The Red-Sequence Cluster Survey

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Abstract. The Red-Sequence Cluster Survey (RCS) is a new galaxy cluster survey designed to provide a large sample of optically selected $0.1 < z < 1.4$ clusters. The planned survey data are 100 square degrees of two color ($R$ and $z'$) imaging, with a $5\sigma$ depth $\sim 2$ mag past $M^*$ at $z = 1$. The combined depth and area of the RCS make it the widest field, moderately deep survey ever undertaken using 4m class telescopes. This paper gives a brief outline of the RCS survey, with particular emphasis on the data reduction strategy. The remainder of the paper focuses on preliminary results from the first set of completely reduced data ($\sim 10$ deg$^2$, of the $\sim 60$ deg$^2$ in hand). We provide a new example of a rich $z > 1$ cluster, illustrative of the dozens discovered in the data so far. Some of the possible science to come from the RCS is illustrated by a qualitative indication of $\Omega_M$ from the first 1/10th of the survey data. A high-precision measurement of the 2-point correlation function of luminous early-type galaxies at $0.4 < z < 1.2$ is also shown.

1. Introduction

Galaxy clusters are the largest gravitationally bound structures in the universe, and as such are markedly important in cosmology and studies of galaxy evolution. Much of the work on clusters done to date at low to intermediate redshifts (typically limited to $\sim 0.8$ or so) would benefit greatly from extension to higher redshifts. However, the cluster samples required for such studies do not exist. The Red-Sequence Cluster Survey (RCS) is designed to rectify this problem. The survey is designed to find galaxy clusters in large numbers out to $z \sim 1.4$, spread over a wide range of RA and DEC in order to facilitate follow-up.

The first observations for the RCS were taken in May 1999, at the CFHT, and at the time of writing we have acquired $\sim 60\%$ of the 100 square degrees of planned survey data. Data acquisition will be completed by the end of 2001. The survey data consist of 22 survey patches (ten $2.1 \times 2.3$ deg$^2$ patches from the CFHT, and twelve $1.8 \times 2.4$ deg$^2$ patches from the CTIO 4m telescope) imaged in the $R_C$ and $z'$ filters to $5\sigma$ point source depths of 25.2 and 23.6 mags respectively. This depth has been chosen to facilitate finding $z \sim 1$ galaxy clusters, which are located in the survey data using an algorithm based on
detecting the early-type galaxies in the clusters cores (Gladders & Yee 2000a). The RCS has been described in more detail elsewhere (Gladders & Yee 2000b), and we will not provide a repetition here. The interested reader is referred to the survey homepage, http://www.astro.utoronto.ca/~gladders/RCS/, which contains a description of the survey strategy, goals, and other relevant data and publications.

The purpose of this paper, rather, is to provide some of the details of the survey design strategy, as these are germane to the topic of this meeting. In addition, we provide some examples of new results coming from the RCS, including a preliminary indication of $\Omega_M$, an example of $z \sim 1$ galaxy clusters, and some of the secondary science related to the identification of individual early-type galaxies using photometric techniques over an unprecedented volume to $z \sim 1$.

2. RCS Survey Strategy

The primary science driver of the RCS is to locate a large sample of high redshift galaxy clusters, suitable both for direct investigations with the survey data and detailed follow-up work. The need for detailed follow-up at these redshifts is mandated by the paucity of known high-redshift galaxy clusters. At a redshift of $\sim 0.8$ and beyond, we know almost nothing about such structures. We thus chose to complete the survey in a large number of (relatively) small patches spread over a wide range in RA and DEC. This basic design means that the RCS sample will be observable from all major observatories at all times of year.

In considering the survey design, it was also recognized that the primary difficulty in producing such a survey is not the telescope time (the entire survey requires only 25 clear nights, split between two telescopes) but rather the ability of the survey team to handle the data flow. Consider, for example, that the CFHT half of the survey consists of $\sim 150$ CFHI2K images (in two filters), or a total of $150 \times 12 \times 2 = 3600$ 2k×4k CCD final science images! This large data flow along with the relatively short exposure times led to the decision to acquire all the data without dithering. This greatly simplifies the construction of final science images, at the expense of some minor loss in area due to inter-chip gaps and cosmetic defects. Cosmic rays, the removal of which is often cited as a reason for dithering, are accounted for in the photometry pipeline. The use of undithered images means that the entire survey can be treated as an assembly of individual 2k×4k images, for which the astrometric and photometric calibration can be performed solely in the final catalog assembly stage.

The survey data reduction pipeline works as follows. Individual chips from the mosaic imagers are pre-processed (de-biassed, flat-fielded, de-fringed etc.) using standard techniques. Object finding, photometry and star-galaxy separation are then done using an updated version of PPP (Yee 1991). For each chip, a preliminary catalog is produced from the object list with no visual checking. A final catalog results once the object finding has been visually checked, an
unavoidably time-consuming process which removes the few defects which are impossible to filter out automatically. The catalogs are then stitched together into a patch catalog using astrometric information from the USNO-A2.0 Catalog and photometric standards from Landolt (1992) and Thuan & Gunn (1976). The RCS will eventually be put onto the Sloan Digital Sky Survey photometric system (Fukugita et al. 1996); this calibration awaits analysis of data now in hand, and publication of the SDSS photometric calibration. Internal cross-checks of the photometry using 30″ overlap regions between each pointing in a patch shows that the preliminary calibration has an internal accuracy of better than 0.05 mags.

3. Preliminary Science Results

The results shown below are drawn primarily from the first ~ 10 deg² of RCS data. The various analyses should be considered preliminary, but are indicative of the overall significance of the survey.

3.1. Cosmology

The redshift evolution of the mass spectrum of galaxy clusters, \( N(M, z) \), provides a strong measure of the cosmological parameters \( \Omega_M \) and \( \sigma_8 \). Analysis of the RCS in this context will be made, at a later stage, using richness as a measure of mass (Yee & Lopez-Cruz 1999) and photometric redshifts. As a qualitative illustration of the cosmology indicated by the RCS, we have used the RCS selection functions (Gladders & Yee 2000a,c) to integrate out the mass dependence in \( N(M, z) \) and compared the measure of \( N(z) \) to predictions from two typical cosmologies. Predictions of \( N(M, z) \) are made from the standard Press-Schechter formalism, and multiplied by the RCS selection functions (expressed in mass and redshift, assuming a cluster with a typical luminosity function shape, galaxy mixture and cluster shape, concentration and size). These selection functions tail off to zero probability at a lower mass limit which becomes progressively more massive at higher redshift and hence limit the contribution to \( N(M, z) \) from lower-mass clusters and groups. The result of these computations, as well as the actual counts from a portion of the RCS, are shown in Figure 1. Clearly, and not surprisingly, the low \( \Omega_M \) and high \( \sigma_8 \) model is preferred.

3.2. High Redshift Clusters

Example high redshift clusters from the RCS have been shown elsewhere (e.g., Gladders & Yee 2000b), and we will not repeat those illustrations here. Instead, Figure 2 shows one of a new set of clusters found in an analysis of ~ 20 deg² of preliminary RCS catalogs. The photometric redshift is in the range \( z > 1.3 \), and this is the single richest high redshift cluster so far discovered in the RCS.

3.3. The 2-Point Correlation Function of Early-Type Galaxies

Over the redshift range in which the RCS filter pair straddles the 4000Å break (0.4 < \( z < 1.2 \)), the bright red edge of the color-magnitude diagram for all galaxies must be dominated by early-types. Moreover, the color is a direct measure of the redshift. This is because, at a given color, all lower redshift
Figure 1. An illustration of the cosmological power of the RCS. The predicted counts for clusters and groups are shown for two different cosmologies (thick lines) as well as the measured counts of significant detections in a subset of the RCS (thin line + asterisk). The low $\Omega_M$ model is vastly preferred. The apparent excess of low redshift objects (resulting in an apparent ‘double-peaked’ appearance) is the result of redshift aliasing from lower redshifts, and the great sensitivity of the RCS to even 300 km s$^{-1}$ groups at moderate redshifts (Gladders & Yee 2000a).

galaxies appear bluer, all higher redshift early-type galaxies appear redder, and all later-type higher redshift galaxies (which may have the same apparent color) appear fainter. Thus, at the bright red edge, at a given color, the sample is dominated almost exclusively by early-type galaxies at a certain redshift. It is thus possible to isolate a sample of luminous early-type galaxies simply by making a magnitude-color cut which selects the bright red edge of the color-magnitude diagram.

We have tested this idea by performing such cuts in the CNOC2 (Yee et al. 2000) database, which provides both redshifts and spectral-energy distributions (a surrogate for morphological classification). Using $V$ and $I_C$ data from CNOC2, and a passively evolving $z = 3$ starburst model to predict elliptical galaxy colors and apparent magnitudes, we find that a cut to a depth of $M^* + 1$ provides an early-type galaxy sample which is minimally contaminated ($\sim 15\%$), and for which individual redshifts are estimated to an accuracy of $\Delta z = 0.05$.

Using this technique, we have isolated a sample of $\sim 10,000$ early-type galaxies from the RCS in the redshift range $0.4 < z < 1.2$, from an area of $\sim 6$ deg$^2$. The sample was split into redshift bins, and the angular two-point correlation
function of each bin was computed. Several example correlation functions are shown in Figure 3. The measured angular correlation was then inverted via the Limber transform (e.g., see Giavalisco et al. 1998) to deduce the physical correlation length. Figure 4 shows these derived correlation lengths, in addition to those recently reported from the CNOC2 redshift survey by Shepherd et al. (2000). These measurements, as well as tests of the robustness of the inversion, are presented in detail in a paper now in preparation (Gladders & Yee 2000d). Note in Figure 4 that, according to this analysis, the correlation length for luminous early-type galaxies is unchanged out to at least redshift one.
Figure 4. The measured co-moving correlation length of luminous early-type galaxies from the RCS (diamonds). Also shown are the CNOC2 derived measurements of Shepherd et al. (2000) (asterisks). Both are expressed relative to correlations lengths with a slope of $\gamma = 1.73$ (see Shepherd et al. for details).

References

Fukugita, M., Ichikawa, T., Gunn, J.E., Doi, M., Shimasaku, K., & Schneider, D.P. 1996, AJ, 111, 1748
Giavalisco, M., Steidel, C., Adelberger, K.L., Dickinson, M.E., Pettinini, M., & Kellog, M. 1998, ApJ, 503, 543
Gladders, M.D., & Yee, H.K.C. 2000a, AJ, 120, 2148
Gladders, M.D., & Yee, H.K.C. 2000b, to be published in ASP proceedings of Cosmic Evolution and Galaxy Formation: Structure, Interactions and Feedback, see astro-ph0002340
Gladders, M.D., & Yee, H.K.C. 2000c, to be submitted to AJ
Gladders, M.D., & Yee, H.K.C. 2000d, to be submitted to ApJ
Landolt, A.U. 1992, AJ, 104, 372
Shepherd, C.W. et al. 2000, submitted to ApJ
Thuan, T.X., & Gunn, J.E. 1976, PASP, 88, 543
Yee, H.K.C, & López-Cruz, O. 1999, AJ, 117, 1985
Yee, H.K.C., Morris, S.L., Lin, H., Carlberg, R.G., Hall, P.B., Sawicki, M., Patton, D.R., Wirth, G.D., Ellingson, E., & Shepherd, C.W. 2000, ApJS, 129, 475