CONSTRAINING THE MATTER POWER SPECTRUM NORMALIZATION USING THE SLOAN DIGITAL SKY SURVEY/*ROSAT* ALL-SKY SURVEY AND REFLEX CLUSTER SURVEYS

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ABSTRACT

We describe a new approach to constraining the amplitude of the power spectrum of matter perturbations in the universe, parameterized by σ_8 as a function of the matter density Ω_0. We compare the galaxy cluster X-ray luminosity function of the *ROSAT*-ESO Flux-Limited X-Ray (REFLEX) survey with the theoretical mass function of Jenkins et al., using the mass-luminosity relationship obtained from weak lensing data for a sample of galaxy clusters identified in Sloan Digital Sky Survey commissioning data and confirmed through cross-correlation with the *ROSAT* All-Sky Survey. We find $\sigma_8 = 0.38\Omega_0^{-0.48+0.27\Omega_0}$, which is significantly different from most previous results derived from comparable calculations that used the X-ray temperature function. We discuss possible sources of systematic error that may cause such a discrepancy and in the process uncover a possible inconsistency between the REFLEX luminosity function and the relation between cluster X-ray luminosity and mass obtained by Reiprich & Böhringer.

Subject headings: cosmological parameters — galaxies: clusters: general — methods: analytical — surveys

1. INTRODUCTION

The present-day number density of galaxy clusters remains one of the most powerful constraints on the amplitude of matter perturbations in the universe. This is usually defined in terms of σ_8, which is the dispersion of the mass field smoothed on a scale of $8\ h^{-1}\ \mathrm{Mpc}^{-1}$, where h is the present value of the Hubble parameter in units of $100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. Most often the local X-ray cluster temperature function is used for this purpose, given that the X-ray temperature has been the best observable from which to estimate cluster mass. While observation can readily give the X-ray temperature of clusters, theory can easily predict only the cluster mass function. To bridge the gap, theoretical modeling of clusters is used to provide a relation between mass and temperature, which in the most sophisticated treatments is taken to depend on both redshift and the underlying cosmology.

However, a drawback in the use of the local X-ray cluster temperature function is that only a few tens of clusters have had their X-ray temperatures estimated. Consequently, authors using samples that only partially overlap have obtained significantly different cluster temperature functions and thus estimates for σ_8 (compare, e.g., Eke, Cole, & Frenk 1996; Henry 1997, 2000; Markevitch 1998; Blanchard et al. 2000; Pierpaoli, Scott, & White 2001). Statistically, the analysis would be more robust if the number density of local clusters could be estimated from much larger samples.

We describe here a new approach that avoids working with the X-ray temperature function. We instead use the luminosity function from the *ROSAT*-ESO Flux-Limited X-Ray (REFLEX) galaxy cluster survey (Böhringer et al. 2001, 2002), which contains 452 clusters, to estimate the local cluster number density. We relate X-ray luminosity to cluster mass by taking advantage of a weak shear lensing analysis (Sheldon et

al. 2001) of a sample of 42 galaxy clusters identified in data from the commissioning phase of the Sloan Digital Sky Survey (SDSS) and cross-checked via correlation with the *ROSAT* All-Sky Survey (RASS; Nichol et al. 2001). This relation is then used to compare the REFLEX luminosity function with the cluster mass function, leading to the estimation of σ_8, without any need to model the cluster mass-temperature relation (as in, e.g., Viana & Liddle 1996, 1999).

2. METHODOLOGY

We consider spatially flat cosmological models, where part of the energy density may be due to a cosmological constant, containing a spectrum of primordial adiabatic density perturbations. This family includes the current standard cosmological model, with a present-day matter density of $\Omega_0 \simeq 0.3$, which provides the best fit to the full compilation of structure formation data (e.g., Durrer & Novosyadlyj 2001; Wang, Tegmark, & Zaldarriaga 2001). We take the present-day shape of the matter power spectrum to be well approximated by that of a cold dark matter model with scale-invariant primordial density perturbations and shape parameter Γ in the range [0.08, 0.28]; this interval is the average of the best-fit values coming from the preliminary analysis of the Two-Degree Field (2dF; Percival et al. 2001) and SDSS (Dodelson et al. 2001; Szalay et al. 2001) data, taking into account both statistical and systematic uncertainties. We assume that Γ has an equal probability of taking any value within the interval given. Note, however, that ultimately the local cluster number density depends significantly on only σ_8 and Ω_0.

The expected halo mass function for each set of cosmological parameters is estimated via the fitting function of Jenkins et al. (2001), obtained by analyzing data assembled from various large *N*-body simulations. Following White (2001), we consider the halo mass to be that given by the virial relation. The high-mass

end of the halo mass function is better estimated using the Jenkins et al. (2001) result rather than the usual Press-Schechter *Ansatz* (Press & Schechter 1974). The latter leads to a smaller number of high-mass halos at fixed σ_8, thus requiring systematically higher values of σ_8, by about 8%, in order for the local cluster abundance to be reproduced. We cautiously model the uncertainty in the normalization of the mass function by means of a Gaussian distribution with a 10% dispersion around the mean (see Fig. 8 of Jenkins et al. 2001).

The local cluster number density was obtained by integrating the REFLEX X-ray luminosity function in the [0.1, 2.4] keV band upward from the mean luminosity of the 42 clusters in the SDSS/RASS sample, which is $(0.17 \pm 0.03) \times 10^{44} \, h^{-2}$ ergs s^{-1}. Their average redshift is 0.1, which roughly coincides with the mean redshift of the REFLEX clusters with similar or higher luminosity. For the 42 SDSS/RASS clusters, Sheldon et al. (2001) obtained, via statistical weak lensing analysis, a mean projected mass within r_{500} of $(0.9 \pm 0.2) \times 10^{14} \, h^{-1} \, M_\odot$, where r_{500} is the radius within which the cluster mean density falls to 500 times the critical density at the redshift of observation. Following Sheldon et al. (2001), we assume the cluster density profile to behave like that of a singular isothermal sphere, i.e., $\rho(r) \propto r^{-2}$. We can now calculate the mean cluster mass within the three-dimensional radius r_{500} and then convert this to a mean virial mass. Taking this mass as the lower limit in the integration of the Jenkins et al. (2001) mass function will then yield the expected local cluster number density for clusters more luminous than the mean of the SDSS/RASS sample, as a function of σ_8 and Ω_0. By comparison with the REFLEX estimate, best-fit values for σ_8 as a function of Ω_0 can then be obtained.

3. RESULTS

Table 1 shows the 95% confidence interval on σ_8, obtained using the REFLEX X-ray luminosity function and the relation between cluster mass and X-ray luminosity for the full SDSS/RASS sample. This interval was determined via Monte Carlo simulations, which incorporated all the uncertainties previously mentioned that affect the present estimation of σ_8. We find that the most probable value for σ_8 can be accurately represented by the fitting function

$$\sigma_8 = 0.38\Omega_0^{-0.48+0.27\Omega_0}, \qquad (1)$$

with a 95% uncertainty around 15%.

This result is significantly lower than—and barely compatible with—most determinations of σ_8 based on the local cluster X-ray temperature function (compare, e.g., Eke et al. 1996; Henry 1997, 2000; Viana & Liddle 1999; Blanchard et al. 2000; Pierpaoli et al. 2001), with the exception of Seljak (2001). His analysis differs from the others in that he used the relation between cluster temperature and mass derived by Finoguenov, Reiprich, & Böhringer (2001) from X-ray data rather than one obtained from hydrodynamical *N*-body simulations. The earlier work of Markevitch (1998) had already hinted at lower values for σ_8, at least in the case of $\Omega_0 \simeq 0.3$, if actual X-ray data were used to relate cluster temperature to mass. Similar results have been reached by Borgani et al. (2001), based on *ROSAT* Deep Cluster Survey data and the observed cluster X-ray temperature–to–luminosity relation, and by Reiprich & Böhringer (2001), by means of an empirical cluster mass function derived using X-ray data from a large cluster sample.

Other methods of measuring σ_8 lead to conflicting results. While high-redshift Lyα forest analyses (Croft et al. 1999,

TABLE 1
MATTER POWER SPECTRUM NORMALIZATION

Ω_0	σ_8
1.0	0.38 ± 0.05
0.9	0.39 ± 0.06
0.8	0.41 ± 0.06
0.7	0.43 ± 0.06
0.6	0.46 ± 0.07
0.5	0.49 ± 0.07
0.4	0.54 ± 0.08
0.3	0.61 ± 0.10
0.2	0.74 ± 0.14
0.1	$1.09^{+0.33}_{-0.23}$

NOTE.—Spectrum normalization using the REFLEX luminosity function and the full SDSS/RASS sample, shown with 95% confidence error bars.

2002; McDonald et al. 2000) support our findings, estimates based on cosmic shear data (Hökstra, Yee, & Gladders 2002; Maoli et al. 2001; Van Waerbeke et al. 2001) tend to favor higher values for σ_8 than those obtained here. Also, the 2dF galaxy survey, when combined with measurements of the amplitude of temperature anisotropies in the cosmic microwave background radiation (Efstathiou et al. 2002; Lahav et al. 2001), seems to require a value for σ_8 close to what we have found.

In order to test whether the low values obtained for σ_8 could be due to hidden systematic errors in the weak lensing method used for cluster mass estimation, we repeated the calculation of σ_8 for the two SDSS/RASS subsamples discussed within Sheldon et al. (2001):

1. The 27 clusters with the lowest X-ray luminosities, on average $(0.09 \pm 0.02) \times 10^{44} \, h^{-2}$ ergs s^{-1}. They have a mean redshift of 0.09 and a mean projected mass within r_{500} of $M_{500}(1) = (0.7 \pm 0.2) \times 10^{14} \, h^{-1} \, M_\odot$.

2. The 15 clusters with the highest X-ray luminosities, on average $(0.51 \pm 0.04) \times 10^{44} \, h^{-2}$ ergs s^{-1}. They have a mean redshift of 0.17 and a mean projected mass within r_{500} of $M_{500}(2) = 2.7^{+0.9}_{-1.1} \times 10^{14} \, h^{-1} \, M_\odot$.

Given that most of the REFLEX clusters with similar luminosities to those in the SDSS/RASS sample have a redshift between 0.05 and 0.2 (Böhringer et al. 2001), with the higher luminosity clusters typically being at higher redshifts, we assume that the REFLEX luminosity function provides a good representation of the underlying cluster luminosity function over this redshift interval. This is supported by an analysis of the Brightest Cluster Survey, which shows that there is no strong evidence for evolution in the cluster luminosity function out to at least $z = 0.2$ (Ebeling et al. 1997).

Surprisingly, the most probable values for σ_8 according to each of these two subsamples are rather different. Subsample 1 yields $\sigma_8 = 0.37\Omega_0^{-0.52+0.32\Omega_0}$, almost indistinguishable from the result obtained from the full SDSS/RASS sample, while subsample 2 gives $\sigma_8 = 0.50\Omega_0^{-0.47+0.24\Omega_0}$, which is substantially higher. This latter result is much more in line with standard σ_8 estimates from the local cluster X-ray temperature function.

4. DISCUSSION

In this section we discuss our results and present several tests to assess their robustness. First, to determine whether our results indicate an internal inconsistency in the weak lensing analysis of Sheldon et al. (2001), we performed Monte Carlo simulations where we used the data from subsample 1 to compute the inferred mean projected masses within r_{500} for the clusters in subsample 2 and vice versa for various values of

Ω_0. We included all the uncertainties previously mentioned in the simulations. We found that provided $\Omega_0 > 0.3$, subsample 1 implies a value for $M_{500}(2)$ at least as large as that deduced by Sheldon et al. (2001) less than 5% of the time, while subsample 2 implies a value for $M_{500}(1)$ as small as that deduced by Sheldon et al. (2001) less than 10% of the time. For values of Ω_0 between 0.1 and 0.3, the discrepancy decreases with Ω_0, but not significantly. We therefore conclude that within the context of the cosmological models we discuss, the mean projected masses for the two SDSS/RASS cluster subsamples presented in Sheldon et al. (2001) are only barely compatible within the uncertainties associated with the estimation of σ_8.

This inconsistency could result from the assumption that the cluster mass profile is that of a singular isothermal sphere (SIS), which was motivated by the fact that within the radius for which there were weak lensing data, the shear profile was close to that of a projected SIS. Although observationally the issue is still unresolved (e.g., Irwin, Bregman, & Evrard 1999; Irwin & Bregman 2000; White 2000; De Grandi & Molendi 2002; Komatsu & Seljak 2001), it has become clear that N-body simulations produce clusters that on average have outer mass profiles up to the cluster virial radius that behave more like $\rho(r) \propto r^{-2.5}$ (Navarro, Frenk, & White 1995, 1996, 1997; Thomas et al. 1998, 2001; Tittley & Couchman 2001). Consequently, we investigated the effect on the virial mass–to–X-ray luminosity relation of assuming an outer cluster mass profile parameterized by $\rho(r) \propto r^{-\beta}$. We varied β between 2 (SIS case) and 3, and as before, we took the mean projected masses within r_{500} to be those given by Sheldon et al. (2001). This translates to fixing the inner projected cluster masses to be $M_{500}(1)$ within 0.39 h^{-1} Mpc for subsample 1, $M_{500}(2)$ within 0.57 h^{-1} Mpc for subsample 2, and $0.9 \pm 0.2 \times 10^{14} M_\odot$ within 0.41 h^{-1} Mpc for the full SDSS/RASS sample (Sheldon et al. 2001). As expected, we find that as β increases, the cluster virial mass decreases, hence lowering σ_8. This change is greater for smaller Ω_0. Consequently, we find that the value for σ_8 derived using the Sheldon et al. (2001) and REFLEX data is barely affected by assuming different outer mass profiles if Ω_0 is close to 1, whereas for low values of Ω_0, assuming an outer mass profile different from the true one may introduce a significant systematic error in the calculation of σ_8. For example, for $\beta = 3$ we obtain $\sigma_8 = 0.37\Omega_0^{-0.41+0.24\Omega_0}$ as the most probable value that results from the weak lensing analysis for the full SDSS/RASS sample. However, it turns out that changing the outer cluster mass density profile does not significantly mitigate the discrepancy between the values obtained for σ_8 using the two SDSS/RASS subsamples, even for low values of Ω_0.

The discrepancy between the σ_8 results obtained for the two Sheldon et al. (2001) subsamples could be alleviated if the mean projected mass of the high-luminosity sample is overestimated or that of the low-luminosity sample is underestimated. The first hypothesis is much more probable and could be due to a contribution to the mean projected mass by filamentary material infalling into the clusters along the line of sight (Cen 1997; Metzler et al. 1999; Reblinsky & Bartelmann 1999; Metzler, White, & Loken 2001). Alternatively, the mean X-ray luminosity of the high-luminosity sample may have been underestimated, or that of the low-luminosity sample overestimated. The latter could be caused by active galactic nucleus contamination, but the initial study of C. J. Miller et al. (2002, in preparation) indicates that this is not a serious problem in the case of the SDSS/RASS cluster survey. Furthermore, the observed relationship between X-ray cluster luminosity and measured velocity dispersion (from the SDSS spectroscopic

sample) for both the Sheldon et al. (2001) and the C. J. Miller et al. (2002, in preparation) samples are in excellent agreement with the L_X-σ_v relation of Mahdavi & Geller (2001).

Reiprich & Böhringer (2001) used *ROSAT* and *ASCA* X-ray data on 106 clusters to obtain the relation between X-ray luminosity in the [0.1, 2.4] keV band and cluster mass in the form of M_{500}, with the cluster masses estimated assuming hydrostatic equilibrium (Finoguenov et al. 2001; Reiprich & Böhringer 2001). They found $L_X = 10^{-18.59 \pm 1.23} \times M_{500}^{1.575 \pm 0.084}$, where L_X is in units of 10^{40} ergs s^{-1} and M_{500} in units of solar mass (assuming $h = 0.5$). Substituting the mean luminosities for the SDSS/RASS full sample and two subsamples into this relation, one finds that the Sheldon et al. (2001) estimates for M_{500} are well within the (extremely wide) range of possible values. Conversely, the relation between L_X and M_{500} can be estimated by combining the Sheldon et al. (2001) results with the shape of the cluster mass function (assumed well described by the results of Jenkins et al. 2001) and the data on the cluster luminosity function from the REFLEX survey (Böhringer et al. 2001, 2002). Assuming the L_X-M_{500} relation to be a power law, we found that the normalization is essentially defined by the Sheldon et al. (2001) data, as expected, while the exponent is mainly governed by the relative shape of the mass and luminosity (cumulative) functions. Taking into account all the uncertainties involved in the normalization of the Jenkins et al. (2001) mass function by means of the Sheldon et al. (2001) data for the full SDSS/RASS sample and those associated with the REFLEX luminosity function, we obtained through Monte Carlo simulations a 95% confidence interval of [1.6, 3.7] for the exponent of the L_X-M_{500} relation. The allowed interval does not change significantly if the data for either of the two SDSS/RASS subsamples are used instead to normalize the mass function. The low-luminosity sample yields [1.8, 3.2], while from the high-luminosity sample we get [1.5, 3.1]. In any case, surprisingly, the preferred value is close to 2.2, substantially higher than the 1.58 ± 0.08 at 1 σ found by Reiprich & Böhringer (2001). This analysis was performed for a flat universe with $\Omega_0 = 0.3$, although very similar results were found for $\Omega_0 = 1$. In order to confirm that the exponent of the L_X-M_{500} relation is only weakly determined by the normalization of the mass function, and thus by the Sheldon et al. (2001) data, we varied σ_8 between 0.5 and 1.2 (for $\Omega_0 = 0.3$) and found that the preferred value for the exponent changes from 2.4 to 1.7. Therefore, assuming the Jenkins et al. (2001) mass function provides an accurate description of the cluster mass function, the discrepancy just found on the exponent of the L_X-M_{500} relation means that such a relation as obtained in Reiprich & Böhringer (2001) is at best only marginally consistent with the Sheldon et al. (2001) data taken together with the REFLEX luminosity function. And only if σ_8 is at the higher end of recent estimates (see, e.g., Viana & Liddle 1999) can the Reiprich & Böhringer (2001) L_X-M_{500} relation be made consistent with the REFLEX luminosity function, within the context of the cosmological models discussed in this Letter.

In calculating σ_8 we assumed that on average a galaxy cluster with the mean X-ray luminosity of the SDSS/RASS full sample has M_{500} equal to the value estimated in Sheldon et al. (2001) for such a sample. This assumption is prone to several biases, one being that assuming there is some dispersion in the associated luminosity, the clusters of a given mass that preferentially end up in a sample selected in the manner of the SDSS/RASS are the most luminous ones. This bias leads to an underestimation of the correct mass corresponding to a given luminosity and consequently to an underestimation of σ_8, although it is difficult to say by how much. The same effect

takes place owing to another, more subtle, type of bias, arising from the fact that the L_X-M_{500} relation is not linear. As a result, for a given sample the mean M_{500} is not proportional to the mean L_X. Given that $M_{500} \propto L_X^n$ with $n < 1$, assuming that a cluster with the mean luminosity has a mass M_{500} equal to the sample mean underestimates M_{500} for such a cluster (because actually the mean M_{500} is proportional to the mean of L_X^n). We have found that for the luminosity dispersion of the clusters in the SDSS/RASS full sample, the most probable value of M_{500} for a cluster with the mean L_X may be underestimated by around 20%. This percentage is robust to changes in the assumed value for the exponent n (between 0.3 and 0.7) and to the possibility of dispersion in the L_X-M_{500} relation. This bias leads to a possible underestimation of σ_8 close to 10%, almost independent of Ω_0. However, given that the mean M_{500} for the SDSS/RASS sample is in fact not a mean of several independently calculated M_{500} but rather the result of a mean shear profile and that the mean L_X is weighted by each cluster contribution to that profile, the above considerations may not be directly applicable to the case at hand. Note that because the dispersion in luminosities is smaller for either of the two SDSS/RASS subsamples as compared to the full sample, the underestimation in σ_8 is smaller when it is estimated from the subsamples, being closer to 5%. Unfortunately, none of these biases seem to be able to significantly narrow the discrepancy between the σ_8 values derived using each SDSS/RASS subsample.

5. CONCLUSIONS

We have applied a new approach for constraining the normalization of the matter power spectrum, using the REFLEX X-ray luminosity function and the relation between cluster X-ray luminosity and mass obtained through weak lensing data from a preliminary small sample of SDSS/RASS clusters. We obtained σ_8 values significantly lower than other estimates based on cluster abundance data, with the exception of the recent results by Borgani et al. (2001), Reiprich & Böhringer (2001), and Seljak (2001). However, systematic biases may affect our analysis, given that barely consistent results are obtained when using subsets of the weak lensing data. This may be due to the small sample of clusters used or an artifact of the techniques used in Sheldon et al. (2001) for co-adding clusters to produce an ensemble averaged weak lensing signal. In the process, we found that comparing the REFLEX luminosity function and the Jenkins et al. (2001) mass function implies that the relation between X-ray luminosity and cluster mass may be significantly steeper than previously thought.

The SDSS/RASS data set we have used will be dwarfed by the final SDSS/RASS catalog (see Nichol et al. 2001), and surveys using the *XMM-Newton* satellite should supply high-quality information on cluster luminosities (e.g., Romer et al. 2001). The prospect of considerably improving the constraint on σ_8 using this approach in the future is therefore great.

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