SPECTROSCOPY OF MODERATELY HIGH REDSHIFT RCS-1 CLUSTERS^{1,2}

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ABSTRACT

We present spectroscopic observations of 11 moderately high-redshift ($z \sim 0.7-1.0$) clusters from the first Red-Sequence Cluster Survey (RCS-1). We confirm that at least 10 of the 11 systems represent genuine overdensities in redshift space and show that for the remaining system, the spectroscopy was not deep enough to confirm a cluster. This is in good agreement with the estimated false positive rate of <5% at these redshifts from simulations. We find excellent agreement between the red-sequence-estimated redshift and the spectroscopic redshift, with a scatter of 10% at z > 0.7. At the high-redshift end ($z \ge 0.9$) of the sample, we find that two of the systems selected are projections of pairs of comparably rich systems, with red sequences too close to discriminate in (R - z') color. In one of these systems, the two components are close enough to be physically associated. For a subsample of clusters with sufficient spectroscopic members, we examine the correlation between B_{gcR} (optical richness) and the dynamical mass inferred from the velocity dispersion. We find these measurements to be compatible, within the relatively large uncertainties, with the correlation established at lower redshift for the X-ray-selected Canadian Network for Observational Cosmology clusters and also for a lower redshift sample of RCS-1 clusters. Confirmation of this and calibration of the scatter in the relation will require larger samples of clusters at these and higher redshifts.

Key word: galaxies: clusters: general

1. INTRODUCTION

Clusters of galaxies provide probes of cosmological parameters, such as those describing the equation of state of dark energy, and are laboratories for studying galaxy evolution. In order to place the strongest constraints on cosmological parameters, clusters at redshifts as high as $z \sim 1$ are crucial (e.g., Levine et al. 2002; Lima & Hu 2004). Observations at these redshifts also provide vital insight into the evolution of galaxies, at an epoch when clusters appear to be assembling (e.g., Ford et al. 2004 and references therein).

Previously, only a handful of systems were known at such redshifts. These were selected in a variety of ways, e.g., from an optical photographic survey (Gunn et al. 1986) and X-ray selection (e.g., Rosati et al. 1999). With the advent of the Red-Sequence Cluster Survey (RCS-1; Gladders & Yee 2005), the size of the sample of clusters at these redshifts has increased manyfold. More importantly, this larger sample possesses a homogeneous and readily quantifiable selection function (Gladders 2002).

RCS-1 is a 90 deg² optical survey (72 deg² after cutting to the highest photometric data quality) aimed at finding galaxy clusters out to redshifts of order unity using only moderate-depth R- and z'-band imaging. The primary science goal of the survey is to measure cosmological parameters through the evolution of the cluster mass function (Gladders et al. 2007). In order to do this efficiently, the survey data themselves are used to estimate the redshift and the mass of the clusters. The redshift is estimated via the position of the cluster red sequence (Gladders

¹ This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.

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et al. 2007), and the mass proxy used is optical richness as measured by the B_{gc} parameter (see Yee & Ellingson 2003 and references therein).⁴

In this paper we present 8 m class spectroscopic observations of a subsample of 11 moderately high redshift RCS clusters in order to confirm the reality of these systems, the accuracy of the redshift estimate, and the applicability of $B_{\rm gcR}$ as a mass estimator.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Sample Selection

Cluster candidates were selected from a preliminary version of the RCS-1 cluster catalog, before the photometric calibration was finalized. The selection was designed to be as close as possible to a richness-selected sample within the desired redshift range and available right ascension range. The earliest cluster candidates for follow-up were prioritized by visual inspection. Possible biases associated with this selection are discussed in § 4.3. Recalibration of the photometry affects the estimated redshift, the measured richness, and the detection significance of a cluster. As a result, two clusters do not appear in the final catalog (see Gladders & Yee 2005 for details of two patches). Both of these were rejected due to the strict significance threshold of 3.3 σ (equivalent to a probability of only 1 in 1000 of occurring by chance) used in the final catalog. One cluster appeared in an early preliminary (2004 December) catalog, and its properties (estimated redshift, significance, and richness) from this were used. In order to measure the parameters of the other candidate in a way consistent with those of the final catalog, the RCS clusterfinding algorithm was rerun with a lower threshold cutoff. It was only necessary to lower the threshold to 3.2 σ in order to recover the remaining candidate. Cluster candidate parameters quoted in this paper are taken from an improved later generation (2005 December) catalog.

2.2. Spectroscopic Observations

Spectroscopy was carried out in three runs on the 6.5 m Walter Baade Telescope: 2001 December 11-13 and 2002 January 15-16 using the Low Dispersion Survey Spectrograph 2 (LDSS-2; Allington-Smith et al. 1994); 2003 December with the Inamori Magellan Areal Camera and Spectrograph (IMACS; Bigelow et al. 1998); and in two queue runs (program IDs GN-2002A-Q42 and GN-2003B-Q-19) with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) on Gemini North. The observations are listed in Table 1. LDSS-2 used the MED/RED grism, giving a dispersion of 5.3 Å pixel⁻¹ centered around 5500 Å with a nominal resolution of 13.3 Å over a $\sim 6.5' \times 5'$ field. The masks comprised ~ 30 7"–10" long and typically 1" wide slits, observed for the total integration times listed in Table 1, usually split into 20 minute subexposures. For IMACS, the G200 grism was used, giving a dispersion of 2.0 Å pixel⁻¹ centered around 6600 Å with a resolution of 11.0 Å over a 27' diameter field. The IMACS masks consisted of ~150 slits, and the instrument was used in nod and shuffle (N&S; e.g., Glazebrook & Bland-Hawthorn 2001) mode. Exposures of 60 s were taken, and after every exposure the telescope pointing was nodded 1.4" along the slit, and the charge shuffled along the detector. This procedure was repeated for the total exposure times given in Table 1. When the data were read out, this resulted in two ob-

 TABLE 1

 Summary of Integration Times for Each Cluster

Mask Name	Total Exposure Time (ks)			
LDSS-2 (Classical MOS)				
RCS 033414–2824.6A	3.60			
RCS 033414-2824.6B	3.60			
RCS 034850-1017.6A	5.40			
RCS 043938-2904.8A	14.65			
RCS 043938-2904.8B	7.20			
RCS 044111-2858.3A	10.80			
RCS 110246-0426.9B	5.72			
RCS 110634-0408.9A	5.40			
RCS 110708-0355.3A	8.10			
RCS 110723-0523.2A	3.00			
RCS 110723-0523.2B	1.50			
IMACS (Nod and Shuff	ile)			
RCS 035231–1020.7	1.5			
RCS 043938-2904.8	5.13			
GMOS-N (Nod and Shu	ffle)			
RCS 141658+5305.2A	7.68			
RCS 141658+5305.2B	21.1			
GMOS-N (Classical MC	DS)			
RCS 162009+2929.4A	9.00			
RCS 162009+2929.4B	6.18			

servations of the same object: with observations of the night sky spectrum in the second exposure at the position of the object in the first exposure and vice versa. Two-dimensional (2D) sky subtraction could then be accomplished by simply subtracting one shuffled region from the other, producing a positive object spectrum at the first position and a negative spectrum of the object at the nodded position. The GMOS-N observations used the R150 grism, and the detector was binned 2×2 , giving a resolution of 11.4 Å at a dispersion of 3.5 Å pixel⁻¹ over a 5.5' field. RCS 1417+5305 was observed in nod and shuffle mode, whereas RCS 1620+2929 was observed with classical multiobject spectroscopy (MOS).

2.3. LDSS-2 Reduction

The LDSS-2 reduction was performed using a set of PYTHON routines written by D. Kelson and available online.⁵ This software is based on earlier FORTRAN routines whose operations are detailed in Kelson et al. (2000). The approach used was to compute the y- (spatial-) distortion along the slits by measuring the curvature of slit edges in a flat field using getrect. Slit edges were identified automatically from the flat fields with the findslits task, and in a few cases adjusted manually using editslits. The x- (spectral-) distortion was calculated by tracing lines from the arc lamp for each slit. The wavelength calibration was then calculated automatically (waverect) from the lamp using a list of reference wavelengths and their approximate relative intensities, coupled with estimates of the starting and ending wavelengths and the approximate dispersion for each data set. A zero-order shift of the wavelength calibration was then calculated using the night sky lines in the science data and applied, if necessary, to compensate for flexure in the instrument.

⁴ We use a modified version of the B_{gc} parameter (B_{gcR} ; see Gladders & Yee 2005), considering only galaxies with colors compatible with the red sequence at the estimated redshift of the cluster

⁵ See http://www.ociw.edu/~kelson/.

The measured distortions were then used to correct the flat fields, which were used to normalize the spectra. The x, y, and wavelength distortions calculated were used to resample the 2D spectral data to a linear frame with the spatial and spectral distortions removed and all the slits aligned in wavelength space. This was performed in a single operation using unrect. We then ran the IRAF⁶ task apall on these 2D rectified data to extract and sky-subtract the spectra.

2.4. IMACS Reduction

The IMACS data were reduced using an early version (1.02)of the Carnegie Observatories System for MultiObject Spectroscopy (COSMOS) software⁷ written by G. Oemler. This uses a map of the IMACS instrumental distortions to enable accurate rectification of the spectra. After checking the alignment of the mask to the sky using the apertures task on a direct image through the mask, alignment of the spectral mask was performed by running the align-mask task on a calibration arc. This task fits for shift and rotation of the mask by comparing the predicted positions (using the distortion model) of a few bright lines in the arc with their observed positions. Once the low-order (alignment) terms have been fitted, the mapping between CCD detector coordinates and spectral coordinates (wavelength and slit position) for the comparison arc was calculated using map-spectra. This mapping was tweaked to fit out the higher order residuals with adjust-map through comparison of the predicted positions of the full list of lines in the arc with their measured positions. After checking the mapping by overplotting the lamp line positions on the arc image, the mapping was applied to the spectroscopic flat field (with Sflat). Once all the mappings had been calculated, the science frames were debiased and flat-fielded using the biasflat routine, and extract-2D was used to create a fully rectified, sky-subtracted 2D spectrum for each slitlet, the sky being subtracted by simply subtracting the nodded spectrum from the unnodded observation. At this point, since 1D extraction had not been implemented for N&S in the COSMOS package, we used our own custom-written IDL routines (detailed below) to extract 1D spectra.

Each slitlet was searched for a peak corresponding to the galaxy continuum using the routine peakinfo taken from the SDSS spec2D package,⁸ after collapsing the image to 1D in the spectral direction. If a peak was found then a corresponding *negative* peak was searched for, at approximately the nod distance away from the positive peak. If this approach failed to yield two consistent peaks, then a smaller search box was used in the wavelength direction, and this box shifted until a pair of peaks was located. If a pair of peaks could not be found, then only the largest positive peak was selected.

For each slit, each spectrum was extracted by weighting the data around the center of the peak by a Gaussian curve of width fitted by peakinfo. Each slitlet typically contained two observations of each object (the positive and negative spectra from the N&S observations) and two exposures for each mask. In order to combine these 1D spectra, the data were co-added after scaling by the exposure time and rejecting highly deviant positive points (or negative in the negative spectra), corresponding to cosmicray hits. This simple sigma rejection removed a large fraction of cosmic rays, but some residual hits were rejected later, manually, by comparing the individual 2D extractions for each slit.

 TABLE 2

 Summary of Redshift Quality Flags

Flag	Comments
1 2	Secure redshift Probable redshift (e.g., one emission line with probable support or several weak features)
3 4 5	One emission line only, but no support (assumed [O II] λ 3727) Possible redshift, but unconvincing No redshift

2.5. GMOS Reduction

Both sets of GMOS data were reduced using the standard Gemini IRAF routines⁹ to bias-subtract, flat-field, and wavelengthcalibrate the data in a manner similar to that described above. The iGDDS package (Abraham et al. 2004) was used to interactively trace the 2D spectra and extract 1D spectra.

3. ANALYSIS

3.1. Redshift Determination

Redshifts were determined using the RVSAO package (Kurtz & Mink 1998) within IRAF. First, all 1D spectra were crosscorrelated (using xcsao) with a range of spectral templates including the E/S0, Scd, and Sab galaxies used by the Canadian Network for Observational Cosmology (CNOC) collaboration (Yee et al. 1996), and the SDSS composite quasar spectrum (Vanden Berk et al. 2001). Next, emission lines were searched for with emsao using the cross-correlation redshift as an initial estimate of the redshift. This task was run interactively and the redshift adjusted manually, in cases where the automated redshift was clearly incorrect, by fitting to emission or absorption features. The 1D and 2D spectra were simultaneously inspected in order to confirm the reality of faint features. In the case of the IMACS (nod and shuffle) data, the 2D spectra of the combined and the individual exposures were "blinked" in order to check for residual cosmic rays masquerading as emission lines. These were easily rejected by noting the presence of a bright feature in one exposure only. In addition, a number of emission-line-only spectra which were not correctly identified and extracted (since no continuum peak was found) were found with this interactive process. The 1D spectra were displayed with features overplotted and visually inspected and then a quality flag assigned (Table 2). Examples of randomly selected spectra from each of the quality classes are shown in Figure 1.

For the GMOS nod and shuffle data, redshifts were estimated in iGDDS by overplotting a variety of templates on the 1D spectra at various trial redshifts. This technique was also compared with the RVSAO method and found to give consistent results. The benefit of iGDDS is the ease with which a variety of different templates can be tested while simultaneously examining the 1D and 2D spectra to confirm the reality of low signal-to-noise ratio features.

3.2. Cluster Confirmation

The simplest and most conservative test to confirm cluster candidates is to plot redshift histograms for the secure (class 1) redshifts and look for overdensities. Figures 2 and 3 show the large-scale redshift histograms for each cluster field, shaded according to the redshift quality. A fixed bin size of z = 0.01 is used, which translates to a width in rest-frame velocity of ~1700

⁶ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc., under contract with the NSF.

See http://www.ociw.edu/~oemler/COSMOS.html.

⁸ See http://spectro.princeton.edu.

⁹ See http://www.gemini.edu/sciops/data/dataSoftware.html.



FIG. 1.—Example LDSS-2 spectra from each quality class. The redshift and quality flag are indicated in the upper left of each panel. Top to bottom panels show spectra of redshift quality flag 1, 2, 3, and 4 (Table 2), respectively. Fluxes are in arbitrary units, and spectra have not been flux-calibrated; labeled lines indicate the expected positions of common emission and absorption features; hatched areas denote regions potentially contaminated by strong night sky line residuals.

to ~1500 km s⁻¹ at redshifts 0.6 to 1.0, respectively, the approximate range for the clusters considered here. This velocity difference corresponds to approximately the velocity dispersion (σ) of a rich cluster of galaxies covering the 1–2 σ range, or a poorer cluster or rich group over 2–3 σ .

This immediately yields seven fields containing at least one peak comprising five or more secure redshifts: RCS 033414–2824.6, RCS 110634–0408.9, RCS 110708–0355.3, RCS 110723–0523.2, RCS 035231–1020.7, RCS 141658+5305.2, and RCS 162009+2929.4. The velocity distribution in the vicinity of the overdensity is plotted in the inset panels. This time a fixed rest-frame velocity bin size of 200 km s⁻¹ is used.

A less conservative test is used on the remaining clusters. We include spectra of other quality flags when searching for overdensities. We find the maximum (i.e., poorest) quality spectra which needed to be included to produce at least three galaxies within a bin. The resulting maximum velocity differences and quality flags for these systems are presented in Table 3. All the systems except for RCS 034850–1017.6 yield at least three galaxies with class 1–3 redshifts within 1300 km s⁻¹. We discuss the significance of such overdensities in § 4.

For the two clusters comprising $\gtrsim 20$ members, it is reasonable to calculate a velocity dispersion. We use the biweight scale estimator as recommended by Beers et al. (1990) for $n \sim 10-20$ galaxies and a jackknife estimate of the uncertainty. Following the procedure of Danese et al. (1980), we subtract in quadrature 100 km s⁻¹, representing the typical uncertainty in an individual redshift measurement.¹⁰ For RCS 033414–2824.6 we find a rest-

frame velocity dispersion of $\sigma = 300 \pm 60 \text{ km s}^{-1}$, and for RCS 110723–0523.2, $\sigma = 700 \pm 300 \text{ km s}^{-1}$, using only class 1 redshifts. Including class 1–3 redshifts the values are $\sigma = 400 \pm 100 \text{ km s}^{-1}$ and $\sigma = 600 \pm 150 \text{ km s}^{-1}$, respectively.

Two further clusters contain $\gtrsim 10$ members, and so it is worth attempting to estimate velocity dispersions for these systems too, although the uncertainties will be higher. The cluster RCS 162009+2929.4 has 13 class 1–3 spectroscopic members. These yield $\sigma = 1100 \pm 350$ km s⁻¹. In addition, RCS 035231–1020.7 has 11 class 1 spectroscopic members, giving a velocity dispersion of $\sigma = 600 \pm 300$ km s⁻¹.

We note that when dealing with ~20 cluster redshifts, a possible source of systematic uncertainty may be structure nearby in redshift space, unresolved along the line of sight. For example, Gal & Lubin (2004) found that, in a supercluster at $z \sim 0.9$, previous velocity dispersion measurements based on ~20 members overestimated the velocity dispersion by ~30%-40%, as compared with their factor of 2 larger spectroscopic data set. This was due to galaxies in nearby foreground and background groups being incorporated into the estimate for the velocity dispersion of the cluster. This 30%-40% uncertainty should probably represent an upper limit to the systematic error, since the probability of incorporating additional structure is higher in such a supercluster environment. We also note that our quoted uncertainties are already of order this amount.

4. RESULTS AND DISCUSSION

4.1. Individual Clusters

4.1.1. RCS 043938-2904.8

The field of RCS 043938–2904.8 offers the possibility of testing the accuracy of redshift measurements of duplicate objects

 $^{^{10}}$ This value is based on our experience with similar data sets, since we do not have enough repeat measurements within this work to determine the measurement uncertainties internally, but see § 4.1.1.



Fig. 2.—Redshift histograms for the RCS clusters observed with LDSS-2. Spectra are labeled according to their redshift quality flag as described in Table 2. Bins are 0.01 in redshift, corresponding to \sim 1700 km s⁻¹ at z = 0.6 down to \sim 1500 km s⁻¹ at z = 1.0. Insets show expanded views in rest-frame velocities around overdensities in redshift space.

taken with different instruments, as it was observed with both LDSS-2 and IMACS. Furthermore, additional data are available, taken with FORS2 on the VLT (Barrientos et al. 2004). Three objects from the IMACS mask were also observed with FORS2. In one of these the object lies on the slit edge in the FORS2 data and cannot be reliably extracted; the next object has a redshift flag of 4 in both data sets but still yields a pleasingly consistent redshift (1.121 from IMACS; 1.119 from FORS2) within 300 km s⁻¹ rest frame; and the third is an emission-line galaxy at z = 0.2945,

agreeing to better than 30 km s⁻¹ between the two instruments. The fact that a class 4 redshift appears to have been reproduced, albeit with a larger uncertainty than the secure measurements, suggests that the classification system is reliable, if somewhat in need of caution.

This field also allows us to test the reproducibility of structures identified with the different instruments. Although no obvious large overdensity is seen in the LDSS-2 data, four galaxies (redshift classes 1-3) are seen within 1300 km s⁻¹ of each other



FIG. 3.—Same as Fig. 2, but for clusters observed with IMACS (top panels) and GMOS-N (bottom panels). The plot for RCS 0439.9–2904 (top right) includes all available data from LDSS-2, IMACS, and FORS2.

at z = 0.960 (Fig. 2, *inset*). A second possible peak of three galaxies at z = 0.869 is also seen. Prominent peaks are visible in the redshift histograms near both these positions in the IMACS data (Fig. 3). This reinforces the idea that marginal confirmations of overdensities comprising only three or four galaxies will be confirmed with supplemental spectroscopy.

Close inspection of the redshift histogram in Figure 3 (top right, right inset) reveals that the overdensity at $z \sim 0.96$ actually appears to comprise two peaks: one at z = 0.945 and one at z = 0.968. This corresponds to a rest-frame velocity difference of 3500 km s⁻¹. Cluster mergers can reach relative velocities of ~ 3000 km s⁻¹ (Sarazin 2002). Thus, it is possible that these two systems may be physically related. The nature of this system will be discussed further in conjunction with X-ray observations in B. Cain et al. (2007, in preparation). For now, we note that this cluster is potentially binary or comprises the projection of two clusters, and associate this system with the target of our spectroscopic observation.

The red-sequence cluster-finding technique offers the possibility of disentangling multiple structures along the line of sight. The two components of RCS 043938–2904.8 (at z = 0.945 and 0.968) are too close to be separated by color information alone, but the other peak in the redshift histogram (Fig. 3) at z = 0.869 is potentially separable. The (R - z') color difference between z = 0.97 and z = 0.87 is expected to be 0.15 mag. We note that this is larger than the intrinsic scatter of the red sequence typically measured at these redshifts (~0.07 from *HST* imaging [e.g.,

Blakeslee et al. 2006], which becomes ~ 0.1 mag with groundbased photometric errors). In order to study the 3D distribution of cluster candidates in this field, we examine red-sequence significance maps centered on the spectroscopic redshifts of the two main peaks (i.e., $z_{\text{spec}} \sim 0.87$ and $z_{\text{spec}} \sim 0.97$). Figure 4 displays the spatial distribution of galaxies with spectroscopic redshifts over contour maps generated from the RCS cluster-detection technique. These contour maps show the significance of overdensities of galaxies having colors and magnitudes compatible with red-sequence cluster members at the redshift of interest (see Gladders & Yee 2000 for details). We denote such redshifts as z_{phot} to show that they refer to redshifts derived from redsequence colors at the given redshift. The left panel shows data for a slice centered on $z_{phot} = 0.87$ and the right a $z_{phot} = 0.96$ slice, corresponding to the two peaks in the redshift histogram. The width of the slices in the cluster-finding algorithm are set by the average color error around M^* at each redshift, and the width approximately corresponds to $\delta z = 0.1$, so there is some overlap between the two model red sequences.¹¹ This means that some of the same broad structure can be seen in both panels (e.g., near the center of the field), but that most of the contours in the $z_{\text{phot}} = 0.96$ slice are of higher significance; i.e., the *peak* of the central overdensity occurs around $z_{phot} = 0.96$, but the

¹¹ Thus, it makes negligible difference to the significance contours whether we center the redshift of the color slice, z_{phot} , on the spectroscopic redshift, z_{spec} , or the value given in the RCS catalog (see Table 3), which is $z_{\text{RCS}} = 0.94$.

TABLE 3								
CLUSTER	PROPERTIES	AND	Spectroscopic	Data				

ID	$\sigma_{\rm RCS}$	$B_{\rm gcR}^{a}$	α (J2000.0)	δ (J2000.0)	z _{phot}	<i>z</i> _{spec}	Comments
				LDSS-2			
RCS 033414–2824.6	4.1	1270 ± 305	03 34 12.3	-28 24 16	0.683	0.668	20 class 1 members, 26 class 1–3 members give $\sigma = 300 \pm 60 \text{ km s}^{-1}$
RCS 034850-1017.6	3.2	710 ± 330	03 48 49.7	-10 17 45	0.879	^b	
RCS 043938-2904.7	4.7	1590 ± 460	04 39 38.0	-29 04 55	0.937	0.869	Three class 1 and 2 redshifts within 1000 km s ^{-1c}
						0.974	Four class 1–3 redshifts within 1500 km s ^{-1}
RCS 044111-2858.2	3.3	830 ± 470	04 41 11.4	-285815	1.079	0.950	Three class 1 and 2 redshifts within 400 km s ⁻¹
RCS 110246-0426.9	4.0	930 ± 250	11 02 45.9	$-04\ 26\ 53$	0.737	0.723	Five class 1 redshifts within 1400 km s ⁻¹
RCS 110634-0408.9	4.0	660 ± 230	11 06 33.3	$-04 \ 09 \ 03$	0.805	0.823	Five class 1 redshifts within 600 km s ⁻¹
RCS 110708-0355.3	3.2	300 ± 190	11 07 17.9	-03 55 04	0.918	0.825	Five class 1 redshifts within 800 km s ⁻¹ (note: this cluster does not appear in the 2005 December cluster catalogs, and the values are taken from the 2004 December catalog)
RCS 110723-0523.3	3.5	980 ± 300	11 07 22.8	-05 23 49	0.767	0.735	20 class 1 members, 23 class 1–3 members give $\sigma = 700 \pm 300 \text{ km s}^{-1}$
				IMACS			
RCS 035231–1020.7 RCS 043938–2904.7	4.0 4.7	$\begin{array}{c} 710 \pm 230 \\ 1590 \pm 460 \end{array}$	03 52 31.0 04 39 38.0	$-10 20 42 \\ -29 04 55$	0.816 0.937	0.709 0.960	12 class 1–3 members give $\sigma = 600 \pm 370$ km s ⁻¹ 10 class 1–3 redshifts within 2400 km s ^{-1 a}
				GMOS-N			
RCS 141658+5305.2	4.7	3110 ± 800	14 16 58.7	+53 05 15	1.150	0.9682	Nine class 1 redshifts within 700 km s ⁻¹ (tentative $\sigma = 1030 \pm 1000$ km s ⁻¹)
						0.8945	Six class 1 redshifts within 300 km s ⁻¹ (tentative $\sigma = 240 \pm 70$ km s ⁻¹)
RCS 162009+2929.4	4.4	930 ± 240	16 20 09.4	+29 29 26	0.885	0.8696	12 class 1 members, 13 class 1–3 redshifts give $\sigma = 1050 \pm 340$ km s ⁻¹

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Columns show cluster name, detection significance in catalog, B_{gcR} (optical richness), right ascension and declination of mask center, photometric redshift, spectroscopic redshift, and details of galaxies identified with possible overdensities in redshift space. For overdensities of more than 10 galaxies, velocity dispersions have been calculated in § 4.3, and the number of members calculated after 3 σ clipping are listed.

^a B_{gcR} is the value which was measured directly from the survey data. No a posteriori correction has been applied here for overlapping red sequences in the cases of RCS 043938–2904.7 and RCS 141658+5305.2 (see §§ 4.1.1 and 4.1.4).

^b The spectroscopy for RCS 034850–1017.6 appears to have been insufficiently deep to confirm a cluster at this redshift (see § 4.1.3).

 $^{\circ}$ For RCS 043938–2904.7 we can add data from Barrientos et al. (2004). For the composite LDSS-2, IMACS, FORS2 data sets we identify a system with a mean redshift of 0.955 with 20 redshifts within 2400 km s⁻¹, but see the discussion in § 4.



Fig. 4.—Significance maps from the RCS technique for RCS 043938–2904.8 with spectroscopic members overlaid. Contours show the significance of structures identified in the RCS technique. Contours are in intervals of 0.3 σ , starting at 1.5 σ . Labels on the highest peaks identify the redshift and significance of peaks identified as cluster candidates. The left panel is for $z_{\text{phot}} = 0.87$ and the right is for $z_{\text{phot}} = 0.96$, corresponding approximately to the two peaks identified in the histogram of Fig. 2. Crosses denote spectroscopic nonmembers of each structure, filled squares show red members with redshifts compatible with the redshift "slice," and open squares denote blue spectroscopic members. There is clearly a large overdensity of red galaxies associated with the cluster candidate at 0.94. Galaxies in the $z_{\text{spec}} = 0.87$ slice are not so spatially concentrated, nor are they predominantly red. There is a possible hint of association with the $z_{\text{RCS}} = 0.88$ cluster candidate just outside the area covered for spectroscopy. See the text for further discussion.

shoulder of the distribution is still visible in the $z_{phot} = 0.87$ slice. Crosses show galaxies with spectroscopic redshifts incompatible with the redshift of the slice, and squares show galaxies whose redshifts are compatible with being at the redshift of the slice. The widths of the slices used for the *spectroscopic* redshifts is 5000 km s⁻¹ rest frame in order to encompass all of the structure visible in both components of the higher redshift system shown in Figure 3. It is immediately apparent that the galaxies in the $z_{spec} = 0.96$ slice are spatially concentrated within the $z_{phot} = 0.96$ contours, thus confirming that our association of this peak in the redshift histogram with our cluster candidate is valid.

Peaks which are identified as cluster candidates are labeled on both maps with their redshift, z_{RCS}^{12} and significance in parentheses. The aforementioned $z_{RCS} = 0.94$ cluster is the most significant peak in the whole field, with $\sigma_{RCS} = 4.7$.

We now consider the identity of the $z_{\text{spec}} = 0.87$ peak in the redshift histogram. A 3.1 σ_{RCS} cluster candidate appears in the RCS catalog at z = 0.88, 4' west of the field center. Recall that our limit for the final catalog is $\sigma_{\text{RCS}} = 3.3$. This system has three spectroscopic members (from the $z_{\text{spec}} = 0.87$ slice) located within the contours shown and a further two members just outside. Thus, by our earlier criterion, this would be considered a confirmed cluster, except for the fact that it lies at a lower significance than clusters in the final RCS catalog, and even lower than the $\sigma_{\text{RCS}} = 3.2$ clusters (RCS 034850–1017.6 and RCS 110708–0355.3) considered confirmed. Regardless, it is clear from these two plots that the red-sequence technique has correctly disentangled the $z_{\text{RCS}} = 0.94$ peak from any $z_{\text{phot}} = 0.88$ structure, and in fact correctly identifies the $z_{\text{spec}} = 0.869$ structure as a low-significance cluster.

4.1.2. RCS 033414-2824.6

RCS 033414–2824.6 (z = 0.668) was also observed with LDSS-2 as part of the survey of K. Blindert et al. (2007, in preparation, hereafter B07). They observed masks at three positions around the cluster: a central pointing close to the position used in this paper, plus north and south flanking fields. Their redshift catalog adds 18 secure cluster members within the region covered by our data. We note in passing that there are four objects in common between our surveys. For only one of these do we both measure a redshift. Our redshift measurements of this galaxy, a cluster member, agree to within 70 km s⁻¹. This is a useful independent check of our measurements, as Blindert et al. used completely different reduction software and redshift measuring code.

4.1.3. RCS 034850-1017.6

RCS 034850-1017.6 is the only cluster for which an overdensity in redshift space could not be identified. Figure 2 shows a paucity of galaxies above $z \sim 0.8$, the redshift for the cluster estimated from the RCS method. It is possible that the depth of the spectroscopy was insufficient to identify galaxies at $z \ge 0.8$.

In order to test this possibility, we used redshifts from the other cluster fields and sampled them, mimicking the selection function from the RCS 034850–1017.6 observations in the following way. We selected every galaxy for which a redshift was successfully measured from all the fields except RCS 034850–1017.6 and excluded galaxies within 15,000 km s⁻¹ of the cluster redshift in each. This formed our field distribution. We added

galaxies from one of the confirmed $z \sim 0.8$ clusters. This formed our mock cluster field. Next we chose galaxies with redshifts from the RCS 034850–1017.6 field and formed a histogram of their magnitudes in 0.5 mag bins. This gave the magnitude selection function: the number of galaxies as a function of magnitude for which a redshift could be obtained. We randomly sampled galaxies from our mock cluster field by applying this selection function (with Poissonian errors on the number drawn from each bin), and examined the redshift histogram of the resulting simulated observation, as in Figure 2, and applied the techniques described in § 3.2 to see if we identified the cluster.

In 1000 repeated bootstraps of this method, we failed to identify the cluster in any realization. This result is unchanged using either of the $z \sim 0.8$ clusters (RCS 110634–0408.9 at z =0.823 or RCS 110708–0355.3 at z = 0.825). We conclude that, at the 3 σ level, we could not have identified a z = 0.8 cluster in the LDSS-2 spectroscopy if one was present. We note that if we were to repeat this test for the z = 0.723 cluster, RCS 110246–0426.9, then we would identify an overdensity 14% of the time, but the z = 0.735 cluster, RCS 110723–0523.2, is not identified in any of the 1000 realizations. So, a $z \sim 0.70$ cluster could be marginally detected if one was present, but a $z \sim 0.73$ one would not. Thus, our failure to confirm a cluster based on these data does not necessarily represent a false positive in the RCS method, but rather is consistent with the limitations of our spectroscopic data.

4.1.4. RCS 141658+5305.2

This field shows three peaks in the redshift histogram over the whole GMOS field. Figure 5 shows the spatial distribution of galaxies in each of these peaks. Clearly, the galaxies in the middle peak, $z \sim 0.89$, are more spatially concentrated than galaxies in the other peaks. Indeed, the lowest redshift peak, $z \sim$ 0.61, does not appear at all concentrated, and galaxies are spread across the entire GMOS field. This peak is best interpreted as large-scale structure rather than a cluster. The image is centered on the position of the cluster candidate, and so it can be seen that not only are the members of the $z \sim 0.89$ peak spatially concentrated, but they are also concentrated around the position of the cluster candidate. The highest redshift peak, $z \sim 0.97$, also appears somewhat concentrated around this area, but not to the extent of the $z \sim 0.89$ galaxies. The object identified as the brightest cluster galaxy in the image is a member of the $z \sim$ 0.891 peak, as are many of its brightest neighbors. Thus, we associate this peak with the RCS cluster candidate, even though the $z \sim 0.97$ peak more closely matches the predicted redshift of the cluster from the RCS technique.

4.1.5. Other Clusters

Holden et al. (1999), Ramella et al. (2000), and Gilbank et al. (2004) have all argued that finding three galaxies within a velocity range appropriate for that of a cluster's velocity dispersion is significant. If we adopt this criterion, all our clusters (except RCS 034850–1017.6) would be significant detections. The lowest quality redshifts needed for this confirmation are class 3. We have demonstrated that even our lowest quality redshift flag (class 4) is reproducible between different data sets. Furthermore, empirical evidence from IMACS follow-up of RCS 043938–2904.8 is very suggestive that these detections based on three or four redshifts will be supported by deeper spectroscopy.

It can be seen from Figure 2 that the highest redshift candidates exhibit far fewer redshifts than those of the lower redshift clusters. We are clearly approaching the limit for measuring

¹² We label these as z_{RCS} to emphasize that they represent a *peak* (i.e., a cluster candidate) as opposed to structure of arbitrary significance at the redshift z_{phot} .



FIG. 5.—RCS 141658+5305.2, with galaxies labeled according to spectroscopic redshift. Objects associated with the $z \sim 0.61$ peak are denoted by large, thin circles, $z \sim 0.89$ by thick circles, and $z \sim 0.97$ by squares. The image is centered on the position of the cluster candidate from the RCS catalog. The $z \sim 0.89$ galaxies are clearly concentrated around the position of the cluster candidate. The $z \sim 0.61$ galaxies are distributed across the field and so represent large-scale structure rather than a genuine cluster. The image is $6.5' \times 5.0'$, corresponding to $3.0 h^{-1}$ Mpc $\times 2.0 h^{-1}$ Mpc at a redshift of 0.89.

redshifts in the optical with LDSS-2. The decreased sensitivity in the red of this instrument is such that even the prominent features such as the Ca [II] H and K lines are not readily identifiable at $z \sim 1$.

4.2. Accuracy of the Estimated Cluster Redshifts

A comparison of the photometric estimates of the cluster redshifts with those of the measured spectroscopic redshifts is shown in Figure 6. The photometric redshifts shown in the figure are raw photometric redshifts from the previous generation of cluster finding. These are based purely on population synthesis models for the evolution of the red sequence. The cluster-finding method involves a recalibration step (as described in Gladders & Yee 2000) to empirically bring the average model colors into agreement with the observed colors, as a function of redshift for a subsample of the clusters with spectroscopy. A low-order polynomial is fitted to photometric versus spectroscopic redshift, and the photometric redshifts re-evaluated to minimize the offset. We emphasize that this correction is applied to *all* photometric redshifts, and there is no correction of redshifts on an individual cluster basis. Since the redshift data presented in this paper have been used as part of the correction, it is more instructive to examine how well the redshift estimation technique works before applying this correction. The dashed line indicates the one-toone relation. The data show a slight trend to overestimate the true redshift of the cluster at the highest redshift end. The bestfit relation is indicated by the dotted line and given by $z_{spec} =$ $(0.88 \pm 0.05)z_{RCS} + (0.05 \pm 0.04)$. The average bias in the redshift estimate (e.g., Wittman et al. 2001) is $\Delta z/(1+z_s) =$ (0.039 ± 0.035) . It is important to note that the scatter in Figure 6



FIG. 6.— Comparison of red-sequence redshift estimates with the measured spectroscopic redshifts of the clusters. Filled circles are from this work, and open circles are from B07. The dashed line indicates the one-to-one relation, and the dotted line is the best fit. There is a slight tendency for the initial photo-*z* based on model colors to overestimate the redshift at the high-redshift end, but note that the scatter in the relation is small, indicating that a simple rescaling of the estimated redshifts will improve the final accuracy.



FIG. 7.—Velocity dispersion vs. richness estimate (red-sequence B_{gcR}). Filled circles with error bars show the four clusters (labeled) with sufficient members to consider velocity dispersions reliable. Open circles with error bars show the two systems in RCS 141658+5305.2 with the B_{gcR} estimate corrected to divide the richness between the two clusters. The line indicates the relation from Yee & Ellingson (2003) derived from the X-ray-selected CNOC1 clusters. Open diamonds (error bars omitted for clarity) show data points from low-redshift RCS-1 (B07). The moderately high-redshift RCS-1 clusters presented here appear consistent, within the broad uncertainties, with both the relation for X-ray clusters and the lower redshift relation for RCS clusters, with the exception of RCS 033414–2824.6. See the text for further discussion. Error bars represent present and do not include any potential systematic error which may be present with modest numbers of redshifts (see § 3.2 for discussion).

(i.e., before this correction) is small. This shows that even using only model colors for the red sequence, the photo-*z* estimate is very good, and improved further by a small correction. The correction just minimizes the average offset between photometric and spectroscopic redshifts as a function of photometric redshift. The corrected values of the photometric redshift, as used in the latest RCS catalog, are given in Table 1. These values give a final accuracy of the red-sequence redshift estimate in this redshift range of 10%.

4.3. Richness Estimates of Velocity Dispersion

Four systems yielded sufficient members to attempt to calculate velocity dispersions (see § 3.2) for the clusters: RCS 033414-2824.6, RCS 035231-1020.7, RCS 110723-0523.3, and RCS 162009+2929.4. For these clusters we can compare the measured values of the velocity dispersions with the values implied using the relation of Yee & Ellingson (2003) from CNOC1 clusters. Figure 7 shows their B_{gc} versus velocity dispersion. Also shown on the plot are data from low-redshift (z < 0.6) RCS-1 clusters (B07). The moderately high redshift RCS-1 clusters presented here appear consistent with both the relation for lower redshift X-ray clusters and the lower redshift relation for RCS-1 clusters, with the exception of the outlier RCS 033414-2824.6. This cluster has a much lower measured velocity dispersion than inferred from its richness. Using the additional redshift data from B07 does not change the measured value of the velocity dispersion, within the measurement errors. We interpret this high-richness, low velocity dispersion system as a much less massive system, i.e., a group, embedded in richer surrounding sheetlike large-scale structure. Indeed, the unusual sheetlike nature of this structure is clear from the wider field spectroscopy of B07

Such outliers to this relation are expected, but, in the following, we argue as to why we might expect them to be rarer than finding one in this current modest sample might suggest. The earliest cluster candidates for spectroscopic follow-up observations (including RCS 033414-2824.6) were prioritized using visual inspection, before accurate B_{gcR} estimates had been calculated. This might have led to a bias toward selecting systems embedded in sheetlike structures (i.e., low velocity dispersion outliers like RCS 033414–2824.6) for a given B_{gcR} . Consider two cluster candidates with equivalent B_{gcR} values. This means an equal overdensity of red galaxies (relative to a fixed global background) within 0.5 h_{50}^{-1} Mpc. Now, if the better candidate of these two is to be selected by eye, initially the eye checks for a concentration of galaxies within some relatively small radius (which we have just set to be the same for both, by construction). After this, preference is likely to be given to the cluster which has the greatest overdensity on larger scales, since the eye cannot impose a strict cutoff in radius, as the B_{gcR} -measuring algorithm does. Thus, a system embedded in surrounding structure is likely to look more impressive and be given higher priority for follow-up than a cluster of comparable B_{gcR} not embedded in larger structure. This is particularly true if overdensities of red galaxies are searched for using color pictures, as was the case with some of the early follow-up selection.

Furthermore, we note that RCS 033414–2824.6 is also the most distant outlier in the B_{gcR} - σ relation from the sample of ~30 clusters of B07. Thus, we expect to find lower incidences of such extreme outliers in the ongoing RCS spectroscopic follow-up, selected using cuts in B_{gcR} and not relying on visual inspection.

It is possible that objects like this, embedded in sheetlike structure, could be identified by comparing B_{gcR} values measured at several different radii. We are investigating methods involving using another parameter, such as B_{gcR} concentration, to try to identify potential outliers like RCS 033414–2824.6 from the survey data alone.

Similarly, the projection of two or more clusters may cause objects to fall off this relation; e.g., RCS 043938-2904.2 comprises two distinct systems in redshift, but close enough that the two may be physically associated. Thus, direct application of the virial theorem to estimate a mass from the velocity dispersion would not be valid. The richness measured for this system would be the sum of the richnesses of the two systems, and thus should not be expected to correlate with its mass. RCS 141658+5305.2 also comprises two systems projected along the line of sight but separated sufficiently in redshift that they are unrelated, and thus velocity dispersions may be calculated individually for both systems. However, the red sequences are so close together in color, $\delta(R - z') = 0.07$, that red-sequence richness estimates for each cluster are contaminated by galaxies from the other. In order to correct for this, we recalculate the B_{gcR} values by dividing the measured values between each system in proportion to the numbers of spectroscopic members in each. These are shown as the two open points with error bars. It can be seen that, after this correction, the two clusters lie on the relation, albeit with large errors due to the small number (<10) of redshifts going into each velocity dispersion estimate.

Without spectroscopy, using the survey data alone, we would not be able to identify such systems as projections. However, it should be noted that these projection effects (both physically associated projections/multicomponent clusters and unrelated line-of-sight projections) are present with all cluster-finding methods: e.g., in the X-ray-selected CNOC1 sample (Yee et al. 1996), one of the 15 MS clusters (MS 0906+11) was found to be binary from the detailed spectroscopy. Similarly, unrelated systems along the same line of sight are also seen projected in X-ray-selected surveys, but examples are relatively scarce in the literature, due to the need for extensive spectroscopic follow-up to reveal such situations. Several examples of unrelated projected systems at low redshift for an X-ray-luminous sample of Abell clusters are given in López-Cruz et al. (2004). The main advantage of X-ray selection is that the mass varies less steeply as a function of X-ray luminosity than optical richness. Thus, projecting two similarly massive clusters together gives a smaller boost to the X-ray luminosity (and hence the detectability in an X-ray survey) than to the optical richness. To measure the frequency of projections within the RCS requires larger spectroscopic samples, and such work is ongoing. One might expect the projection rate to increase toward the high-redshift end of the sample, where red sequences for different redshifts become degenerate ($z \ge 0.8$ for this filter set). We currently lack the data to test the redshift dependence of the projection rate within the RCS. However, an initial estimate can be made by adding the 10 confirmed clusters studied here to those of B07. Of the 19 RCS systems they studied at 0.3 < z < 0.6,¹³ B07 find only one comparably rich system whose red sequence actually appears to be made up of the projection of a pair of equally rich clusters. If we adopt redshift bins of 0.3 < z < 0.8 and 0.8 < z < 1.0, we then find that the fraction of projected systems is 1/23 and 2/6, respectively. Assuming Poisson errors leads to rates of $4\% \pm 4\%$ and $33\% \pm 24\%$. Thus, there is slight evidence (~1 sigma) to suggest that the projection rate may increase at z > 0.8. A detailed analysis of the expected projection rate derived from cosmological simulations will be presented in future work.

The concordance of the points from our moderately high redshift sample with the lower redshift B_{gcR} - σ relation is in good agreement with the results from the cosmological study of Gladders et al. (2007), who found that, based on a self-calibration technique, the evolution in the mass- B_{gcR} relation over the redshift range 0.35–0.95 was consistent with no evolution. We note that the definition of B_{gcR} includes a passively evolving luminosity limit for the galaxies included in the measurement, so a result of no evolution in this relation means that evolution in the massrichness relation is consistent with simple passive evolution of the red-sequence cluster galaxies. Lin et al. (2006) and Muzzin et al. (2007) also recently found that the evolution of the relation between cluster mass and total *K*-band galaxy number (or luminosity) is consistent with passive evolution of the member galaxies.

5. CONCLUSIONS

We have performed multiobject spectroscopy of 11 RCS clusters at moderately high redshifts ($z \sim 0.7-1.0$). Using a very conservative criterion we clearly confirm seven of the 11 clusters. Another three are confirmed using the less stringent requirement of three galaxies within 1500 km s⁻¹ of each other. Deeper spectroscopy of one of these three clusters supports the reality of this system, and we use this to argue that 10 of the 11 systems should be considered confirmed clusters. We demonstrate that for the remaining cluster candidate the spectroscopic data are too shallow to have identified the cluster, and that this does not necessarily constitute a false positive in the RCS technique. In addition, this cluster lies just below the sig-

nificance threshold for the final cluster catalog and would not have been included. While a much larger sample of both clusters and redshifts is needed to quantitatively assess the contamination rate as a function of cluster redshift, these first results are broadly consistent with the $\sim 5\%$ false-positive rate estimated from simulations (Gladders 2002).

The RCS technique provides redshift estimates accurate to within 10% in this redshift range. Two of the RCS clusters comprise projections of pairs of comparably rich systems. In one of these, the two components are close enough in redshift that they may be physically related. Thus, we might consider these two projections to be made up of (1) a binary cluster (RCS 043938-2904.4; such a binarity fraction would be comparable, within the large uncertainties for such a small sample, with that found in other cluster surveys); and (2) an artificially enhanced detection due to the projection of two unrelated clusters (RCS 141658+5305.2). We note that, in both of these cases, the clusters lie at z > 0.8, and this may be due to the increasing degeneracy of red-sequence colors at these redshifts. In the former case, we demonstrate how the red-sequence technique also reliably disentangles the cluster from foreground structure. Comparison with the sample of B07 supports the idea that the projection rate from unrelated clusters at lower redshifts in the RCS survey is likely to be lower.

We present a first look at the correlation between cluster richness, B_{gcR} , and velocity dispersion for a subsample of six clusters at these redshifts. These measurements appear consistent, within broad uncertainties, with the relation found at lower redshift.

This paper presents initial results from a larger campaign of follow-up spectroscopy of moderately high and high-redshift clusters from the Red-Sequence Cluster Survey. A high-redshift sample based on observations with FORS2 on the VLT and GMOS on Gemini will be reported by L. F. Barrientos et al. (2007, in preparation). An ambitious project using ultraplex IMACS observations at the Magellan Baade telescope of a well-defined core sample from the RCS, targeting ~40 clusters selected in bins of richness and redshift (covering $0.3 < z \leq 0.85$) is underway. A spectroscopic survey of a comparable number of RCS clusters, extending the high-redshift end to $z \sim 1$ using the upgrade to LDSS-2 (LDSS-3), is ongoing.

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