

\[ \Omega_m \text{ FROM THE TEMPERATURE-REDSHIFT DISTRIBUTION OF EMSS CLUSTERS OF GALAXIES} \]

Megan Donahue and G. Mark Voit

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; donahue@stsci.edu, voit@stsci.edu

Received 1999 June 10; accepted 1999 July 22; published 1999 September 2

ABSTRACT

We constrain $\Omega_m$ through a maximum likelihood analysis of temperatures and redshifts of the high-redshift clusters from the Extended Medium-Sensitivity Survey (EMSS). We simultaneously fit the low-redshift Markevitch sample (an all-sky sample from ROSAT with $z = 0.04-0.09$), a moderate redshift EMSS sample from Henry (nine clusters with $z = 0.3-0.4$), and a more distant EMSS sample (five clusters with $z = 0.5-0.83$ from Donahue et al.) finding best-fit values of $\Omega_m = 0.45 \pm 0.1$ for an open universe and $\Omega_m = 0.27 \pm 0.1$ for a flat universe. We individually analyze the effects of our governing assumptions, including the evolution and dispersion of the cluster luminosity-temperature relation, the evolution and dispersion of the cluster mass-temperature relation, the choice of low-redshift cluster sample, and the accuracy of the standard Press-Schechter formalism. We examine whether the existence of the massive distant cluster MS 1054-0321 skews our results, and we find its effect to be small. From our maximum likelihood analysis we conclude that our results are not very sensitive to our assumptions, and bootstrap analysis shows that our results are not sensitive to the current temperature measurement uncertainties. The systematic uncertainties are $\sim \pm 0.1$, and $\Omega_m = 1$ universes are ruled out at greater than 99.7% ($3 \sigma$) confidence.

Subject heading: cosmology: observations — dark matter — galaxies: clusters: general — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

Massive distant clusters of galaxies can be used to constrain models of cosmological structure formation (see, e.g., Peebles, Daly, & Juszkiewicz 1989; Arnaud et al. 1992; Oukbir & Blanchard 1992; Eke, Cole, & Frenk 1996; Viana & Liddle 1996; Bahcall, Fan, & Cen 1997a, 1997b; Donahue et al. 1998; Borgani et al. 1999). The mass function of clusters reflects the sizes and numbers of the original perturbations, and the evolution of the mass function depends sensitively on $\Omega_m$, the mean density of matter. In a critical universe with $\Omega_m = 1$, perturbation growth continues forever, while in a low-density universe ($\Omega_m < 1$), growth significantly decelerates once $z \sim \Omega_m^{-1} - 1$.

The Extended Medium-Sensitivity Survey (EMSS; Gioia et al. 1990; Henry et al. 1992) has proved cosmologically interesting because it contains several massive high-redshift clusters (Henry 1997; Eke et al. 1998; Donahue et al. 1999, hereafter D99). We report here our analysis of a complete, high-redshift sample of clusters of galaxies culled from the EMSS, including the most distant EMSS clusters (D99). We use maximum likelihood analysis to compare the unbinned temperature-redshift data with analytical predictions of cluster evolution from Press-Schechter models, normalized to two different low-$z$ cluster samples (Henry & Arnaud 1991; Markevitch 1998).

Section 2 briefly describes the model for cluster evolution, § 3 describes the cluster samples, and § 4 describes the implementation of the maximum likelihood technique. Section 5 discusses our results and their sensitivity to various assumptions, and § 6 outlines the results of a bootstrap resampling of our cluster catalogs. Section 7 summarizes our findings.

2. THE MODEL

The Press-Schechter formula (Press & Schechter 1974), as extended by Lacey & Cole (1993), adequately predicts the evolution of the cluster mass function ($dn/dM$) in numerical simulations (see, e.g., Eke et al. 1996, hereafter ECF; Borgani et al. 1999; Bryan & Norman 1998). To obtain predicted cluster temperature functions ($dn/dT$) from this mass function we use a mass-temperature ($M$-$T$) relation appropriate for all values of $\Omega_m$ (Voit & Donahue 1998, 2000). At $z = 0$ we normalize this relation to the simulations of Evrard, Metzler, & Navarro (1996). We will show in § 5 that the $M$-$T$ relation of ECF yields similar results.

In this description of cluster evolution, the three main variables are the mean density of the universe $\Omega_m$, the slope $n$ of the initial density perturbation spectrum near the cluster scale, and $\nu_s$, a parameter that reflects the abundance of virialized perturbations on a given mass scale at a particular moment in time. For a given $\Omega_m$, $n$, and $\nu_s$, the number of clusters per unit steradian expected in a given redshift range is $(dn/dM)(dM/dT)(dV/dz)f(T, z)$ integrated over the relevant redshift and temperature ranges, where $f(T, z)$ is a window function defined by the flux and redshift limits of a given sample and the luminosity-temperature relation (see § 4).

3. CLUSTER SAMPLES

Our fitting procedure compares three cluster samples each covering distinct redshift ranges to the model (§ 2). The EMSS provided two samples of distant clusters. Because the EMSS has multiple flux limits (Henry et al. 1992), it is equivalent to multiple surveys each with different flux limits and sky coverages. To compute the volumes associated with the EMSS samples, we correct the predicted flux of a cluster to that measured within a 2.4' × 2.4' detection cell (Henry et al. 1992). The $z = 0.5-0.9$ EMSS sample, described in D99, consists of five EMSS clusters at $z = 0.5-0.9$ (Gioia et al. 1990; Henry et al. 1992). These are all of the EMSS clusters with 0.5-3.5 keV fluxes $> \phi = 1.33 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. (MS 2053 may also belong in this sample, but at a flux limit below what is listed in Henry et al. 1992.) The $z = 0.3-0.4$ sample is described in Henry (1997). D99 modified that sample slightly by revising the redshift of one cluster upward to 0.54 (MS 1241), leaving nine clusters in the Henry sample. The Henry sample
has already been used to constrain $\Omega_m$ by Eke et al. (1998) and Henry (1997). This Letter extends the previous analysis from $z = 0.4$ to $z = 0.8$, at which the cluster evolution is expected to be much more dramatic.

To establish a baseline for assessing cluster evolution, we used two different low-$z$ samples: the Markevitch sample and the HEAO sample. The Markevitch sample of clusters from the ROSAT All Sky Survey with $z = 0.04-0.09$ (Markevitch 1998), covers a sky area of $8.23 \text{ sr}$ to a $0.2-2.5 \text{ keV}$ flux limit of $2.0 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2}$. The HEAO cluster sample is also an all-sky sample (Henry & Arnaud 1991), with a $2-10 \text{ keV}$ flux limit of $3.0 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2}$. To compute the volumes available to these samples we assume that the detection techniques in both cases were sensitive to the total extended flux. We explore the consequences of our choice of low-redshift sample in § 5.

4. METHODS AND ASSUMPTIONS

To assess how well cosmological models fit the cluster temperature data, we adopt the maximum likelihood technique described by Marshall et al. (1983). Specifically, we minimize the maximum likelihood function:

$$ S = -2 \sum_i \left[ \ln \left( \frac{dn}{dT}(z_i, T_i) \right) + \ln \left( \frac{dV}{dz}(z_i) \right) \right] + 2 \sum_i \int_0^\infty T \int_{z_{\min, i}}^{z_{\max, i}(T)} \frac{dn}{dT} \frac{dV}{dz} \Omega(T, \Delta) dz, $$

where $z_i$ and $T_i$ are the redshift and temperature of cluster $i$, $z_{\min, i}$ is the minimum redshift of sample $k$, and $z_{\max, i}(T)$ is the maximum redshift at which a cluster of temperature $T$ can be seen in sample $k$. $V$ is the comoving volume per unit solid angle, and $\Omega$ is the solid angle corresponding to sample $k$. In practice, the temperature integral is calculated between 3 and $15 \text{ keV}$. Only clusters with temperature greater than $3 \text{ keV}$ are included in the analysis. Intervals around the minimum $S$ are distributed like $\chi^2$ so differences in $S$ are similar to the familiar $\Delta \chi^2$.

The $z_{\max, i}(T)$ values for our samples depend on the cluster luminosity-temperature ($L-T$) relation. Low-redshift clusters of galaxies have a fairly well-defined $L-T$ relation (see, e.g., David et al. 1993; Markevitch 1998) that high-redshift clusters of galaxies seem to follow (D99; Mushotzky & Scharf 1997). This relationship has a finite dispersion which we handle in two ways. One method is to replace the $L-T$ relation with a line bounding the lower $1 \sigma$ envelope in $L$ (Henry 1997), explicitly compute $z_{\max}(T)$ for each flux limit, and set $F(T, z) = 1$. The second method is to incorporate the dispersion relation into the a window function $F(T, z)$ (Eke et al. 1998). We have done this calculation both ways, and both methods yield very similar results. Since the window function seems to be the most realistic description of the data, we use it for our default analysis and the same dispersion as assumed in Eke et al. (1998). We explore the effect of including evolution in the $L-T$ relation in § 5.

We vary three parameters for our model to span a cube of parameter space: $0.1 < \Omega_m < 1.0$, spectral index $-2.8 < n < -1.0$, and $2.4 < \nu_0 < 3.1$, where $\nu_0 = \nu(5 \text{ keV}, z = 0)$. We compute a multidimensional matrix of $S$ for 25 temperatures between $T = 3$ and $15 \text{ keV}$. The $2-10 \text{ keV} L-T$ relation from David et al. (1993) defines the EMSS and HEAO volumes, appropriately $k$-corrected. The volume of the Markevitch (1998) sample, our default low-$z$ sample, is defined by its own $L-T$ relation.

This procedure yields a best fit of $\Omega_m = 0.45 \pm 0.10$, $n = -2.4 \pm 0.2$, and $\nu_0 = 2.77^{+0.05}_{-0.05}$, corresponding to a $\sigma_0 = 0.64 \pm 0.04$ when $\Lambda = 0$. We achieve a similar degree of correspondence between observed and predicted temperature functions for flat models when $\Omega_m = 0.27 \pm 0.1$, $n = -2.2 \pm 0.2$, $\nu_0 = 2.62^{+0.08}_{-0.08}$, corresponding to a $\sigma_0 = 0.73^{+0.03}_{-0.03}$. Figure 1 plots the observed temperature functions (D99) and the theoretical temperature function corresponding to the best fit to the temperature and redshift data for $\Lambda = 0$. Note that we fit the discrete, unbinned temperature-redshift data, not the binned temperature function. Figure 2 shows that our 3 $\sigma$ confidence limits on $\Omega_m$ exclude $\Omega_m = 1$.

Our value for the best-fit $\Omega_m$ is consistent with that derived...
for the low-redshift subset of our data by Henry (1997), Eke et al. (1998), and Viana & Liddle (1999). However, Viana & Liddle (1999) report less stringent constraints than the previous studies because they were more conservative about uncertainties in the low-z normalization of the temperature function. The maximum likelihood method we use naturally accounts for the uncertainty of the low-z determination of the normalization; we investigate the use of somewhat different low-z samples in the next section. Because our sample extends to higher redshifts, our 3 σ confidence limits are considerably stronger than those found by earlier cluster studies.

5. RESULTS AND DISCUSSION

Our best-fit values for Ω_m are fairly robust. This section briefly describes the sensitivity of Ω_m to the assumptions in our model and procedure. Results for various assumptions are listed in Table 1.

1. Changing the low-redshift sample. If we use the updated HEAO sample (Henry & Arnaud 1991, with best-fit temperature updates provided by J. P. Henry 1999, private communication) instead of the Markevitch sample, we obtain Ω_m,0.3 rather than ~0.45 because of the somewhat lower normalization at z = 0. We also used the Markevitch sample with uncorrected temperatures and a flatter low-z L-T relation (Markevitch 1998), and obtained a somewhat lower best-fit value for Ω_m, Ω_m = 0.4 ± 0.1.

2. Varying the M-T relation. We find our bounds on Ω_m change little when we switch to the ECF M-T relation. Because the best-fit Ω_m turns out to be more than 0.3, the unphysical behavior of the ECF M-T relation at low Ω and low z is not a factor. (See Voit & Donahue 2000 for more details.)

3. Dispersion in the M-T relation. Our default assumption was that the M-T relation has a finite dispersion of 7% (Evrard 1997). Neglecting the dispersion results in a negligible difference in Ω_m; increasing the dispersion to 20% and using the ECF M-T relation increases Ω_m slightly to 0.50. Dispersion in the M-T relation scatters some of the more numerous low-mass clusters to higher temperatures, making the observed temperature function flatter, and somewhat enhancing the observed numbers of hot clusters relative to cool clusters.

4. Evolution of the L-T relation. If we allow the normalization of the L-T relation to evolve such that L ≈ T^n(1 + z)^k and A = 2, we find no significant differences in Ω_m values. This null result is in contrast to similar exercises in modeling the evolution of the cluster luminosity function (see, e.g., Borgani et al. 1999), where evolution of the L-T relation in the appropriate direction (A = 2) allows models with larger Ω_m (~1) to nearly fit. L-T evolution only modestly affects the sample volume used to predict the distribution of cluster temperatures.

5. Omitting MS 1054–0321. MS 1054–0321, the hottest (kT = 12.3 keV) and most distant (z = 0.83) cluster in our sample (Donahue et al. 1998), may well be anomalous. However, omitting MS 1054–0321 had virtually no effect on the best-fit Ω_m.

6. Missing high-redshift clusters in the EMSS. The EMSS could be incomplete due to the use of a single detect cell aperture, which could bias its cluster selection in favor of high central surface brightness even at high z (Ebeling et al. 1997; Lewis et al. 1999). If the EMSS is missing clusters at higher redshift, the values for Ω_m derived here are upper limits.

7. Deviations from Press-Schechter orthodoxy. Some numerical simulations indicate that massive, high-z clusters might be more common than the standard PS formula predicts (Governato et al. 1999; A. E. Evrard 1999, private communication). We have tested the effects of reducing the standard evolution of p_v by a factor (1 + z)^0.125 (Governato et al. 1999), and find that the best-fit Ω_m rises to 0.5 ± 0.03. Of all the systematic effects, this one has the largest effect on the best-fit Ω_m. Even so, Ω_m = 1 is barely allowed at the 3 σ level.

8. A larger high-redshift sample. We simulated the effect of tripling the size of the EMSS by tripling the assumed sky coverage of the EMSS and replicating the existing T-z data pairs. Tripling the number of known clusters with z = 0.3–0.9 reduces the statistical uncertainty of Ω_m by a factor of ~2. Because the uncertainty in the current estimate is now equal parts systematic and statistical, theoretical refinements will be needed if we wish to take full advantage of larger surveys.

6. BOOTSTRAP CATALOGS AND EXPERIMENTAL UNCERTAINTIES

In order to investigate the effects of measurement uncertainties within our cluster T-z catalogs, we generated bootstrap catalogs with resampled temperatures. For the EMSS clusters, we used the mean temperatures from Gaussian fits to temperature probability distributions derived from the X-ray data (D99, Table 4). Ten thousand boot-strap catalogs were generated for each of the three original samples, Markevitch (1998), Henry (1997), and D99. The number of clusters in each catalog was predetermined from a Poisson distribution based on the number of clusters in the original catalog. Each set of data was then fitted to obtain a best-fit Ω_m, normalization, and slope, using all of the standard assumptions. Out of 10,000 catalog combinations, we obtained a best fit +50% for only three. These three catalog combinations were the ones for which the

| Assumption                        | Ω   | r_v | a_q | n   |
|-----------------------------------|-----|-----|-----|-----|
| Baseline Model                    | 0.45| ± 0.1| 2.8 ± 0.1| 0.64 ± 0.04| -2.3 ± 0.2|
| Open, HEAO sub. for Markevitch    | 0.3 ± 0.08| 2.9 ± 0.1| 0.66 ± 0.05| -2.0 ± 0.2|
| Uncorrected Markevitch            | 0.4 ± 0.1| 2.8 ± 0.15| 0.65 ± 0.05| -2.2 ± 0.06|
| Flat, A = 0                       | 0.27 ± 0.1| 2.62 ± 0.1| 0.73 ± 0.05| -2.2 ± 0.2|
| No MS 1054                        | 0.5 ± 0.1| 2.8 ± 0.04| 0.62 ± 0.03| -2.3 ± 0.2|
| ECF M-T Relation                  | 0.45 ± 0.1| 2.8 ± 0.1| 0.64 ± 0.04| -2.3 ± 0.2|
| L-T evolution A = 2               | 0.45 ± 0.1| 2.8 ± 0.1| 0.62 ± 0.04| -2.3 ± 0.2|
| No M-T dispersion                 | 0.45 ± 0.1| 2.8 ± 0.1| 0.64 ± 0.04| -2.3 ± 0.2|
| 20% M-T dispersion + ECF MT      | 0.5 ± 0.1| 2.8 ± 0.04| 0.64 ± 0.04| -2.3 ± 0.2|
| Modified Press-Schechter          | 0.5 ± 0.1| 2.7 ± 0.03| 0.63 ± 0.03| -2.5 ± 0.15|

TABLE 1

Results and Effects of Governing Assumptions

[Table with data provided in the text]
low-redshift catalog had a high number of clusters, while the high-redshift cluster catalogs were nearly empty. We got very similar results when we repeated bootstrap resampling of the three catalogs while assuming temperature measurement uncertainties for the EMSS clusters that were half the original uncertainty. This similarity suggests that temperature measurement errors do not dominate the uncertainty in this method of estimating $\Omega_m$.  

7. SUMMARY

We have used a maximum likelihood Press-Schechter analysis of the temperatures and redshifts of two high-$z$ EMSS samples of clusters of galaxies and two low-$z$ all-sky samples of clusters to constrain $\Omega_m$. We find a simultaneous best fit to the low-$z$ Markevitch (1998) sample, a moderate-$z$ EMSS sample from Henry (1997), and a high-$z$ EMSS sample (D99) of $\Omega_m = 0.45 \pm 0.1$ for an open universe and $\Omega_m = 0.27 \pm 0.1$ for a flat universe, quoting statistical uncertainties only. Our results are not very sensitive to the assumptions within our cluster evolution model, with systematic uncertainties $\sim \pm 0.1$. Universes with $\Omega_m = 1$ are ruled out at greater than 99.7% (3 $\sigma$) confidence in the scenarios described here.

We acknowledge the NASA grants NAG5-3257, NAG5-6236, NAG5-3208, and NAG5-2570 for partial support of this work. We benefited greatly from exchanges with J. Patrick Henry in the development of the code and by his generous release of revised temperature data for the low-$z$ Henry & Arnaud (1991) sample.

REFERENCES

Arnaud, M., et al. 1992, ApJ, 390, 345
Bahcall, N. A., Fan, X., & Cen, R. 1997a, ApJ, 485, L53
———. 1997b, ApJ, 490, L123
Borgani, S., Rosati, P., Tozzi, P., & Norman, C. 1999, ApJ, 517, 40
Bryan, G. L., & Norman, M. L. 1998, ApJ, 495, 80
David, L. P., Slyz, A., Jones, C., Forman, W., Vrtilek, S. D., & Arnaud, K. A. 1993, ApJ, 412, 479
Donahue, M., Voit, G. M., Gioia, I., Lupino, G., Hughes, J. P., & Stocke, J. T. 1998, ApJ, 502, 550
Donahue, M., et al. 1999, ApJ, in press (D99)
Ebeling, H., et al. 1999, ApJ, submitted (astro-ph/9905321)
Eke, V. R., Cole, S., & Frenk, C. S. 1996, MNRAS, 282, 263 (ECF)
Eke, V. R., Cole, S., Frenk, C. S., & Henry, J. P. 1998, MNRAS, 298, 1145
Evrard, A. E. 1997, MNRAS, 292, 289
Evrard, A. E., Metzler, C. A., & Navarro, J. F. 1996, ApJ, 469, 494
Gioia, I. M., Maccacaro, T., Schild, R. E., Wolter, A., & Stocke, J. T. 1990, ApJS, 72, 567
Governato, F., Babul, A., Quinn, T., Tozzi, P., Baugh, C. M., Katz, N., & Lake, G. 1999, MNRAS, submitted (astro-ph/9810189)

Henry, J. P. 1997, ApJ, 489, L1
Henry, J. P., & Arnaud, K. A. 1991, ApJ, 372, 410
Henry, J. P., Gioia, I. M., Maccacaro, T., Morris, S. L., & Stocke, J. T. 1992, ApJ, 386, 408
Lacey, C., & Cole, S. 1993, MNRAS, 262, 627
Lewis, A., Stocke, J. T., Ellingson, E., & Gaidos, E. 1999, BAAS, 194.8904
Markevitch, M. 1998, ApJ, 504, 27
Marshall, H. L., Avni, Y., Tananbaum, H., & Zamorani, G. 1983, ApJ, 269, 35
Mushotzky, R., & Scharf, C. A. 1997, ApJ, 482, L13
Oukbir, J., & Blanchard, A. 1992, A&A, 262, L21
Peebles, P. J. E., Daly, R., & Juszkiewicz, R. 1989, ApJ, 347, 563
Press, W., & Schechter, P. 1974, ApJ, 187, 425
Viana, P. T. P., & Liddle, A. R. 1996, MNRAS, 281, 323
———. 1999, MNRAS, 303, 535
Voit, G. M., & Donahue, M. 1998, ApJ, 500, L111
———. 2000, in preparation