The CNOC1 cluster survey measures $\Omega_M$ via Oort’s method, $\Omega_M \equiv M/L \times j/\rho_c$, where $M/L$ is the field mass-to-light ratio, $j$ is the field luminosity density and $\rho_c$ is the closure density. A wide range of potential systematic effects are explicitly controlled by independently deriving the mean cluster mass profile (finding good agreement with theoretical predictions), the cluster light profile, the redshift evolution of both cluster and field galaxies, the differential evolution between the two, and the field and cluster efficiencies for the conversion of baryons into galaxies.

We conclude that $\Omega_M = 0.19 \pm 0.06$ where the errors are objectively evaluated via resampling methods. The redshift evolution of the numbers of clusters per unit comoving volume over the $0 \leq z \leq 0.6$ range is found to be very slow, as is required for consistency with a low density universe. The evolution of galaxy clustering in the field is compatible with a low density universe, and strongly disfavors models of galaxy evolution that associate low density halos with individual galaxies.

1 The Mean Mass Density of the Universe

In the Friedmann-Robertson-Walker solution for the structure of the universe the geometry and future of the expansion uniquely depend on the mean mass density $\rho_0$, and a non-zero cosmological constant. It is a statement of arithmetic that $\Omega_M \equiv \rho_0/\rho_c = M/L \times j/\rho_c$, where $M/L$ is the average mass-to-light ratio of the universe and $\rho_c/j$ is the closure mass-to-light ratio, with
\(j\) being the luminosity density of the universe. Estimates of the value of \(\Omega_M\) have a long history with a substantial range of cited results\(^4\). Both the “Dicke coincidence” and inflationary cosmology would suggest that \(\Omega_M = 1\). The main thrust of our survey is to clearly discriminate between \(\Omega_M = 1\) and the classical, possibly biased, indicators that \(\Omega_M \approx 0.2\).

Rich galaxy clusters are the largest collapsed regions in the universe and are ideal to make an estimate of the cluster \(M/L\) which can be corrected to the value which should apply to the field as a whole. To use clusters to estimate self-consistently the global \(\Omega_M\) we must, as a minimum, perform four operations.

- Measure the total gravitational mass within some radius.
- Sum the luminosities of the visible galaxies within the same radius.
- Measure the luminosity density in the field of an identically defined galaxy sample.
- Account (and ideally physically understand) the differential luminosity and density evolution between the clusters and the field.

The Canadian Network for Observational Cosmology (CNoC) designed observations to make a conclusive measurement of \(\Omega_M\) using clusters. The clusters are selected from the X-ray surveys, primarily the Einstein Medium Sensitivity Survey\(^1\), which has a well defined flux-volume relation. The spectroscopic sample, roughly one in two on the average, is drawn from a photometric sample which goes nearly 2 magnitudes deeper, thereby allowing an accurate measurement of the selection function. The sample contains 16 clusters spread from redshift 0.18 to 0.55, meaning that evolutionary effects are readily visible, and any mistakes in differential corrections should be more readily detectable. For each cluster, galaxies are sampled all the way from cluster cores to the distant field. This allows testing the accuracy of the virial mass estimator and the understanding of the differential evolution process. We introduce some improvements to the classical estimates of the velocity dispersion and virial radius estimators, which have somewhat better statistical properties. A critical element is to assess the errors in these measurements. The random errors are relatively straightforward and are evaluated using either the statistical jackknife or bootstrap methods\(^5\). These resampling methods are completely objective and follow the entire complex chain of analysis beginning from the input catalogues to the result.

As a result of these measurements and tests we find that \(\Omega_M = 0.19 \pm 0.06\), which is the formal 1\(\sigma\) error. In deriving this result we apply a variety of corrections and tests of the assumptions.

- The clusters have statistically identical \(M/L\) values, once corrected for evolution\(^6\).
• Cluster and field galaxies are evolving at a comparable rate with redshift, approximately one magnitude per unit redshift.
• Cluster galaxies exhibit no excess in their star formation with respect to the field. On the average they are faded between 0.1 and 0.3 magnitudes with respect to luminous field galaxies.
• The virial mass overestimates the true mass of a cluster by about 15%, which can be attributed to the neglect of the surface term in the virial equation.
• There is no significant change of $M/L$ with radius within the cluster.
• The mass field of the clusters is remarkably well described by the NFW profile, both in shape and scale radius.
• The evolution of the number of clusters per unit volume is very slow, in accord with the PS predictions for a low density universe.
• The clusters have statistically identical efficiencies of converting gas into stars, which is identical to the value in the field.

These results rule out $\Omega_M = 1$ in any component with a velocity dispersion less than about 1000 km s$^{-1}$.

2 The Future of Clusters as Cosmological Indicators

The dark matter distribution within clusters is now quite well understood and the differential of field and cluster galaxies is becoming well observed and to some degree understood. With much larger samples it will be possible to more tightly constrain many cosmological quantities. Of particular interest is that $\Omega_\Lambda$ can be measured via the redshift dependence of the $M/L \times j/\rho_c$ indicator, being nearly a 50% change from redshift zero to unity. The main complication is to make sure that differential field-to-cluster evolution is accurately measured and physically well understood at a somewhat better level of precision. Statistically this is not a problem, since the survey will contain sufficient galaxies in both cluster and field to make the measurement. Straightforward simulations show that it is statistically possible to measure $\Omega_\Lambda$ with a sample of 30 or so clusters distributed over the $0 \leq z \leq 1$ range. With a sample of 200 to 300 clusters over this range it will be possible to measure the $\Omega$ parameters to an accuracy of better than 10%, as well as developing an impressive sample of both field and cluster galaxies.

3 Slow Structure evolution for $\Omega_M = 0.2$

A low density universe “freezes out” structure at redshift $z \simeq \Omega_M^{-1}$ with relatively slow growth in clustering after that. This allows a test of both the value of $\Omega_M$ and the understanding of the relation between the clustering of
dark matter and the galaxies that we observe. The measurements of clustering can be conveniently approximated at a level appropriate for existing data by a double power law in pairwise separation (measured in physical or proper lengths) and in $1 + z$.

$$\xi(r|z) = \left(\frac{r}{r_0}\right)^{-\gamma} (1 + z)^{-(3+\epsilon)}.$$  \hspace{1cm} (1)

The $(1+z)^{-3}$ dilution of the correlation function is simply a result of the change of the background density of the universe with redshift. At low redshifts, $\gamma \simeq 1.7 - 1.8$. Very crudely, there are three “interesting” value of $\epsilon$.

- $\epsilon \simeq 0$ for a low density, e.g. $\Omega_M \simeq 0.2$, universe,
- $\epsilon \simeq -1$ for a high density, $\Omega_M = 1$, universe,
- $\epsilon \simeq 1$ for low overdensity, $\langle \rho \rangle \simeq 200\rho_c$, dark halos.

The last possibility is interesting since a number of “semi-analytic” models of galaxy formation identify galaxies with these objects, partly because they can be counted using the Press-Schechter formula. The correlation properties of halos depend on the details, but to a rough approximation the low overdensity halos cluster with a correlation length that is fixed in co-moving co-ordinates.

Figure 1: The evolution of measured correlations of red selected galaxies, R band for LCRS at $z = 0.1$ and the Hawaii K sample at higher redshifts. The lines show the predicted evolution for the full mass field (left) and the $200\rho_0$ (not $200\rho_c$) halos on the right and the $\epsilon = +1.2$ “fixed in co-moving co-ordinates” clustering as the solid straight line.

The predictions for three model universes, $[\Omega_M, \Omega_\Lambda]$ of $[1, 0]$, $[0.2, 0]$ and $[0.2, 0.8]$, are compared to R band selected data from the Las Campanas Redshift Survey and the Hawaii K-band survey in Figure 1. Predictions are
made for both “galaxies-trace-mass” and for “dark halos-trace-mass” galaxy identification schemes. Red selected galaxies are used because they are found to be more reliable tracers of the mass distribution in the cluster survey, as expected on the basis of a reduced sensitivity in the redder pass bands to the history of star formation. However in detail the question of how galaxies trace the mass distribution remains open to investigation and is a major motivating factor in the CNOC2 survey of galaxies in the field. The major conclusion to be drawn from Figure 1 is that low overdensity halos, or any other object which clusters in such a way that its correlations remain roughly constant in co-moving co-ordinates, are in conflict with the available measurements of clustering evolution.

4 The CNOC2 Field Survey

Figure 2: The physical distance in the Dec direction from the field center plotted against redshift in two of the CNOC2 fields. Note the strong large scale clustering. The survey has a greater RA extent at smaller Dec (the patches are roughly “L” shaped) hence the greater density of points at the bottom of the pies.

The CNOC2 field survey is designed to study the dynamics and clustering of faint galaxies and its relation to galaxy properties. The survey is statistically complete to Cousins $R = 21.5$ mag and $B = 22.5$ mag. The survey covers approximately 1.5 square degrees of sky, in 4 patches having approximately an “L” shape with the largest separations being 1.5°, and a central block of 0.5° on a side. The survey is now about 75% complete and contains more than 5000 galaxies with redshifts accurate to about 70 km s$^{-1}$ in the rest frame. In addition there are more than 20,000 galaxies, about 1 mag deeper, with accurate UBgRI photometry, which is essential for measuring the selection
function and understanding galaxy evolution.

Acknowledgments
This research was supported by NSERC and NRC of Canada. We thank the Canadian TAC of CFHT for a generous allocation of telescope time.

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