

The Red-Sequence Cluster Surveys

H. K. C. Yee,¹ M. D. Gladders,² D. G. Gilbank,¹ S. Majumdar,³ H. Hoekstra,⁴ E. Ellingson,⁵ and the RCS-2 Collaboration⁶

Abstract. The Red-Sequence Cluster Surveys (RCS-1 and RCS-2) are large optical imaging surveys optimized to create well-characterized catalogs of clusters of galaxies up to a redshift of ~ 1 . We describe our first cosmological analysis, using the self-calibration technique, of a cluster sample of ~ 1000 from the 90 sq. deg RCS-1, using optical richness as a mass proxy. We obtain values for the cosmological parameters Ω_m and σ_8 that are in excellent agreement with the year-three WMAP results. Furthermore, the derived cluster richness-mass relationship is entirely consistent with those measured directly using dynamical mass measurements.

We describe briefly the on-going RCS-2, which is a 1000 sq. deg survey carried out using the one-square-degree MegaCam on the CFHT. This survey, in z' , r and g bands, will produce a cluster sample of several 10^4 clusters up to $z \sim 1$, and will allow us to constrain the dark energy equation of state, w , and provide a large cluster sample for the studies of cluster evolution and lensing.

1. Introduction

Galaxy clusters, the largest mass concentrations in the Universe, have long played significant roles in the study of galaxy evolution and the determination of cosmological parameters. In both cases, the leverage and advantages offered by having a sample with a large redshift grasp are significant. In the case of cluster evolution, at the redshift of ~ 1 we are approaching the formation epoch of clusters, often put at $z \sim 2$ to 5, so that evolutionary effects can be more easily discerned. For the determination of cosmological parameters, a large baseline of redshift allows us to measure the evolution of the mass function, breaking the degeneracy between Ω_m and σ_8 . The measurement of the mass function at $z \sim 1$ of a sufficiently large sample will also provide a chance to constrain w .

The red-sequence method (Gladders & Yee 2000) was developed with the specific aim to create large, robust galaxy cluster samples efficiently out to $z > 1$ using optical data. This technique uses the red-sequence (early-type) galaxies as

¹Dept. of Astronomy & Astrophysics, Univ. of Toronto, Toronto, ON, M5S 3H4, Canada

²Dept. of Astronomy & Astrophysics, Univ. of Chicago, Chicago, IL 60637, USA

³CITA, Univ. of Toronto, Toronto, ON, M5S 3H8, Canada

⁴Dept. of Physics & Astronomy, Univ. of Victoria, Victoria, BC, V8P 5C2, Canada

⁵CASA, Univ. of Colorado, Boulder, CO, 80309, USA

⁶www.rcs2.org

markers for clusters, searching for enhanced galaxy surface densities in successive cuts in the color-magnitude plane, which act to provide a discrimination in the third dimension, mitigating the projection contamination problem inherent in searching for high redshift galaxy clusters. This technique is inexpensive, as it requires photometry from only two filters, and can be used to map large regions of the sky efficiently.

In this paper we describe the application of the first Red-Sequence Cluster Survey (RCS-1) to the determination of Ω_m and σ_8 , and the on-going 1000 square degree RCS-2 survey, with the goal of measuring w . The creation of these large cluster samples to $z \sim 1$ also enables us to carry out many other studies, some of which are presented in these proceedings, including an analysis of the Butcher-Oemler effect using over 1000 clusters (Ellingson et al., these proceedings), and the discovery of a large number of strong gravitational lenses (Gilbank et al., these proceedings).

2. Measuring Cosmological Parameters with RCS-1

The RCS-1 provides for the first time a cluster sample which is large, well-characterized, and covering a sufficiently large redshift range to measure Ω_m and σ_8 directly using cluster abundance. The details are reported in Gladders et al. (2007); we present a brief description of the results here.

The RCS-1 survey contains a total of ~ 90 sq. deg of imaging data obtained using the CFHT-12K camera and the MOSAIC-II camera on the CTIO 4m with coverage in the R_c and z' bands (see Gladders & Yee 2005 for details). Both cameras provide a field of view of $\sim 1/3$ sq. deg. We select a ‘best’ sample using 72 sq. deg based on depth and photometric calibration accuracy. The sample contains 956 clusters in the redshift range of $0.35 < z < 0.95$. We use a somewhat restricted redshift range which provides the most robust red-sequence photo- z and cluster richness estimates. We use the cluster richness parameter B_{gcR} (see Gladders & Yee 2005), computed using the net galaxy count in the red-sequence, as a mass proxy. Cluster richness, or other similar measurements such as cluster light, has been shown to be correlated with mass, T_x , and L_x in a number of investigations (e.g. Yee & Ellingson 2003; Hansen et al. 2005). We link the observable to mass (M_{200}) using a power-law $M_{200} = 10^{A_{Bgc} B_{gcR}^\alpha (1+z)^\gamma}$, where γ allows for possible evolution in the relationship. We use the self-calibration analysis technique suggested by Majumdar & Mohr (2003), in which the parameters of the mass-observable relation are simultaneously fitted with the cosmological parameters.

The cosmological parameters are estimated by fitting the number of clusters at different redshifts ($dN/dz(z)$) to a mass limit $M_{lim}(z)$ to that expected from the Jenkins et al. (2001) mass function, using a Markov-Chain Monte-Carlo (MCMC) method. We effectively fit two cosmological parameters (Ω_m and σ_8) and three cluster parameters (the mass limit as a combination of the A_{Bgc} and α parameters, γ , and the fractional scatter f_{sc} in the mass- B_{gcR} relation). We use WMAP priors for h (0.72 ± 0.08), Ω_b (0.046, fixed), and n (0.99, fixed). The results are shown in Figure 1. We obtain $\Omega_m = 0.31^{+0.11}_{-0.10}$ and $\sigma_8 = 0.67^{+0.18}_{-0.13}$, which are in excellent agreement with those from the year-3 WMAP results Spergel et al. (2007).

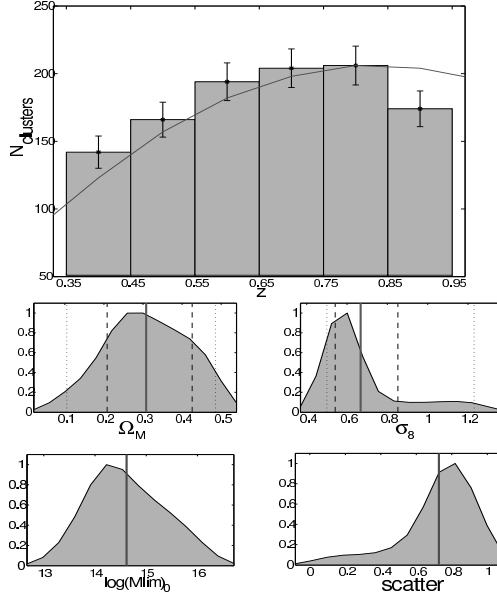


Figure 1. Cosmological parameter analysis from the RCS-1. Top Panel: Histogram of the observed cluster counts with richness $B_{gcR} > 300$. The solid line shows the best-fitting cosmology + richness-mass model. Central panels: The likelihood function of Ω_m and σ_8 , marginalized over the other fitting parameters. The solid vertical line in each panel indicates the mean value. Bottom panels: The likelihood function of the fitted scatter and mass limit of the cluster sample.

An equally interesting result in our analysis is the comparison between the cluster parameters derived from the self-calibration cosmology fit to those measured explicitly from cluster samples, specifically those obtained from the CNOC1 survey (Yee & Ellingson 2003) and a sample of 33 $z < 0.6$ RCS-1 clusters with dynamical mass measurements (Blindert et al. 2007). We perform this comparison of the B_{gc} -mass relation by fitting with 4 cluster parameters, replacing M_{lim} with A_{Bgc} and α . We find that the richness to mass relation as derived from the cosmology fit produces entirely consistent results to those from direct measurements of the relation. We obtain A_{Bgc} and α values of $10.55^{+2.27}_{-1.71}$ and 1.64 ± 0.90 , respectively, compared to 9.89 ± 0.89 and 1.64 ± 0.28 using the CNOC1 sample (Yee & Ellingson 2003). Similar results are also obtained by Blindert et al. (2007) from the RCS-1 spectroscopic sample. Furthermore, the best fit scatter $f_{sc} = 0.73 \pm 0.22$ is also in excellent agreement with that determined from the Blindert et al. sample of ~ 0.7 . The fact that the fitting results for both the cosmological parameters and the cluster parameters are in excellent agreement with other completely independent measurements is a strong endorsement of both the use of cluster mass function, including that derived from an optical sample such as the RCS, as a cosmological probe, and the self-calibration methodology.

3. The RCS-2

The RCS-2 is the first large scale imaging survey with sufficient area and depth for constraining w using cluster abundance. The recent commissioning of the MegaPrime Camera (MegaCam) on CFHT provides the field of view on a sufficiently large telescope required to carry out such a survey for the first time. The MegaCam is a one-square-degree camera consisting of a mosaic of thirty-six 4612×2048 pixels, with a scale of $0.18''/\text{pix}$. The survey will image 820 sq. deg using z' , r , and g filters of relatively shallow depths with integration times of 6, 8 and 4 minutes, attaining 5σ magnitudes of 22.5, 24.8, and 25.3, respectively. A total coverage of ~ 1000 sq. deg is obtained when combined with the 170 sq. deg of the wide component of the CFHT Legacy Survey. The survey area for the 820 sq. deg is divided up into 13 patches of 9×9 or 6×6 pointings of the MegaCam. The survey is expected to be completed by the end of 2007. The depths of the survey allow us to be able to detect galaxy clusters of richness of about half that of Coma out to redshift 1. The inclusion of the g band filter will allow for the proper characterization of the galaxy sample down to redshift as low as 0.1.

In any survey of significant size, the only feasible way to obtain the mass observable is from the survey data themselves, in our case, the optical richness. A large observational effort is also underway, using primarily clusters from RCS-1, to calibrate and provide strong priors on the cluster mass-richness relation. Having strong priors to the mass-richness relation over several redshift bins (to estimate γ), and including an estimate of the scatter, will provide much tighter constraints on the cosmological parameters, and is essential for the measurement of w . Our calibration efforts include using weak lensing cluster mass as our primary mass calibrator, augmented by dynamical mass measurements from multi-object spectroscopy for a core sample of ~ 70 clusters, and X-ray observations. The study of cluster galaxy evolution, using multi-color optical and IR photometry and spectroscopy, will also allow us to account for galaxy evolution when computing the richness of clusters at different redshifts. The results from RCS-1 bode well for the use of RCS-2 as a probe for w . Scaling with the RCS-1 as a guide, we expect to obtain a cluster sample of the order of 20,000 clusters with $0.15 < z < 1.0$ of similar richness. With priors on the mass-richness relation from our follow-up program, we expect to be able to measure to an accuracy of $\sim 10\%$ in w , ~ 0.02 in Ω_m , and ~ 0.05 in σ_8 .

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