REDSHIFT EVOLUTION OF GALAXY CLUSTER DENSITIES

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ABSTRACT

The number of rich galaxy clusters per unit volume is a strong function of Ω, the cosmological density parameter, and σ8, the linear extrapolation to z = 0 of the density contrast in 8 h−1 Mpc spheres. The Canadian Network for Observational Cosmology (CNOC) cluster redshift survey provides a sample of clusters, the average mass profiles of which are accurately known, which enables a secure association between cluster numbers and the filtered density perturbation spectrum. We select from the CNOC cluster survey those Extended Medium-Sensitivity Survey clusters with bolometric Lx ≥ 10^45 erg s−1 and a velocity dispersion exceeding 800 km s−1 in the redshift ranges 0.18–0.35 and 0.35–0.55. We compare the number density of these subsamples with similar samples at both high and low redshift. Using the Press-Schechter formalism and cold dark matter (CDM) style structure models, the density data are best described with σ8 = 0.75 ± 0.1 and Ω = 0.4 ± 0.2 (90% confidence). The cluster dynamical analysis gives Ω = 0.2 ± 0.1 for which σ8 = 0.95 ± 0.1 (90% confidence). The predicted cluster density evolution in an Ω = 1 CDM model exceeds that observed by more than 1 order of magnitude.

Subject headings: cosmology: large-scale structure of universe—galaxies: clusters

1. INTRODUCTION

The clustering of galaxies grows via gravity from density perturbations that are characterized by their power spectrum, P(k). Various theories predict the shape of P(k), but they do not accurately predict its amplitude. An integral constraint on the normalization is conventionally parameterized as σ8, the fractional mass variance in 8 h−1 Mpc spheres calculated using the linear extrapolation of P(k). Rich galaxy clusters are particularly sensitive probes of σ8. N-body simulations have established that the Press-Schechter formalism (Press & Schechter 1974, hereafter PS) gives a remarkably accurate prediction of the number of clusters per unit cosmological volume as a function of mass. Modeling the low-redshift data with the Press-Schechter formula, and using cold dark matter (CDM) style P(k), leads to a range of possibilities, from Ω = 1 and σ8 ≈ 0.5 to Ω ≈ 0.2 and σ8 ≈ 1 and values that interpolate between the two (Henry & Arnaud 1991, hereafter HA; White, Efstathiou, & Frenk 1993; Viana & Liddle 1996; Bond & Myers 1996; Eke, Cole, & Frenk 1996, hereafter ECF). The Ω dependence can be disentangled from σ8 if data giving n(M) dM are available as a function of redshift (Oukbir & Blanchard 1996).

The Canadian Network for Observational Cosmology (CNOC) cluster sample and observational strategy (Yee, Ellingson, & Carlberg 1996) was specifically designed to produce data useful for a σ8 measurement. The sample’s primary advantage is that the cluster masses are accurately known near the virial radius, which is essential for a reliable estimate of the linear mass scale from which the cluster collapsed. Here we combine our results with similarly selected clusters at higher and lower redshifts in § 3. The data are modeled in § 4 to draw conclusions about the values of σ8 and Ω.

2. PRESS-SCHECHTER PREDICTIONS

The number density of clusters in the mass range M to M + dM is predicted to be

\[ n(M) \, dM = \frac{-3\delta(z)}{(2\pi)^{3/2}\Delta} \frac{d \ln \Delta}{dM} \times \exp \left[ -\frac{\delta(z)^2}{2\Delta^2} \right] dM, \]

where \( \delta(z) = \delta(\Omega)/D(z, \Omega) \) gives the linear overdensity at which a collapsed structure is approximately virialized. The function \( \delta_0 = 0.15(12\pi)^{3/2}/\Omega^{1/2} \) is nearly constant at \( \delta_0 \approx 1.68 \) (Navarro, Frenk, & White 1996). The growth factor, \( D(z, \Omega) \), gives the redshift dependence of the linear amplitude of the density perturbations (Peebles 1993). The quantity \( \Delta(r_{1s}) \) measures the fractional linear mass variance in spheres of radius \( r_{1s} \).

It is calculated using a top-hat filter from a parameterized version of the CDM spectrum (\( \Omega \) fixed at 0.2; Efstathiou, Bond, & White 1992) with its normalization adjusted such that \( \sigma_8 = \Delta(8 h^{-1} \text{Mpc}) \). The “just virialized” radius is near 1.5 h−1 Mpc and has an overdensity of \( \approx 178 \Omega^{-0.6} \) (White et al. 1993). Near 1.5 h−1 Mpc \( M(r) \approx r^2 \), where \( r \approx 0.64 \) for the CNOC data (Carlberg, Yee, & Ellingson 1997). The top-hat filtering scale, \( r_{1s} \), is related to \( M_{1s} \) as \( r_{1s} \approx 8.431(\Omega_{0})^{0.59} \Omega_{0}^{0.5} [M_{1s}/6.97]^{1/2} \times 10^{15} h^{-1} \text{M}_{\odot}/\Omega^{0.5} \) (1 + z) \( \Omega_{0}^{0.5} h^{-1} \text{Mpc} \) (a generalization of White et al. 1993), where \( \Omega(z) \) is the value of \( \Omega \) at redshift \( z \).

We integrate equation (1) from the minimum mass in the sample to infinity to derive \( n(>M_{1s}) \). For comparison with measurements, we average the density predictions over the redshift ranges of interest. These predictions are plotted in Figures 1 and 2 for \( \Omega = 0.2 \) and \( \Omega = 1 \), respectively.

3. CLUSTER DENSITY ESTIMATES

The CNOC sample was drawn from the Extended Medium-Sensitivity Survey (EMSS) cluster survey (Henry et al. 1992), supplemented with a few high-redshift clusters identified later (Luppino & Gioia 1995). We impose the constraints \( f_{X} \approx 4 \times \)

\[ \frac{L_{X}}{10^{45} \text{ergs s}^{-1}} \approx 10^{-3.5} \Omega^{-1/2} (\Omega_{0})^{0.59} \Omega_{0}^{-0.5} \]

for \( \Omega_{0} \approx 0.2 \). The EMSS clusters were found to be consistent with \( \Omega_{0} = 0.2 \) (we refer to this subset of the sample as EMSS2).

\[ n_{\text{EMSS2}}(M) \approx 10^{1.2} \Omega_{0}^{-0.5} \Omega_{0}^{-0.5} \]

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$10^{-13}$ ergs cm$^{-2}$ s$^{-1}$, $L_X(0.3-3.5$ keV) $\geq 4 \times 10^{44}$ ergs s$^{-1}$, redshifts between 0.18 and 0.55, and in the declination range $-15^\circ$ to $+65^\circ$. We have recalculated the $f_X$ and $L_X$ to better allow for the redshift dependence of the flux in the “detect cell.” The main difference is that the cluster MS 0302+16 now falls below our luminosity cut, although this has a negligible affect on the results (see also Nichol et al. 1997).

The $M_{1.5}$ masses for each cluster in the CNOC sample are estimated to be $M_{1.5} b_{M}(1.5$ h$^{-1}$ Mpc $r_v)^r$, where $b_{M}$ is the virial mass bias, $r_v$ is the virial radius calculated as a ringwise potential (Carlberg et al. 1996), and $M_{1.5}$ is the resulting virial mass. For the CNOC clusters $b_{M} \approx 0.85$ on the average (Carlberg et al. 1997); that is, the virial mass is always an overestimate. The masses $M_{1.5}$ are calculated from the $M_{1.5}$ and $r_v$ of the CNOC clusters (Carlberg et al. 1996 as updated slightly by the use of the finalized catalogs).

### 3.1. Correcting for X-Ray Selection

We need to count the number of clusters having $M_{1.5}$ larger than a specified mass within some redshift range. A significant complication is that we have a sample defined by its X-ray properties, but we want to make a measurement based on its distribution of characteristic masses. It is well known that there is a strong $L_X M_{1.5}$ correlation, but with a substantial scatter (see, e.g., Edge & Stewart 1991, hereafter ES). That is, some clusters that are in the $L_X$ limited sample will be below the specified mass limit and vice versa. To correct from an X-ray–selected sample to a mass-selected sample, we proceed as follows. We use the ES study of the X-ray and optical properties of nearby clusters, which appear to be essentially identical to the CNOC sample in the relevant parameters (see

Fig. 3). The ES sample is effectively a mass-selected sample, at least for the rich clusters that are our concern here. All the selected clusters have a bolometric $L_X \approx 10^{45}$ ergs s$^{-1}$. Examining Figure 3, we see that setting the minimum mass equal to that for a cluster with $\sigma_v \approx 800$ km s$^{-1}$ will help maximize the number of clusters in the sample while keeping the corrections...
from the \( L_X \)-selected sample to the \( \sigma_v \)-selected sample relatively small.

There are two different correction factors for \( L_X \)-defined samples, depending on whether or not the parent sample has known velocity dispersions. In the ES sample there are 12 clusters with \( \sigma_v \geq 800 \) km s\(^{-1}\), of which six are also above \( L_X \geq 10^{45} \) ergs s\(^{-1}\). Therefore we estimate that for a sample selected with both the \( L_X \) and \( \sigma_v \) limits, the true density of clusters with \( \sigma_v \geq 800 \) km s\(^{-1}\) is a factor of \( f_{\sigma v} = 12/6 = 2 \pm 1 \) times the density measured. There are eight ES clusters with \( L_X \geq 10^{45} \) ergs s\(^{-1}\) for all velocity dispersions and 12 with \( \sigma_v \geq 800 \) km s\(^{-1}\). Therefore, for a sample selected with only the \( L_X \) limit, we estimate that the number of clusters above \( \sigma_v = 800 \) km s\(^{-1}\) is \( f_{\sigma v} = 12/8 = 1.5 \pm 0.7 \) times the measured density. Although these corrections are not very accurate, they illustrate that the corrections are not large, and their errors are comparable in size to those from the subsamples themselves.

3.2. The CNOC Sample

To convert from EMSS 0.3–3.5 keV luminosities to the bolometric luminosity, we derive a mean bolometric correction of a factor of 2.20 at 6.8 keV and 3.12 at 13.6 keV, with only a small dependence on the H\(^1\) column. We adopt a uniform bolometric correction of a factor of 2.5 for the CNOC clusters (see the high-\( L_X \) sample of Henry, Jiao, & Gioia 1994 for representative EMSS cluster temperatures). Imposing the limit \( \sigma_v \geq 800 \) km s\(^{-1}\) reduces the CNOC sample size from 12 clusters to eight (two of the 16 clusters observed being dropped as being below the X-ray limits, one cluster is not from EMSS, and one has a poorly determined \( \sigma_v \)). Using the \( V_c/V_{\text{max}} \) method (Avni & Bahcall 1980) we then measure the volume density of these clusters, allowing for the EMSS sky area in the CNOC region as a function of flux (see Henry et al. 1992 for more details on this procedure and also for a sample table of EMSS all-sky coverage). The mean densities of these clusters for \( \Omega = 0.2 \) are reported in Table 1. The CNOC sample is split into a low-redshift subsample, \( 0.18 \leq z \leq 0.35 \), which has a smallest \( M_{5/2} \) of \( 4.8 \times 10^{14} \) h\(^{-1}\) M\(_{\odot}\) and a moderate redshift subsample, \( 0.35 \leq z \leq 0.55 \), which is found to have a smallest \( M_{5/2} \) of \( 6.7 \times 10^{14} \) h\(^{-1}\) M\(_{\odot}\). The \( f_{\sigma v} \)-corrected densities are given in Table 1.

3.3. Low-Redshift Samples

At low redshift there are several samples to consider as sources of density estimates. The most straightforward data set is that of HA, who provide an X-ray luminosity function at low redshift, which when integrated from \( L_X = 10^{40} \) ergs s\(^{-1}\) to infinity yields an \( f_{\sigma v} \) volume density of \( \approx 7.5 \times 10^{-7} \) h\(^3\) Mpc\(^{-3}\). The velocity dispersions of these clusters extend below

![Image](image330x481.png)

Fig. 4.—Plot of \( x^2 \) for the all independent samples (solid lines) and excluding the high-redshift EMSS sample (dotted lines). The contours are the 90% and 99% confidence levels. The results of the CNOC analysis, \( \Omega = 0.19 \pm 0.06 \), with its 1 \( \sigma \) range, are indicated.

800 km s\(^{-1}\), but none below 750 km s\(^{-1}\) (Zabludoff, Huchra, & Geller 1990), which we adopt as the minimum velocity dispersion. We scale the cluster masses with velocity dispersion as \( M \propto \sigma_v^3 \) with a reference value of \( 5.7 \times 10^{14} \) h\(^{-1}\) M\(_{\odot}\). We estimate the \( M_{5/2} \) of the HA sample as \( 4.7 \times 10^{14} \) h\(^{-1}\) M\(_{\odot}\).

The ESO Cluster Survey (Mazure et al. 1996) finds a cluster density of \( 2.5 \times 10^{-6} \) h\(^3\) Mpc\(^{-3}\) for \( \sigma_v \geq 800 \) km s\(^{-1}\) at \( z \leq 0.1 \). However, the ESO and CNOC velocity dispersions are not calculated in the same manner. The CNOC velocity dispersions are estimated using an explicit background subtraction. On the average we find that our velocity dispersions are about 7% lower than those calculated from precisely the same dispersions using the iterated bi-weight estimator (Beers, Flynn, & Gebhardt 1990; Carlberg et al. 1997). As we increase the redshift range of the data given to the bi-weight estimator up to 25%, the velocity dispersion rises an average of 13% and then remains reasonably stable. We adjust the ESO velocity dispersions downward by 13%, to arrive a velocity dispersion of 708 km s\(^{-1}\). We derive a mass limit for the ESO \( \approx 800 \) km s\(^{-1}\) sample of \( M_{5/2} = 4.0 \times 10^{14} \) h\(^{-1}\) M\(_{\odot}\). The sample is not X-ray–selected, so it needs no density correction.

An upper limit to the low-redshift density for the Northern Abell sample with velocity dispersions has been derived previously (White et al. 1993). The same sample, when compared with X-ray results, confirms that the median velocity dispersion is somewhat overestimated (ECF) and argues that the velocity dispersion is about 650 km s\(^{-1}\). Because this sample is very similar to the ESO sample, we adopt the same minimum velocity dispersion as we derived above, 708 km s\(^{-1}\), and hence the same minimum mass. This sample requires no density correction.

3.4. A High-Redshift Sample

The EMSS sample contains a fair sample of clusters ranging from redshifts of about 0.14 to redshift 0.83 (Henry et al. 1992;
Luppino & Gioia (1995). The high-redshift sample (Luppino & Gioia 1995) is cautiously assigned the same minimum mass,
\[ M_{1.5} = 4.7 \times 10^{14} \, h^2 \, M_\odot \]
as we used for the HA subsample. Given the richness of these clusters we expect that the clusters actually have higher masses, consequently, this is a conservative assumption. The mean density derived from the four clusters in the redshift range \(0.55 \leq z \leq 0.85\) for \(\Omega = 0.2\) and 1 is given in Table 1 and includes the \(f_5\) correction. Reassuringly, they are similar to the densities derived elsewhere (Luppino & Gioia 1995) using the same clusters, but a different analysis. It is known that at least one of these clusters, MS 1054–03, likely has a mass well over the limit to be included in the sample (Luppino & Kaiser 1997). The minimum mass is uncertain but likely at least that of the moderate \(z\) CNOC sample. In particular, these are very rich clusters that the very strong richness-\(\sigma_r\) relation (Carlberg et al. 1996) indicates to be high-\(\sigma_r\) clusters. We expect \(\sigma_r \approx 900 \, \text{km s}^{-1}\).

4. PARAMETER PROBABILITIES AND CONCLUSIONS

The \(\chi^2\) probability contours of the PS predictions and the observed densities are plotted in Figure 4. The sample variances are calculated as the quadrature sum of the \(N^{1/2}\) of the sample and the errors in the sample correction factors. The observed densities as a function of \(\Omega\) are estimated as a linear interpolation between the values at \(\Omega = 0.2\) and \(\Omega = 1\). The mass errors are known to be about 25\% for a single cluster (Carlberg et al. 1996), which in the mean for the various samples will be reduced to about 8\%–15\%, depending on sample size. This relatively small error is neglected in calculating \(\chi^2\).

The minimum \(\chi^2\) is near \(\Omega \approx 0.4\) and \(\sigma_8 \approx 0.75\), although \(\Omega\) between 0.2 and 0.6 are statistically acceptable within the 90\% confidence interval. For our preferred \(\Omega = 0.2\) we find that \(\sigma_8 = 0.95 \pm 0.05\). A model with \(\Omega = 1\) is excluded at more than 99\% confidence, although this is dependent on the estimated masses of the high-redshift EMSS sample.

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REFERENCES

Avni, Y., & Bahcall, J. N. 1980, ApJ, 235, 694
Beers, T. C., Flynn, K., & Gebhardt, K. 1990, AJ, 100, 32
Bond, J. R., & Myers, S. T. 1996, ApJS, 103, 63
Carlberg, R. G., Yee, H. K. C., & Ellingson, E. 1997, ApJ, 478, 462
Carlberg, R. G., Yee, H. K. C., Ellingson, E., Abraham, R., Gravel, P., Morris, S. M., & Pritchet, C. J. 1996, ApJ, 462, 32
Edge, A. C., & Stewart, G. C. 1991, MNRAS, 252, 428 (ES)
Efstathiou, G., Bond, J. R., & White, S. D. M. 1992, MNRAS, 258, 1P
Eke, V. R., Cole, S., & Frenk, C. S. 1996, preprint, astro-ph/9601088 (ECF)
Henry, J. P., & Arnaud, K. A. 1991, ApJ, 372, 410 (HA)
Henry, J. P., Gioia, I. M., Maccacaro, T., Morris, S. L., Stocke, J. T., & Wolter, A. 1992, ApJ, 386, 408
Henry, J. P., Jiao, L., & Gioia, I. M. 1994, ApJ, 432, 49
Luppino, G. A., & Gioia, I. M. 1995, ApJ, 445, L77
Luppino, G. A., & Kaiser, N. 1997, ApJ, 475, L20
Mazure, A., et al. 1996, A&A, 310, 31
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Nichol, R. C., Holden, B. P., Romer, A. K., Ulmer, M. P., Burke, D. J., & Collins, C. A. 1997, ApJ, in press
Oukbir, J., & Blanchard, A. 1996, A&A, submitted
Peebles, P. J. E. 1993, Principles of Physical Cosmology (Princeton: Princeton Univ. Press)
Press, W. H., & Schechter, P. 1974, ApJ, 187, 425 (PS)
Viana, P. T. P., & Liddle, A. R. 1996, MNRAS, 281, 323
White, S. D. M., Efstathiou, G., & Frenk, C. S. 1993, MNRAS, 262, 1023
Yee, H. K. C., Ellingson, E., & Carlberg, R. G. 1996, ApJS, 102, 269
Zabludoff, A. I., Huchra, J. P., & Geller, M. J. 1990, ApJS, 74, 1