The $\Omega_M - \Omega_\Lambda$ Constraint from CNOC Clusters

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The CNOC redshift survey of galaxy clusters measures $\Omega_M$ from $\Omega_e(z) = M/L \times j/\rho_c$, which can be applied on a cluster-by-cluster basis. The mass-to-light ratios, $M/L$, are estimated from rich galaxy clusters, corrected to the field population over the $0.18 \leq z \leq 0.55$ range. Since the luminosity density depends on cosmological volumes, the resulting $\Omega_e(z)$ has a strong dependence on cosmology which allows us to place the results in the $\Omega_M - \Omega_\Lambda$ plane. The resulting $\Omega_M$ declines if $\Omega_\Lambda > 0$ and we find that $\Omega_\Lambda < 1.5$.

1 Introduction

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 possible cosmological constant. It is a statement of arithmetic that at redshift zero $\Omega_M \equiv \rho_0/\rho_c = M/L \times j/\rho_c$, 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. 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 $\Omega_M \simeq 0.2$.

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 field luminosity density at the cluster redshift.
- Understand the differential luminosity and density evolution between the clusters and the field.

2 Survey Design

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, 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, which follow the entire complex chain of analysis from catalogue to result. The data are designed to correct from the $M/L$ values of clusters to the field $M/L$.

3 Results

We find that $\Omega_M = 0.19 \pm 0.06$ (in a $\Omega_\Lambda = 0$ cosmology, which is the formal 1σ 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.
- High luminosity cluster and field galaxies are evolving at a comparable rate with redshift, approximately one magnitude per unit redshift.
- Cluster galaxies have no excess star formation with respect to the field.
- Cluster galaxies are 0.1 and 0.3 magnitudes fainter than similar 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 consistent with 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$^{-1}$.
4 $\Omega_\Lambda$ dependence

The luminosity density, $j$, contains the cosmological volume element which has a very strong cosmology dependence. The cosmological dependence of the $\Omega_c(z)$ can be illustrated by expanding the cosmological terms to first order in the redshift, $z$,

$$\Omega_c(z) \simeq \Omega_M[1 + \frac{3}{4}(\Omega_M^i - \Omega_M + 2\Omega_\Lambda)z],$$

where $\Omega_M$ and $\Omega_\Lambda$ are the true values and $\Omega_M^i$, with $\Lambda = 0$ is the cosmological model assumed for the sake of the calculation. If there is a non-zero $\Lambda$ then $\Omega_c(z)$ will vary with redshift. The available data are the CNOC1 cluster $M/L$ values and the 3000 galaxies of the preliminary CNOC2 field sample for $j$. To provide a well defined $\Omega_c(z)$ we limit both the field and cluster galaxy luminosities at $M^{k,e}_r \leq -19.5$ mag, which provides a volume limited sample over the entire redshift range. A crucial advantage is of using high luminosity galaxies alone is that they are known to have a low average star formation rate and evolve slowly with redshift, hence their differential corrections are small, and reasonably well determined. The results are displayed in Figure 1. The fairly narrow redshift range available does not provide a very good limit on $\Omega_\Lambda$, although values $\Omega_\Lambda > 1.5$ are ruled out. The power of this error ellipse is to use it in conjunction with other data, such as the SNIa results which provide complementary constraints on the $\Omega_M - \Omega_\Lambda$ pair.

![Figure 1](image-url)

Figure 1: The CNOC1 cluster $M/L$ values combined with the CNOC2 measurements of $j$ for $M^{k,e}_r \leq -19.5$ mag galaxies, gives an $\Omega_c(z)$ which leads to the plotted $\chi^2$ (68% and 90% confidence) contours.

The limit on the $\Omega_M - \Omega_\Lambda$ pair in Figure 1 has been corrected for known systematic errors which are redshift independent scale errors in luminosity and mass. The high luminosity galaxies in both the cluster and field populations are evolving at a statistically identical rate with redshift, which is close passive evolution. If the cluster galaxies are becoming more like the field with redshift (i.e. the Butcher-Oemler effect, which is partially shared with the field), so that they need less brightening to be corrected to the field, then that would raise the estimated $\Omega_\Lambda$, although the correction is so small that the correction would be $\Delta \Omega_\Lambda \simeq 0.3$ over this redshift interval. The results are completely insensitive to galaxy merging that produces no new stars. The data indicate that there is no excess star formation in cluster galaxies over the observed redshift range, with galaxies fading as they join the cluster. The fact that evolution of the
high luminosity field galaxies is very slow and consistent with pure luminosity evolution (Lin, et al. in preparation) gives us confidence that the results are reasonably well understood. It will be very useful to have data that extends to both higher and lower redshift, which would allow a measurement of $\Omega_\Lambda$ and better constraints on any potential systematic errors.

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