detailed mass estimates. Because these mass proxies require significantly less data than detailed mass estimates, they can be applied to large samples of survey-quality data and thus probe larger volumes than CIRS. However, an important assumption in this method is that residuals from the scaling relation must be well behaved (the residuals are usually assumed to follow a lognormal distribution; e.g., Mantz et al. 2008).

For the CIRS mass function, we use detailed dynamical mass estimates for the individual clusters to compute the mass function. The dynamics of cluster galaxies provided the first evidence for dark matter when Zwicky (1933, 1937) applied the virial theorem to the Coma Cluster. Since then, the use of virial mass estimators has been refined and this method has proved to be a powerful tool for measuring cluster masses (e.g., Biviano et al. 2006). Rines & Diaferio (2006) show the infall patterns of the 72 CIRS clusters and compute the mass profiles from both the caustic technique and the virial theorem. With the dense redshift samples available from SDSS, cluster members can be cleanly separated from foreground and background galaxies, and the statistical uncertainties in the virial mass estimates are relatively small.

Compared to X-ray studies, virial mass estimates are sensitive to larger scales ($V_{\text{max}}$, rather than $r_{\text{vir}}$, where $r_{\text{vir}}$ is the radius within which the enclosed density is $\Delta$ times the critical density). This difference allows comparisons with theoretical mass functions with significantly less extrapolation (White 2002). Also, virial masses can be estimated for poor clusters and rich groups, whereas X-ray mass estimates of these systems are complicated by possible energy input from supernovae and AGNs (e.g., Loewenstein 2000). Probing these smaller masses enables a direct constraint on fluctuations on the scale $8\ h^{-1}\ Mpc$, rather than the $\sim 14\ h^{-1}\ Mpc$ scale probed by $\sim 10^{15}\ h^{-1}\ M_\odot$ clusters (Pierpaoli et al. 2001).

We used the virial mass function to obtain cosmological constraints; these constraints can be parameterized as $\alpha_
u(\Omega_m/0.3)^{1.5} = 0.81^{+0.08}_{-0.05}$ (68% confidence level; Rines et al. 2007). Evrard et al. (2008) showed that the CIRS velocity dispersion function yields similar results to the CIRS mass function. Using stacked clusters from the maxBCG sample to determine scaling relations, Becker et al. (2007) found a velocity dispersion function in good agreement with that found by CIRS. These comparisons support our claim that the CIRS mass function is accurate.

3. COMPARING TO WMAP5 AND WMAP5+SN+BAO

Figure 1 shows the mass functions for the best-fit cosmological parameters from WMAP1 (Spergel et al. 2003), WMAP3 (Spergel et al. 2007), WMAP5 (Dunkley et al. 2008), and WMAP5+SN+BAO (Komatsu et al. 2008) at $z = 0.062$, the mean redshift of the CIRS sample, using the mass function of Jenkins et al. (2001). The WMAP5+SN+BAO constraints combine the WMAP5 data with supernova data from recent surveys (Astier et al. 2006; Riess et al. 2007; Wood-Vasey et al. 2007) and estimates of baryon acoustic oscillations from Percival et al. (2007). The WMAP1 and WMAP3 predictions straddle the CIRS results, while the WMAP5 and WMAP5+SN+BAO show excellent agreement with the CIRS mass function. In fact, the mass function predicted by the WMAP5+SN+BAO parameters is almost indistinguishable from the best-fit CIRS mass function (Fig. 1, green curve).

Figure 2 compares the CIRS cosmological constraints in the $(\Omega_m, \alpha_
u)$-plane with constraints from WMAP5, WMAP5+SN+BAO, and cosmic shear. Cosmic shear is the cumulative weak gravitational shear caused by large-scale structure. We use recent results from the Canada-France-Hawaii
We compare the recent revisions to cosmological parameter estimates available from WMAP 5 year data to the mass function of galaxy clusters in the local universe. The differences between WMAP3 and WMAP5 have a large effect on the expected mass function. In particular, our determination of the cluster mass function found a larger cluster abundance than expected for the parameters estimated by WMAP3 (Rines et al. 2007). The revised parameters bring the expected mass function into much better agreement with our data.

Large velocity segregation between galaxies and the underlying dark matter could produce a significant offset between the observed and true mass function (due to systematically overestimating or underestimating cluster masses). Such large velocity segregation is not expected from state-of-the-art numerical simulations (Diemand et al. 2004; Gao et al. 2004; Faltenbacher & Diemand 2006; Biviano et al. 2006); Evrard et al. (2008) summarize the theoretical expectation as \( \sigma_{\text{sys}}/\sigma_{\text{DM}} = 1.00 \pm 0.05 \). With the WMAP5 parameters, modest velocity segregation \( (\sigma_{\text{sys}}/\sigma_{\text{DM}} \approx 1.13^{+0.06}_{-0.05}) \) is sufficient to produce agreement. When combined with constraints from supernovae and baryon acoustic oscillations, the implied velocity segregation is small \( (\sigma_{\text{sys}}/\sigma_{\text{DM}} \approx 1.05 \pm 0.05) \), consistent with expectations from simulations. If the WMAP5 and CIRS results are correct, then cluster galaxies are indeed robust tracers of the velocity distribution (and dynamics) of the underlying dark matter.

Similarly, one can compare the specific thermal energy of the ICM to the specific energy of dark matter from the ratio

\[
b_{i}^{2} = \frac{kT_{i}/\mu m_{p}}{\sigma_{\text{DM}}^{2}},
\]

where \( \mu \) is the mean molecular weight and \( m_{p} \) is the proton mass. If the number density of clusters of a given temperature \( n(T_{c}) \) is known (Ikebe et al. 2002; Henry 2004), then for any given cosmology, one can estimate \( b_{i}^{2} \) by determining the mass of dark matter halos with the same number density [i.e., find \( M \) such that \( n(M) = n(T_{c}) \)] and applying virial scaling to infer \( \sigma_{\text{DM}}^{2} \). Applying this procedure to the WMAP3+SDSS es-

**Fig. 1.** Mass function of the CIRS sample. Green and blue points and error bars are computed using virial masses and caustic masses, respectively (the error bars show 68% uncertainties). The dash-dotted lines show the mass functions computed using the cosmological parameters from the WMAP1 results (upper line) and WMAP3 results (lower line) using the results of Jenkins et al. (2001). The green line shows the best-fit mass function for the CIRS virial mass function. The orange and magenta lines show the expected mass functions from the WMAP5 and WMAP5+SN+BAO parameters, respectively.

**Fig. 2.** Cosmological constraints from the CIRS virial mass function compared to other results. Green/yellow contours show 68% and 95% confidence levels for \( \Omega_{m} \) and \( \sigma_{8} \). Blue, orange, and magenta contours show the 68% and 95% confidence levels for CFHTLS, WMAP5, and WMAP5+SN+BAO, respectively (Fu et al. 2008; Dunkley et al. 2008; Komatsu et al. 2008).
imate of $S_8 = \sigma_8(\Omega_m/0.3)^{0.35} = 0.69 \pm 0.07$ leads to an estimate of $b_T^2 \sim 1.4 \pm 0.2$ (Evrard et al. 2008). Comparing this estimate to the expected value of $b_T^2 = 0.96 \pm 0.07$ from gasdynamic simulations (after corrections to match realistic observations), Evrard et al. (2008) conclude that $S_8 = 0.69$ requires the ICM to be a factor of $\sim 1.5$ hotter than expected from current simulations. If true, this result requires that current gasdynamic simulations are significantly underestimating the specific thermal energy of the ICM. Alternatively, Evrard et al. (2008) note that a larger value of $S_8 = 0.8$ would imply that the ICM has comparable specific energy to the dark matter ($b_T^2 = 1.1$, which is within 2 $\sigma$ of the value expected from simulations). The WMAP5 results indicate $S_8 = 0.75$, while the WMAP5+SN+BAO results indicate $S_8 = 0.80$, exactly the value suggested above as a possible resolution of the tension between WMAP3+SDSS and X-ray cluster observations and gasdynamic simulations. The new cosmological constraints therefore suggest that the specific energy of the ICM is comparable to both that of the underlying dark matter and that of the cluster galaxies.

The excellent agreement between the WMAP5 results and local cluster abundance measurements supports the case for future large cluster surveys as potential cosmological probes (e.g., Haiman et al. 2001; Hu 2003; Vikhlinin et al. 2003; Majumdar & Mohr 2004; Mantz et al. 2008). We conclude that a large spectroscopic program to measure virial masses of an X-ray selected sample at moderate redshift would provide an independent measurement of the evolution of the mass function. If other cosmological probes provide tighter (and consistent) constraints on cosmological parameters than those achievable with cluster surveys, the data can be used to probe the dynamical history of clusters, e.g., by measuring the evolution of velocity segregation and the thermal history of the ICM.

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