The Gemini/HST Galaxy Cluster Project: Redshift 0.2–1.0 Cluster Sample, X-Ray Data, and Optical Photometry Catalog

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Abstract

The Gemini/HST Galaxy Cluster Project (GCP) covers 14 $z = 0.2$–1.0 clusters with X-ray luminosity of $L_{500} \geq 10^{44} \text{erg s}^{-1}$ in the 0.1–2.4 keV band. In this paper, we provide homogeneously calibrated X-ray luminosities, masses, and radii, and we present the complete catalog of the ground-based photometry for the GCP clusters. The clusters were observed with either Gemini North or South in three or four of the optical passbands $g'$, $r'$, $i'$, and $z'$. The photometric catalog includes consistently calibrated total magnitudes, colors, and geometrical parameters. The photometry reaches $\approx 25$ mag in the passband closest to the rest-frame $B$ band. We summarize comparisons of our photometry with data from the Sloan Digital Sky Survey. We describe the sample selection for our spectroscopic observations, and establish the calibrations to obtain rest-frame magnitudes and colors. Finally, we derive the color–magnitude relations for the clusters, and briefly discuss these in the context of evolution with redshift. Consistent with our results based on spectroscopic data, the color–magnitude relations support passive evolution of the red sequence galaxies. The absence of change in the slope with redshift constrains the allowable age variation along the red sequence to $<0.05$ dex between the brightest cluster galaxies and those four magnitudes fainter. This paper serves as the main reference for the GCP cluster and galaxy selection, X-ray data, and ground-based photometry.

Key words: galaxies: clusters: individual: (Abell 1689, Abell 851, RX J1347.5–1145, MS 0451.6–0305, RX J1226.9+333) – galaxies: photometry

Supporting material: machine-readable table

1. Introduction

Galaxy evolution can be studied through observations of galaxies at different redshifts. Systematic surveys of clusters published in the mid to late 1990s investigated the evolution of the galaxy population out to $z \approx 1$ using photometric measurements, in some cases combined with low-resolution spectroscopic data. Examples include the Canadian Network for Observational Cosmology (CNOC) surveys (Yee et al. 1996, 2000) and the “MORPHS” project led by Smail and Dressler (Smail et al. 1997; Dressler et al. 1999).

The goal of the CNOC cluster survey was to establish the mass distribution within the clusters. However, the data, combined with CNOC2 field galaxy data, were also used for investigations of the evolution of galaxies from $z \approx 0.6$ to the present. Schade et al. (1996a, 1996b) studied the evolution of luminosities as a function of redshift and sizes, and tested for environmental effects. The results supported passive evolution for bulge-dominated galaxies, and showed no environmental dependence of the evolution of disk- or bulge-dominated galaxies. Balogh et al. (1997, 1998) focused on the star formation rates (SFRs) as measured from the [O II] emission lines and demonstrated the significantly lower SFRs present in cluster disk galaxies compared to those in similar galaxies in the field.

The MORPHS project provided imaging with Hubble Space Telescope (HST) (Smail et al. 1997) and low-resolution spectroscopy (Dressler et al. 1999) of 10 clusters at $z = 0.37$–0.56. The data have been used for studies of morphological evolution (Dressler et al. 1997), evolution of $(U - V)$ colors with redshift (Ellis et al. 1997), as well as studies of star formation history. In particular, Dressler et al. (2004) used stacked MORPHS spectra, combined with similar data for higher-redshift clusters, to establish that younger stellar populations were present in the higher-redshift clusters.

With increased access to 8 m class telescopes, a number of surveys focused on more detailed studies of the spectral properties of the cluster galaxies have been carried out. The European southern Observatory (ESO) large project ESO Distant Cluster Survey (EDisCS) targeted clusters at $z = 0.4$–0.9 (White et al. 2005). Based on these data, Sánchez-Blázquez et al. (2009) studied the stellar populations from stacked spectra, while Saglia et al. (2010) investigated the size evolution and established the fundamental plane (FP; Dressler et al. 1987; Djorgovski & Davis 1987) for the clusters. The results support passive evolution of bulge-dominated galaxies, but also indicate that a large fraction of the new passive galaxies entered the red sequence between $z \approx 0.8$ and $z=0.4$.

The Gemini Cluster Astrophysics Survey (GCLASS) consists of spectroscopic follow-up of 10 of the richest $z \approx 1.1$ clusters from the Spitzer Adaptation of the Red Sequence Survey (SpARCS) survey (Muzzin et al. 2009; Wilson et al. 2009). One of the key results from GCLASS concerns the relative roles of environment or galaxy mass as the driver of the evolution of the galaxies (Muzzin et al. 2012). These authors conclude that the environment primarily affects the fraction of star-forming galaxies, while the galaxy mass determines the stellar populations.
Beyond \( z \approx 1 \), deep spectroscopic observations become very challenging. The survey GOGREEN (Gemini Observations of Galaxies in Rich Early ENvironments) aims to study the stellar populations of both red sequence and star-forming galaxies, and to cover a large range in galaxy masses (Balogh et al. 2017). The project includes 12 clusters and nine groups at \( z = 0.8–1.5 \). The spectroscopy is of sufficient spectral resolution to study absorption lines, but cannot be used to determine the velocity dispersions of the galaxies.

Another approach is to use primarily imaging data at these redshifts. For example, the HAWK-I Cluster Survey (PI: Lidman) covers nine clusters at \( z = 0.8–1.5 \) with near-IR imaging obtained with the VLT; see the project summary in Cernło et al. (2016). The project aims to study galaxy populations of \( z > 0.8 \) clusters, primarily from multiband photometry. The sample includes some of the most massive known clusters at these redshifts.

The above brief summary of large projects is by no means a complete list of past and ongoing effort, but serves to show examples of the different approaches taken in this field. Ultimately, all of the projects aim to establish aspects of the galaxy evolution from high redshift to the present by quantifying the galaxy properties at different redshifts.

Our project, the Gemini/HST Galaxy Cluster Project (GCP) shares this aim. The clusters in the GCP are significantly more massive than the bulk of the clusters in EDisCS and GOGREEN. The GCP data include multiband optical photometry obtained with Gemini, high-resolution imaging primarily from HST, and deep ground-based optical spectroscopy. Our spectroscopic observations have signal-to-noise ratio (S/N) higher than those reached by other projects covering similar redshifts, and have sufficient spectral resolution for reliable measurements of velocity dispersions and absorption line indices for individual galaxies. The original GCP, which is the topic of this paper, covers \( z = 0.2–1 \) (Jørgensen & Chiboucas 2013; Jørgensen et al. 2017). Our high-redshift extension of the project, xGCP, is aimed at \( z = 1.2–2.0 \). The first results for \( z > 1 \) galaxies include measurements of galaxy velocity dispersions and line strengths, and we establish for the first time the FP for a significant cluster sample at \( z = 1.3 \) (Jørgensen et al. 2014). Future papers will provide more detail and results for the xGCP.

In this paper, we present the X-ray data and catalog of the ground-based photometry for the \( z = 0.2–1.0 \) GCP clusters. We start by describing the main science goals, methods, and observing strategy of the GCP in Section 2. The section also details the cluster selection, contains an overview of previously published papers originating from the project, describes the calibration of the cluster X-ray, data and summarizes the properties of the GCP clusters. The processing of the ground-based imaging and the determination and calibration of the photometry are covered in Sections 3–4. Comparisons with photometry from the Sloan Digital Sky Survey (SDSS) are used to ensure consistently calibrated magnitudes and colors. Section 5 presents the fully calibrated photometry. The catalog is available as a machine-readable table. In our analysis of the GCP data, we make use of photometry calibrated to the rest-frame B band as well as to the rest-frame colors \((U - B)\) and \((B - V)\). These calibrations are established in Section 6. In Sections 7 and 8, we describe the sample selection for our spectroscopic observations, establish the color–magnitude relations in the observed bands, and finally discuss the evolution of the color–magnitude relations as a function of redshift. Section 9 summarizes the paper.

Throughout this paper, we adopt a ΛCDM cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \) and \( \Omega_{\Lambda} = 0.7 \).

2. The Gemini/HST Galaxy Cluster Project

2.1. Science Goals, Cluster Sample, Observing Strategy, and Methods

The Gemini/HST Galaxy Cluster Project (GCP) was designed to study the evolution of bulge-dominated passive galaxies in very massive clusters. The main scientific goals of the project are to investigate to what extent these galaxies share a common evolutionary path and to map such a path. In the process, we can quantify the dependence on galaxy properties and possibly on cluster properties. This present paper serves as the main reference for GCP cluster selection, project description, X-ray data, and the catalog of the ground-based photometry.

The original cluster selection was based on X-ray luminosities and spectroscopic redshifts as available in the literature in the period 2000–2004. Fifteen clusters were selected for the project, with the aim to have three to four clusters for each 0.2 interval in redshift from \( z = 0.2 \) to \( z = 1.0 \). MS 1610.4+6616, selected as a cluster at \( z = 0.65 \), turned out not to be a massive cluster. The apparently extended X-ray emission detected by the Einstein satellite likely originates from several point sources. Our spectroscopic data of galaxies in this field show no well-defined concentration in redshift space consistent with a massive cluster. This leaves us with 14 clusters, and also the effect that the redshift interval \( z = 0.6–0.8 \) is rather sparsely covered by our sample.

Using the X-ray data from Piffaretti et al. (2011), the luminosity limit for the sample is \( L_{500} = 10^{44} \text{ erg s}^{-1} \) in the 0.1–2.4 keV band and within the radius \( R_{500} \). The radius \( R_{500} \) is the radius within which the average cluster overdensity is 500 times the critical density of the universe at the redshift of the cluster. The cluster properties are summarized in Table 1, including information on \( L_{500}, R_{500}, \) and the corresponding masses \( M_{500} \).

For each cluster, we have obtained ground-based imaging in three or four of the passbands \( g', r', i', \) and \( z' \). The photometry typically reaches a limiting magnitude of 25 mag in the passband closest to the \( B \) band in the rest frame of the clusters. The photometry is used for (1) sample selection for spectroscopic observations and (2) calibration of both the ground-based photometry and photometry from higher spatial resolution imaging to rest-frame magnitudes and colors.

The spectroscopic samples contain 30–60 candidate members in each cluster. This usually results in spectroscopic data for 20 or more passive bulge-dominated members in each cluster. The S/N and resolution of the spectra are sufficient to reliably measure velocity dispersions and absorption line strength for individual galaxies. Our samples span from the brightest cluster galaxies with typical dynamical masses of \( \approx 10^{12.6} M_{\odot} \) to galaxies with dynamical masses of \( \approx 10^{10.3} M_{\odot} \), equivalent to a velocity dispersion of about 100 km s\(^{-1}\). All collection of ground-based imaging and spectroscopy was done in the period 2001–2005 with Gemini North and South, using the Gemini Multi-Object Spectrographs GMOS-N and GMOS-S. See Hook et al. (2004) for a description of the instruments.

The GCP makes use of high spatial resolution imaging of the clusters primarily from the Advanced Camera for Surveys (ACS)
Table 1

Cluster Properties

| Cluster                  | Redshift | \( \sigma_{\text{cluster}} \) km s\(^{-1} \) | \( L_{\text{500}} \) \( 10^{44} \) erg s\(^{-1} \) | \( M_{\text{500}} \) \( 10^{14} M_\odot \) | \( R_{\text{500}} \) Mpc | \( N_{\text{member}} \) | References |
|-------------------------|----------|---------------------------------|--------------------------------|--------------------------------|----------------|----------------|------------|
| Abell 1689/RX J1311.4–0120 | 0.1865 ± 0.0010 | 2182\(^{+150}_{-163} \) | 12.524 | 8.392 | 1.350 | 72 | J2017 |
| RX J0056.2+2622/Abell 115 | 0.1922 ± 0.0008 | 1444\(^{+119}_{-140} \) | 7.485 | 6.068 | 1.206 | 58 | J2017 |
| RX J0056.2+2622N\(^a\) | 0.1932 ± 0.0010 | 1328\(^{+233}_{-213} \) | 3.935 | 4.100 | 1.058 | 12 | J2017 |
| RX J0056.2+2622S\(^b\) | 0.1929 ± 0.0010 | 1218\(^{+204}_{-164} \) | 4.094 | 4.200 | 1.067 | 22 | J2017 |
| RX J0142.0+2131 | 0.2794 ± 0.0009 | 1283\(^{+166}_{-136} \) | 5.587 | 4.761 | 1.079 | 30 | B2005 |
| RX J0027.6+2616 | 0.3650 ± 0.0009 | 1232\(^{+162}_{-122} \) | 8.376 | 5.684 | 1.108 | 34 | J2017 |
| RX J0027.6+2616 group | 0.3404 ± 0.0003 | 172\(^{+27}_{-27} \) | ... | ... | ... | ... | J2017 |
| Abell 851 | 0.4050 ± 0.0008 | 1391\(^{+112}_{-102} \) | 4.907 | 3.970 | 0.980 | 50 | H2018 |
| RX J1347.5–1145\(^b\) | 0.4506 ± 0.0008 | 1259\(^{+210}_{-210} \) | 8.278 | 5.264 | 1.046 | 43 | J2017 |
| RX J2146.0+0423 | 0.532 | ... | 1.912 | 2.015 | 0.736 | ... | In preparation |
| MS 0451.6–0305 | 0.5398 ± 0.0010 | 1450\(^{+105}_{-159} \) | 15.352 | 7.134 | 1.118 | 47 | J2013 |
| RX J2016.5–1747 | 0.578 | ... | 2.267 | 2.147 | 0.738 | 36 | In preparation |
| RX J1334.3+5030 | 0.620 | ... | 3.406 | 2.656 | 0.779 | ... | In preparation |
| RX J1716.6+6708\(^c\) | 0.809 | ... | 4.368 | 2.623 | 0.718 | ... | In preparation |
| MS 1610.4+6616 field\(^d\) | 0.8300 ± 0.0011 | 681\(^{+129}_{-105} \) | ... | ... | ... | 12 | In preparation |
| RX J0152.7–1357 | 0.8350 ± 0.0012 | 1110\(^{+147}_{-174} \) | 6.291 | 3.222 | 0.763 | 29 | J2005 |
| RX J0152.7–1357N\(^b\) | 0.8372 ± 0.0014 | 681 \(\pm 232 \) | 1.933 | 1.567 | 0.599 | 7 | J2005 |
| RX J0152.7–1357S\(^b\) | 0.8349 ± 0.0020 | 866 \(\pm 266 \) | 2.961 | 2.043 | 0.657 | 6 | J2005 |
| RX J1226.9+3332 | 0.8908 ± 0.0011 | 1298\(^{+177}_{-122} \) | 11.253 | 4.386 | 0.827 | 35 | J2013 |
| RX J1415.1+3612\(^c\) | 1.0269 ± 0.0010 | 676\(^{+54}_{-29} \) | 7.773 | 3.109 | 0.698 | 18 | In preparation |

Notes. Column 1: galaxy cluster. Column 2: cluster redshift. Column 3: velocity dispersion. Column 4: X-ray luminosity in the 0.1–2.4 keV band within the radius \( R_{\text{500}} \). X-ray data are from Piffaretti et al. (2011), except as noted. Column 5: Cluster mass derived from X-ray data within the radius \( R_{\text{500}} \). Column 6: radius within which the mean overdensity of the cluster is 500 times the critical density at the cluster redshift. Column 7: number of member galaxies for which spectroscopy has been obtained. Column 8: references for redshifts, velocity dispersions, and spectroscopic data. B2005—Barr et al. (2005), updated to use a consistent method for determining the velocity dispersion; J2005—Jørgensen et al. (2005); J2006—Jørgensen & Chiboucas (2013); J2013—Jørgensen et al. (2017); H2018 P. Hibon et al. (2018, in preparation). In preparation: papers in preparation. Except for MS 1610.4+6616 and RX J1415.1+3612, our spectroscopic data for these clusters are not fully processed. Thus, we do not list the cluster velocity dispersions.

\( \alpha/\text{Fe} \)

or the Wide Field and Planetary Camera 2 (WFPC2) on board *HST*. The data are in part archive data obtained for other programs and in part a result of our approved programs. RX J0056.2+2622 was covered by high-resolution ground-based imaging in the \( r' \) band obtained with Gemini North. High spatial resolution imaging is used to measure half-light radii, mean surface brightnesses, and total magnitudes from fits with Sérsic profiles (Sérsic 1968) and \( r^{1/2} \) profiles. The Sérsic indices are used to ensure that our final samples for the analysis are indeed bulge-dominated galaxies. The details of our methods for determining these parameters can be found in Chiboucas et al. (2009). Table 2 gives an overview of the relevant *HST* data. Additional two-dimensional photometry derived from these data will be included in future papers. For some of the clusters, data are available for filters with wavelengths shorter than those listed in the table, but these are not used in the GCP.

Our main methods for analysis so far have been to (1) study how the scaling relations like the FP and velocity dispersion—line strength relations evolve with redshift, and (2) investigate the distributions of ages, metallicities, and abundance ratios as well as establish how these parameters depend on galaxy velocity dispersion, redshift, and possibly the cluster environment. Our previous papers detail the results of this analysis of eight of the clusters, see Jørgensen et al. (2005, 2006, 2007, 2017), Barr et al. (2005), Jørgensen & Chiboucas (2013). The next section provides a brief overview of these and other papers relevant for the project.

### 2.2. Previous Papers from the GCP

In our first paper from the GCP, Jørgensen et al. (2005), we presented results for RX J0152.7–1157 \((z = 0.84)\) based on ground-based photometry and spectroscopy. The data support passive evolution, but also highlighted that the cluster appears to contain galaxies with unusually high abundance ratios, \( \alpha/\text{Fe} \). The paper contains all spectroscopic measurements for the cluster members, as well as a grayscale image showing the sample and the X-ray data.

Barr et al. (2005, 2006) studied the \( z = 0.28 \) cluster RX J0142.0+2131. The cluster has scaling relations with unusually high scatter, and may be a merging cluster. At the time of publication, no *XMM-Newton* or *Chandra* X-ray data of the cluster existed, making it difficult to evaluate the presence of a cluster merger. Barr et al. (2005) present all spectroscopic measurements for the cluster members.

In Jørgensen et al. (2006, 2007), we established the FP for the two clusters RX J0152.7–1157 \((z = 0.84)\) and RX J1126.9+3332 \((z = 0.89)\). Our results showed for the first time that the FP, when viewed as a relation between the dynamical
mass-to-light ratios and the dynamical masses, is steeper at higher redshift than that found for our local reference sample. We interpreted this to be due to the presence of a younger stellar population in the lower-mass galaxies than in the higher-mass galaxies.

In order to provide a homogeneous photometric calibration to apply to all of the ground-based photometry used in the GCP, we processed all standard star observations obtained with GMOS-N in the period 2001 August to 2003 December. The magnitude zero-points and color terms established from these data were presented in Jørgensen (2009) and are used in the present paper.

The methods used for deriving two-dimensional photometry from the HST data are described in Chiboucas et al. (2009). The paper contains measurements of effective radii, total magnitudes, and Sérsic (1968) indices for our sample galaxies in RX J0142.0+2131, RX J0152.7–1157, and RX J1226.9+3332.

In Jørgensen & Chiboucas (2013), we presented the joint analysis of the spectroscopic and photometric data of three clusters, MS 0451.6–0305 (z = 0.54), RX J0152.7–1157, and RX J1226.9+3332. We do not detect any size evolution of the galaxies from z ≈ 0.9 to the present. Our results based on the FP indicated a lower formation redshift than what we found from the Balmer absorption lines. We speculated that the difference may be due to evolution in the dark matter content affecting the FP result. This paper contains all spectroscopic measurements of cluster members in MS 0451.6–0305 and RX J1226.9+3332, as well as photometric parameters for galaxies in MS 0451.6–0305 based on the available HST imaging. We also provide grayscale images of MS 0451.6–0305 and RX J1226.9+3332 showing the samples and the X-ray imaging of the clusters.

Woodrum et al. (2017) analyzed the stellar populations of the non-member galaxies in the fields of MS 0451.6–0305, RX J0152.7–1157, and RX J1226.9+3332. The data show an absence of size evolution also for the field galaxies, an FP in agreement with our results for the cluster galaxies, and formation redshifts that are also consistent with our results for cluster galaxies. This paper contains the spectroscopic measurements for all non-member galaxies in the three fields.

Our analysis in Jørgensen et al. (2017) is focused on the seven most massive clusters in the GCP z = 0.2–1.0 sample. We analyzed the joint spectroscopic data for the clusters Abell 1689 (z = 0.19), RX J0056.2+2622 (z = 0.19), RX J0027.6+2616 (z = 0.37), RX J1347.5–1145 (z = 0.45), MS 0451.6–0305, RX J0152.7–1157, and RX J1226.9+3332. In addition to revisiting the formation redshift of the passive galaxies, we also established the age–velocity dispersion, [M/H]–velocity dispersion, and [α/Fe]–velocity dispersion relations. We found a flat age–velocity dispersion in apparent disagreement with results for local galaxies. The two other relations are steep and tight, in agreement with results for local galaxies. The paper contains all spectroscopic measurements for the cluster members in Abell 1689, RX J0056.2+2622, RX J0027.6+2616, and RX J1347.5–1145, as well as grayscale images of these clusters showing the samples and the X-ray imaging.

### 2.3. Calibration of X-Ray Data

The comprehensive X-ray cluster catalog by Piffaretti et al. (2011) provides consistently calibrated X-ray data for the majority of the GCP clusters. However, RX J1716.6+6708 and RX J1415.1+3612 are not included in this catalog, and it treats the binary clusters RX J0056.2+2622 and RX J0152.7–1357 as single clusters. To cover these clusters, we calibrate X-ray data from Ettori et al. (2004, 2009), Stott et al. (2010), Mahdavi et al. (2013, 2014), and Pascut & Ponman (2015) to be consistent with the Piffaretti et al data. In addition, we use updated (and calibrated) values for RX J1347.5–1145 from Ettori et al. (2004), who correct the X-ray measurements for diffuse emission from an infalling subcluster to the southeast of the main cluster; see also Jørgensen et al. (2017) for a discussion of this cluster.
Table 3

| Catalog      | Primary measure | N  | Mean  | Median | rms  | Δ    |
|--------------|-----------------|----|-------|-------|------|------|
| Ettori et al. (2004) | $R_{500}, M_{500}$ | 14 | 0.23  | 0.23  | 0.21 | 0.23 |
| Ettori et al. (2009) | $R_{500}, M_{500}$ | 31 | 0.24  | 0.29  | 0.23 | 0.29 |
| Stott et al. (2010) | $T_X, M_{500}$ | 7  | 0.18  | 0.27  | 0.19 | 0.18 |
| Mahdavi et al. (2013, 2014) | $M_{\text{Hydro}}$ | 29 | 0.02  | 0.00  | 0.14 | 0.00 |
| Pascut & Ponman (2015) | $R_{500}, M_{500}$ | 20 | 0.08  | 0.08  | 0.13 | 0.08 |

Note. Column 1: reference for X-ray data. Column 2: primary parameter from catalog; see the text. Column 3: number of clusters in common with Piffaretti et al. (2011). Column 4: mean of the differences in $\log M_{500}$; differences are calculated as Catalog – Piffaretti. Column 5: median of the differences. Column 6: rms of the differences. Column 7: adopted offset in $\log M_{500}$ to reach consistency with Piffaretti et al.

In the calibration, we use conversions between radii $R_{500}$, masses $M_{500}$, and luminosities $L_{500}$ as given by Piffaretti et al. in their Equations (2) and (3). We reproduce them here for clarity:

$$h(z)^{-7/3} \left( \frac{L_{500}}{10^{44} \text{erg s}^{-1}} \right) = C \left( \frac{M_{500}}{3 \cdot 10^{14} M_\odot} \right)^{\alpha},$$

(1)

where $h(z)$ is the Hubble factor at redshift $z$, $\log C = 0.274$, and $\alpha = 1.64$, and

$$M_{500} = \frac{4\pi}{3} R_{500}^3 \rho_\Lambda(z),$$

(2)

where $\rho_\Lambda(z) = 3H(z)^2/(8\sqrt{\pi} G)$ is the critical density of the universe at redshift $z$.

We convert the X-ray data from the literature to $M_{500}$. As needed, we also adopt the following conversions from Piffaretti et al.: $L_{500} = 0.91 L_{\text{total}}$, $R_{500} = 1.52 R_{\text{iso}}$, and $L_{500} = 0.96 L_{200}$. The relation between $R_{500}$ and $R_{\text{iso}}$ is equivalent to $M_{500} = 1.40 M_{\text{iso}}$; cf. Equation (2). When other conversions are used in the literature, we remove those and apply the above conversions before comparing with data from Piffaretti et al.

We determine the offsets in $\log M_{500}$ between the other catalogs and Piffaretti et al. to establish the best offset for each set of data. Table 3 and Figure 1 summarize the comparisons and the adopted offsets.

2.4. Cluster Properties

Table 1 summarizes the properties for all GCP clusters. In Figure 2 we show the cluster masses versus redshifts for these clusters. For reference, the figure also shows our local reference sample and the clusters from Piffaretti et al. (2011). We show sample models for the growth of cluster masses with time, based on simulations from van den Bosch (2002). These models are in general agreement with newer and more detailed analyses of the results from the Millennium simulations (Fakhouri et al. 2010).

Grayscale optical images with X-ray data overlaid of clusters for which we previously have published results are available in those papers as follows: RX J0152.7–1357 is published in Jørgensen et al. (2005), MS 0451.6–0305 and RX J1226.2+3332 are published Jørgensen & Chiboucas (2013), and Abell 1689, RX J0056.2+2622, RX J0027.6+2616, and RX J1347.5–1147 are published in Jørgensen et al. (2017). The remaining clusters are shown in Appendix C of the current paper, Figures 20–27. The grayscale images show the spectroscopic sample, and when available at this time, information about cluster membership and galaxy properties. In Appendix C, we also describe each of the clusters, including providing the original references for their discovery and main references for substantial results on the cluster properties and, when available, the star formation history of their members.
The Astrophysical Journal Supplement Series, 235:29 (37pp), 2018 April

Jørgensen et al.

5. Mosaicking of the images from the three GMOS detectors into one image, using the transformations available in the Gemini IRAF package task gmosaic.

6. Stacking of images taken in the same filter to obtain a co-added cosmic-ray cleaned image, normalized to one of the exposures taken in photometric conditions. This was done using the Gemini IRAF package task imcoadd. The stack made as the average of good pixels was used for all photometry.

7. Observations taken unbinned were rebinned to 2 × 2. This applies to the observations taken during 2001 and to the RX J0216.5–1747 z'-band observations. The resulting pixel scale for all GMOS-N observations is 0.1454 arcsec pixel−1, while the GMOS-S observations have a pixel scale of 0.146 arcsec pixel−1.

8. The images were calibrated to astrometric consistency with the USNO catalog (Monet et al. 1998) by means of simple offsets. Only linear calibrations were used. The rms scatter of the calibrations is ≈0.7 arcsec.

We refer to the final stacked images as the “co-added images.” The original processing of the data as described in Jørgensen et al. (2005) used prototypes of the tasks released later for fringe correction of GMOS data. Because the released tasks provide better object cleaning of the fringe correction frames than the prototypes, and because the fringes in the z' band are quite strong (5% peak-to-peak for GMOS-N), we have reprocessed z'-band imaging from the raw data available in the Gemini Observatory Archive, using currently released tasks for the processing. The r'-band observations of RX J1415.1+3612 were also reprocessed in order to achieve a better correction for the scattered light in these observations.

3. Ground-based Imaging

Ground-based imaging of the clusters was obtained with GMOS-N and GMOS-S in the period from 2001 to 2005. Each cluster was observed in three or four of the filters g', r', i' and z'. Table 4 summarizes the instrument information, while Table 16 in Appendix A gives detailed information on the available observations, including the Gemini program IDs. That table also lists the adopted Galactic extinction for each of the fields and filters. Abell 1689 and RX J0056.2+2622 were observed with two pointings, while all other clusters have data for one pointing.

3.1. Processing of Imaging Data

The basic processing of the data was done in a standard fashion using the Gemini IRAF package. We followed procedures similar to those described for RX J0152.7–1357 in Jørgensen et al. (2005), involving the following steps:

1. Bias subtraction with master bias frame for the month of the observations.
2. Flat fielding with normalized twilight flat created from 10–20 individual twilight flats.
3. For the i' and z' bands, fringe correction with scaled fringe frames established from the science data.
4. For the g' and r' bands, as needed, scattered light correction with scaled scattered light images established from the science data.
5. Deblending of objects in these fairly crowded fields. For Abell 1689 and RX J1334.3+5030, even lower minimum contrast for a deblending of 0.0002 was

3.2. Derived Photometric Parameters

The co-added images were processed with SExtractor version 2.8.6 (Bertin & Arnouts 1996). We used SExtractor in dual-image mode, with the images pre-registered to each other. The image in the filter closest to the rest-frame B band was used for detections, while the images in the other filters were used only for photometry. For consistency between clusters, the threshold for detection was defined as a surface brightness. The detection thresholds combined with the requirement of meeting the threshold over a minimum of 9 pixels correspond to an S/N of 8–10. The analysis threshold in the other bands was then defined using the approximate expected colors of the cluster members on the red sequence. In all cases, we maintain analysis thresholds corresponding to an S/N of 5–6 or better over the minimum detection area of 9 pixels. Thus, for objects on the red sequence, roughly the same aperture size in each band is used to derive the geometrical parameters. The geometrical parameters are used by SExtractor to derive the class_star parameter, which we use to separate galaxies and stars. Table 5 lists the filter used for detection and the adopted thresholds.

The SExtractor background mesh size was adjusted to avoid systematic effects from the galaxies with the largest angular size. We typically use a background mesh size of 256 pixels, with a filter size of 5 pixels. We used 64 subthresholds and a minimum contrast for the deblending of only 0.0005 (the default is 0.005). This enables deblending of objects in these fairly crowded fields. For Abell 1689 and RX J1334.3+5030, even lower minimum contrast for a deblending of 0.0002 was
needed to deblend fainter objects in the vicinity of either the brightest galaxies in the cluster center (Abell 1689) or at close angular distance to bright stars (RX J1334.3+5030). For Abell 1689, the lower deblending contrast is used only within 30 arcsec of the cluster core (for this purpose defined as the position of the galaxy with ID 626). For RX J1334.3+5030, the detections were done in the $i'$ band, which has an image quality of FWHM = 0.87 arcsec (measured as the FWHM from a Gaussian fit to stars in the image). We used the better seeing $z'$-band image (FWHM = 0.54 arcsec) to check that the...
Figure 5. Uncertainties on the magnitudes mag_auto vs. the magnitude mag_auto in the detection band for three of the clusters, RXJ0142.0+2131 at \( z = 0.28 \), MS 0451.6−0305 at \( z = 0.54 \), and RX J1415.1+3612 at \( z = 1.03 \). The figure illustrates the depth of the data at different redshifts. All objects detected in the fields are included. The points are color-coded by filter: blue—\( g' \), green—\( r' \), orange—\( i' \), and red—\( z' \).

deblending was correct. In all cases, we use the SExtractor convolution file Gauss_2.0_3x3.conv. We visually inspected all fields to ensure that galaxies in our spectroscopic samples were correctly deblended.

SExtractor was run without a weight image. However, the catalogs were cleaned of spurious detections along the edges of the field and along the edges of any vignetting from the GMOS on-instrument wavefront sensor (OIWFS) when this is inside the field of view. Table 5 lists the effective area for object detection after such cleaning.

We adopt mag_auto from SExtractor as the total magnitudes of the objects, as these magnitudes are consistently derived based on apertures 2.5 times the Kron radii, \( r_{Kron} \) (Kron 1980). See Graham & Driver (2005) for a discussion of the implementation of the Kron radius in SExtractor. In some cases of close neighbors, the magnitudes may be affected by these. We also provide the isophotal magnitudes, mag_iso, in the photometry table. In Section 3.4, we discuss to what extent mag_auto is different from true total magnitudes, and we derive aperture corrections for point sources.

Differences in image quality between the observations in the different passbands can complicate the determination of colors of the galaxies. Various techniques to address this issue have been used in the past. One approach is to used fixed size apertures, but to convolve all images of a given field to a common (worst) resolution, or, less drastically, convolving the images only in pairs as described by Meyers et al. (2012) and used by, e.g., Cerulo et al. (2016). Alternatively, one may obtain “global” colors of the galaxies, using mag_auto as the basis for the colors. We note that mag_auto is also the only choice of the SExtractor “total” magnitudes that use the same size aperture for all frames.

Instead of convolving the images, we take the approach of measuring the aperture colors, using aperture sizes chosen to minimize the effect of image quality differences on the measured colors. To decide on the aperture sizes, we first estimate aperture diameters in arcsec using the image quality, FWHM, and the half-light radius of typical small galaxies in the clusters. Specifically, the aperture diameter in arcsec is chosen to be

\[
D_{app} = 2 \cdot 2.355((\text{FWHM}/2.355)^2 + r_{\text{galaxy}}^2)^{0.5},
\]

where \( r_{\text{galaxy}} \) is the half-light radius in arcsec at the redshift of the cluster, corresponding to a physical size of 2.5 kpc. For those clusters with differences between \( D_{app} \) in the different passbands of less than 10%, we then used the largest of those diameters as the aperture size for all of the passbands. For RX J1347.5−1145 and RX J1334.3+5030, the differences between \( D_{app} \) for the different passbands were larger than 10%. Thus, for these clusters, we used two different aperture sizes. Aperture sizes are listed in Table 5. In the catalog table (see Section 5), we give the aperture magnitudes. For reference, we also provide aperture magnitudes within an aperture with a diameter of 2.5 arcsec.

Other adjustments to the SExtractor parameters were trivial adjustments to the magnitude zero-points and the image quality.

Stars and galaxies were separated based on the SExtractor classification parameters class_star for all available bands. We derive the product and the median of those available, and define

\[
P(\text{class}\_\text{star}) = \prod \text{class}\_\text{star},
\]

\[
M(\text{class}\_\text{star}) = \text{median}(\text{class}\_\text{star}).
\]

Objects are classified as stars if they meet the criterion

\[
P(\text{class}\_\text{star}) \geq 0.8^n || M(\text{class}\_\text{star}) \geq 0.8,
\]
while all other objects were considered galaxies. $N$ is the number of bands available for a given field. The classification of saturated stars was set manually. Figure 3 shows $M(\text{class\_star})$ versus $P(\text{class\_star})$ for two of the clusters, RX J2146.0+0423 with photometry in three bands and RX J0216.5−1747 with photometry in four bands. The image quality for the observations of these two clusters is comparable, 0.50–0.65 arcsec. The parameters $P(\text{class\_star})$ and $M(\text{class\_star})$ are included in the table of the photometric data (see Section 5), allowing users to reclassify the objects based on the available data. Figure 4 shows $P(\text{class\_star})$ and $\text{class\_star}$ in the detection band versus magnitudes.

Figure 6. Distribution of $\text{mag\_auto}$ for stars (blue) and galaxies (red) in the fields. The vertical dashed lines mark the 5σ detection limit; see Table 5.
Table 5

Photometry Overview

| Cluster     | Detection band | Thresholds (in mag arcsec^2) | Apertures (in arcsec) | 5σ limit | N_star | N_galaxy | Area (in arcmin^2) |
|-------------|----------------|-------------------------------|----------------------|----------|--------|----------|-------------------|
| Abell 1689  | g'             | 25.5, 24.5, 24.0, ...         | 4.35                 | 24.8     | 90     | 1981     | 44.9^a            |
| RX J0056.2-2622 | g'          | 25.5, 24.5, 24.0, ...         | 4.18                 | 25.1     | 113    | 991      | 53.3^a            |
| RX J0142.0-2131 | r'          | 27.0, 25.5, 24.9, ...         | 3.08                 | 24.8     | 55     | 1546     | 28.6              |
| RX J0027.6+2616 | r'          | 27.0, 25.5, 24.9, ...         | 2.66                 | 25.2     | 75     | 1291     | 28.0^b            |
| Abell 851   | r'             | 27.0, 25.5, 24.9, ...         | 2.61                 | 25.2     | 60     | 1684     | 28.5              |
| RX J1347.5-1145 | r'          | 27.0, 25.5, 24.8, ...         | 3.09, 2.51           | 25.0     | 100    | 952      | 27.1^a            |
| RX J2146.0-0423 | r'          | 27.0, 25.5, 24.5, ...         | 2.17                 | 25.0     | 156    | 1223     | 28.8              |
| MS 0451.6-0305 | r'          | 27.0, 25.5, 24.5, 24.1        | 2.44                 | 25.4     | 95     | 1453     | 27.5^b            |
| RX J0216.5-1747 | i'           | 27.0, 25.5, 24.5, 24.1        | 2.24                 | 24.8     | 49     | 710      | 26.8^a            |
| RX J1334.3+5030 | i'           | ... 26.3, 25.3, 24.9          | 2.74, 2.04           | 25.1     | 50     | 967      | 27.1^b            |
| RX J1716.6+6708 | i'           | ... 26.5, 25.3, 24.6          | 2.14                 | 24.9     | 104    | 1126     | 27.2^b            |
| MS 1610.4+6616 field | i'        | ... 26.3, 25.3, 24.9          | 2.25                 | 25.1     | 98     | 1180     | 27.8              |
| RX J0152.7-1357 | i'           | ... 26.5, 25.3, 24.6          | 2.06                 | 24.7     | 51     | 1732     | 28.6              |
| RX J1226.9+3332 | i'           | ... 26.5, 25.3, 24.7          | 2.17                 | 25.0     | 61     | 1056     | 27.8              |
| RX J1415.1+3612 | i'           | ... 26.5, 25.4, 24.7          | 2.04                 | 24.2     | 76     | 1132     | 26.8^b            |

Notes. Column 1: galaxy cluster. Column 2: filter used for detections. Column 3: thresholds in mag arcsec^2 in the order (g', r', i', z'). Column 4: diameter of apertures in arcsec. For RX J1347.5-1145, 3.09 arcsec was used for g' and 2.52 arcsec for r' and i', while for RX J1334.3+5030, 2.74 arcsec was used for r' and i' and 2.04 arcsec was used for z', see the text. Column 5: 5σ detection limit in magnitudes in the detection band; see Section 3.3. Column 6: number of stars in catalog. Column 7: number of galaxies in catalog. Column 8: area observed in arcmin^2. Abell 1689 and RX J0056.2-2622 were both observed with two slightly overlapping GMOS-N fields. The other clusters were covered with one field. Small variations in the final area are due to differences in dither patterns and vignetting from the OIWFS as noted.

^a Areas affected by vignetting by the OIWFS are excluded from the total area.

^b Areas around bright foreground galaxies are excluded from the total area.

Figure 7. Flux missed by mag_auto, Δm, as a function of mag_auto for stars observed in the four filters. The dashed lines mark the median missed flux, 0.06 mag in g', r', and z' and 0.075 mag in i'.

Illustrating how the use of P(class_star) aids in the classification of especially faint objects within ∼2 mag of the detection limit. In our original sample selection of targets for spectroscopic observations, we required class_star < 0.80 in the detection band. In a few cases, our refined classification would have excluded a spectroscopic sample target from the sample. In all such cases, except the Seyfert galaxy RX J1415.1+3612 ID 983, the spectra confirm that the objects are indeed stars. In Table 5, we list the number of objects classified as galaxies and as stars in each cluster field.

While our ground-based imaging in general is not of sufficient spatial resolution to warrant detailed two-dimensional photometry, we do provide measures of sizes as an isophotal radius, r_iso, as well as position angles and ellipticities, which may be useful for sample selections for other follow-up studies of the clusters. We use the isophotal area iso_area_image determined by SExtractor in pixels to derive a circularized isophotal radius in arcseconds as

\[ r_{\text{iso}} = (\text{iso}_\text{area}_\text{image}/\pi)^{0.5} \text{pixelscale}, \]

where “pixelscale” is the pixel scale for the image in arcsec pixel^{-1}. The surface brightnesses used for the determinations are listed in Table 5.

3.3. Uncertainties on Magnitudes

The uncertainties in the magnitudes estimated by SExtractor are based on the sky noise per pixel, σ_{sky}, combined with the Poisson noise of the signal from the objects. It is assumed that the noise from the sky scales with the area, A, of the aperture in pixels such that the total uncertainty on the flux, F, measured from an object can be expressed as

\[ \sigma_{\text{object}} = (4\pi^2 \sigma_{\text{sky}}^2 + F \text{gain}^{-1})^{1/2}, \]

where F is in counts and “gain” is the gain of the image in e^-/counts. Several studies have shown that these uncertainties in general are underestimated. In particular, Labbé et al. (2003) find that even for HST imaging and small apertures the effect can be a factor of 2. Due to imperfect corrections for scattered light and/or fringing, ground-based imaging often has stronger large-scale variations of the background than those typically found in HST imaging. We adopted a combination of the method used by Labbé et al. and that by Guo et al. (2013) to...
determine the correction factor for the noise estimates, given the sizes of the apertures.

For each field and filter combination, we mask out pixels containing signal from objects. We then place empty apertures with areas from 16 to 400 pixels, equivalent to aperture diameters of 0.65–3.3 arcsec. For the largest size apertures, we typically place 200–300 empty apertures across the masked images, while for the smaller sizes, 600–800 empty apertures were used. The background was subtracted using the sky image produced by SExtractor. We then measure the flux in each of the empty apertures. For each size aperture, we determine the scatter of the fluxes from a Gaussian fit to their distribution. As
also found by Labbé et al., the scatter for a given field and filter can be parameterized as

$$\sigma_i = A^{1/2} \sigma_{sky} (a_i + b_i A^{1/2}).$$

We determine the coefficients $a_i$ and $b_i$ from least-squares fits. Table 6 summarizes the determinations, the sky noise per pixel $\sigma_{sky}$ normalized to 1 s, and the resulting correction factor $a_i + b_i A^{1/2}$ for an aperture with a diameter of 2.5 arcsec. The correction factors are between 1.8 and 6.7, with a median value of 3.2. The median of the coefficients $a_i$ is 1.25, reflecting the typical correlation of noise between pixels due to the stacking of multiple frames, cf., Labbé et al. The coefficients $b_i$, reflecting the typical large-scale variations in the background, have a median value of 0.13.

The uncertainties of all magnitudes were then derived using the coefficients and the relevant sizes of the apertures. Figure 5 shows uncertainties on $\text{mag}_\text{auto}$ as a function of $\text{mag}_\text{auto}$ for three of the clusters spanning the redshift range of the sample and illustrating the typical depth of the data as a function of redshift and passband. In Figure 6, we show the magnitude distribution of the objects for each field in the

Figure 9. Galaxy simulations matching the observations of RX J1226.9+3332 (z = 0.89). The layout and symbols are as in Figure 8. For this cluster, we show the ($i' - z'$) colors.
detection band. The 5σ detection limits are listed in Table 5 and marked on the figure.

3.4. SExtractor Magnitudes versus Total Magnitudes

The SExtractor magnitudes $mag_{\text{auto}}$ are known to miss a small fraction of the total flux from objects. Bertin & Arnouts (1996) determined from simulations the loss to be 0.03–0.06 magnitudes. Theoretical work by Graham & Driver (2005) shows that the fraction lost for galaxies depends on their luminosity profile. For galaxies with Sérsic (1968) profiles, the fraction lost is ≈4% for an exponential profile, increasing to ≈10% for an $r^{1/4}$ profile. However, Graham & Driver also point out that if the Kron radius (used as the basis for $mag_{\text{auto}}$) is derived from integration over only 1–2 effective radii of the galaxies, the lost flux can be substantially larger.

We first derived aperture corrections for the point sources in a standard fashion, using magnitudes derived through large apertures for bright isolated stars. The resulting aperture corrections, $\Delta m_{\text{aper}}$, for the adaptive aperture sizes defined in Equation (3) as well as for the fixed aperture size of 2.5 arcsec diameter are listed in Table 7. As expected, the aperture correction for the fixed aperture size is strongly correlated with the image quality, increasing from ≈0.05 mag for the best seeing images to ≈0.15 mag at a seeing of 0.8 arcsec. The flux missed from $mag_{\text{auto}}$ can then be derived as

$$\Delta m = mag_{\text{auto}} - (mag_{\text{aper}} + \Delta m_{\text{aper}}).$$

Figure 7 shows $\Delta m$ versus $mag_{\text{auto}}$ for the unsaturated stars in the detection bands. The median missed flux is 0.06 mag in $g'$, $i'$, and $z'$. The missing flux in the $r'$ band is slightly higher at 0.075 mag, presumably due to differences in the point-spread functions.

To assess the fraction of flux lost from $mag_{\text{auto}}$ of the galaxies in the observed fields, we performed detailed simulations matching 5 of the 15 clusters, spanning the relevant parameter space in redshifts, image quality, and filters. The simulations were created using Python software by R. Peterson et al. (2018, in preparation), produced during Peterson’s internship with the GCP. The simulation software calls the galaxy-fitting program GALFIT (Peng et al. 2002) to make the model galaxies.

For each cluster, we made simulated images matching the three (or four) available filters. Each simulated image contains 500–1000 model galaxies. The model galaxies have distributions in total magnitudes matching the $mag_{\text{auto}}$ distributions of the real data, and two-dimensional distributions in effective radii and total magnitudes, which, once convolved with the point-spread function (PSF), match the two-dimensional distributions in $(mag_{\text{auto}}, \text{flux radius})$ of the real data. The galaxies were assumed to have Sérsic profiles. For each galaxy, values of the Sérsic indices, $n_{\text{ser}}$, ellipticities; and position angles were chosen randomly from uniform distributions. We assumed $n_{\text{ser}}$ between 0.5 and 5, ellipticities between zero and 0.7, and position angles between $-90$ and $+90$ degrees. We then used GALFIT to create noiseless model images of each galaxy. Each model galaxy was convolved with the empirical PSF of the real data. The PSFs were established from 10 to 15 isolated stars in the fields. The model galaxies were randomly placed into empty images of the same size as our GMOS images and with a background level matching the real data. Thus, these images have crowding of the objects similar to the real observations, except for the very center of the clusters. Finally, noise was
Table 6
Noise Parameters

| Cluster          | $g'$ Band          | $r'$ Band          | $i'$ Band          | $z'$ Band          |
|------------------|--------------------|--------------------|--------------------|--------------------|
|                  | $a$ (2)            | $b$ (3)            | $\sigma_{\text{sky}}$ (4) | $\text{Factor}$ (5) | $a$ (10)       | $b$ (11)       | $\sigma_{\text{sky}}$ (12) | $\text{Factor}$ (13) | $a$ (14)       | $b$ (15)       | $\sigma_{\text{sky}}$ (16) | $\text{Factor}$ (17) |
| A1689 F1         | 1.42               | 0.196              | 0.048              | 4.41               | 0.85           | 0.280           | 0.071              | 5.13               | 0.78           | 0.163           | 0.210              | 3.26               |
| A1689 F2         | 1.25               | 0.223              | 0.047              | 4.65               | 0.62           | 0.259           | 0.091              | 4.56               | 0.87           | 0.111           | 0.213              | 2.56               |
| RX J0056p2p2622 F1 | 0.96               | 0.075              | 0.084              | 2.09               | 1.18           | 0.148           | 0.100              | 3.44               | 1.61           | 0.057           | 0.136              | 2.48               |
| RX J0056p2p2622 F2 | 1.15               | 0.045              | 0.080              | 1.83               | 1.21           | 0.140           | 0.095              | 3.34               | 1.39           | 0.162           | 0.115              | 3.85               |
| RX J0142p0p2131  | 1.23               | 0.162              | 0.028              | 3.70               | 0.86           | 0.169           | 0.087              | 3.44               | 1.37           | 0.081           | 0.083              | 2.61               |
| RX J0027p6p2616  | 1.24               | 0.168              | 0.029              | 3.80               | 0.79           | 0.121           | 0.068              | 2.64               | 1.12           | 0.341           | 0.074              | 6.32               |
| A0851            | 1.16               | 0.146              | 0.026              | 3.39               | 1.03           | 0.094           | 0.085              | 2.47               | 1.57           | 0.088           | 0.077              | 2.90               |
| RX J1347p5m1145  | 1.24               | 0.249              | 0.038              | 5.04               | 0.97           | 0.130           | 0.117              | 2.96               | 1.27           | 0.193           | 0.098              | 4.21               |
| RX J2146p0p0423  | 1.38               | 0.166              | 0.020              | 3.91               | 0.70           | 0.190           | 0.070              | 3.59               | 1.33           | 0.099           | 0.063              | 2.84               |
| MS 0451p6m0305   | 1.30               | 0.261              | 0.017              | 5.28               | 0.84           | 0.155           | 0.047              | 3.20               | 1.50           | 0.213           | 0.061              | 4.75               |
| RX J0216p5m1747  | 1.78               | 0.087              | 0.030              | 3.11               | 1.65           | 0.041           | 0.065              | 2.28               | 1.26           | 0.048           | 0.115              | 2.00               |
| RX J1334p3p5030  | 0.38               | 0.101              | 0.020              | 3.91               | 0.70           | 0.190           | 0.070              | 3.59               | 1.33           | 0.099           | 0.063              | 2.84               |
| RX J1716p6p6708  | 0.94               | 0.259              | 0.044              | 4.89               | 0.97           | 0.097           | 0.094              | 2.44               | 1.47           | 0.089           | 0.068              | 2.82               |
| MS 1610p4p6616   | 1.88               | 0.064              | 0.041              | 2.86               | 1.16           | 0.046           | 0.101              | 1.87               | 1.97           | 0.032           | 0.055              | 2.45               |
| RX J0152p7m1357  | 1.16               | 0.081              | 0.035              | 2.94               | 1.21           | 0.090           | 0.065              | 3.49               | 1.61           | 0.071           | 0.026              | 2.69               |
| RX J1226p9p3332  | 0.94               | 0.094              | 0.026              | 3.12               | 0.78           | 0.198           | 0.054              | 3.80               | 1.44           | 0.066           | 0.126              | 2.44               |
| RX J1415p1p3612  | 1.09               | 0.282              | 0.033              | 5.40               | 1.08           | 0.367           | 0.056              | 6.67               | 1.51           | 0.077           | 0.051              | 2.69               |

Note. Column 1: galaxy cluster and field. Column 2: $g'$-band noise correction coefficient $a$. Typical uncertainties are 0.11. Column 3: $g'$-band noise correction coefficient $b$. Typical uncertainties are 0.009. Column 4: $g'$-band sky noise per pixel, $\sigma_{\text{sky}}$, normalized to 1 s. Column 5: $g'$-band noise correction factor $a_i + b_iA_i^{1/2}$ for an aperture with a diameter of 2.5 arcsec. Columns 6–9: same information for the $r'$ band. Columns 10–13: same information for the $i'$ band. Columns 14–17: same information for the $z'$ band.
Figure 11. Star colors in the GCP fields, showing our GMOS photometry compared to the SDSS photometry. Small blue crosses—SDSS standard star data; these data are shown on all the panels and provide a reference for the location of stars in the color–color spaces. Black circles—photometry for stars in the cluster fields, colors based on total magnitudes mag_auto; circles with thicker outlines are those stars also included in SDSS. Cyan—photometry from SDSS for stars in each of the 10 fields with SDSS photometry available. The photometry shown in the figure has not been corrected for Galactic extinction. The correction is <0.04 for (g′−r′), and <0.02 in (i′−z′) for all clusters, except for RX J1214.0+0423 for which the correction of (g′−r′) is 0.06. Offsets to obtain the best calibration have been applied to our data as described in the text.
mode on the simulations, with all parameters set identically to those used for the real data. The simulations use the adaptive aperture sizes, Equation (3), for aperture magnitudes and colors. Figures 8 and 9 summarize the results from the simulations matching RX J0142.0+2131 ($z = 0.28$) and RX J1226.9+3332 ($z = 0.89$), serving as representatives for the relevant parameter space. Panels (a)–(c) of the figures show how the simulated data match the real data in magnitudes, sizes, and colors. In particular, panels (b) show the ratio $R = 2r_{\text{Kron}}/r_{\text{flux}}$ between the aperture size within which the Kron radius is determined by SExtractor ($2r_{\text{Kron}}$) and the effective radius here approximated with $r_{\text{flux}}$ from SExtractor.

Panels (d)–(f) in the figures show the lost flux, $\Delta m$, as a difference between the SExtractor $\text{mag\_auto}$ and the input total magnitude. Fainter galaxies have larger $\Delta m$. However, the main drivers for the difference are the ratio $R$, which depends on the magnitudes of the galaxies (panels (b)), and the assumed Sérsic index. In panels (e), we show for galaxies brighter than 23 mag $\Delta m$ as a function of $n_{\text{Sersic}}$. The points are color-coded for $R$ larger (orange) or smaller (blue) than 3. The simulations follow the expected dependency established by Graham & Driver, and shown on the figure. To further illustrate the dependency on both $R$ and $n_{\text{Sersic}}$, panels (f) show the effect as $\Delta m$ versus the ratio $R$, color-coded for $n_{\text{Sersic}}$. Based on our simulations for five clusters, we conclude that there are no significant differences in $\Delta m$ due to differences in filters, image quality, or redshift of the clusters. In summary, the median $\Delta m$ for galaxies brighter than 23 mag and with $R \geq 3$ is 0.06, 0.13, and 0.21 for $n_{\text{Sersic}} \leq 2$, 2–3.5, and $\geq 3.5$, respectively. The galaxies included in our spectroscopic samples and our investigation of the red sequence (Section 7) typically have $R \geq 3$. In practice, we do not know $n_{\text{Sersic}}$ from our ground-based data. However, we expect that galaxies on the red sequence have $n_{\text{Sersic}} \geq 2$, and therefore will have $\Delta m \approx 0.1$–0.2 mag.

In panels (g)–(h), we show the simulation results for the main color for the two clusters. In both cases, colors based on $\text{mag\_auto}$ reproduce the input colors better than colors based on aperture magnitudes, even when aperture sizes are chosen to match the seeing; cf. Equation (3). However, when evaluating which to use to investigate the colors of the real galaxies, it should also be kept in mind that the aperture magnitudes usually have lower uncertainties due to background noise. The simulations assumed no internal color gradients in the galaxies. Color gradients in the real galaxies will of course cause differences between aperture colors and colors using $\text{mag\_auto}$. In our discussion of the color–magnitude relation for the clusters, Section 7, we show both colors.

4. Photometric Calibration

4.1. Initial Calibration

The photometry from GMOS-N observations has been calibrated using magnitude zero-points and color terms established in Jørgensen (2009). As described in that paper, the expected absolute accuracy of the calibrations is $\approx 0.05$ mag. For convenience, the specific relations used for the color terms are reproduced in Table 8 with the original calibration numbers from Jørgensen (2009) noted. The $i'$-band observations were calibrated using the $(r'-i')$ color terms, except for the three highest-redshift clusters for which the $i'$ band was calibrated using the $(i'-z')$ color terms. This is done to avoid color terms spanning the 4000 Å break at the redshifts of the clusters. Ideally, the added, taking into account read-out noise and Poisson noise. We did not attempt to model the correlated noise due to the image stacking, or the contribution from the non-flat sky background in the real data. We do not expect these effects to contribute significantly to the fraction of lost flux.

For each cluster, we used the same seed to generate the random samples for each of the three (or four) filters. Thus, a given model galaxy will have identical $n_{\text{Sersic}}$, ellipticity, and position angle in the three (or four) filters. The color of the model galaxy will represent the average color of galaxies in the field at the given magnitude. SExtractor was run in dual-image mode on the simulations, with all parameters set identically to those used for the real data. The simulations use the adaptive aperture sizes, Equation (3), for aperture magnitudes and colors.

Figures 8 and 9 summarize the results from the simulations matching RX J0142.0+2131 ($z = 0.28$) and RX J1226.9+3332 ($z = 0.89$), serving as representatives for the relevant parameter space. Panels (a)–(c) of the figures show how the simulated data match the real data in magnitudes, sizes, and colors. In particular, panels (b) show the ratio $R = 2r_{\text{Kron}}/r_{\text{flux}}$ between the aperture size within which the Kron radius is determined by SExtractor ($2r_{\text{Kron}}$) and the effective radius here approximated with $r_{\text{flux}}$ from SExtractor.

Panels (d)–(f) in the figures show the lost flux, $\Delta m$, as a difference between the SExtractor $\text{mag\_auto}$ and the input total magnitude. Fainter galaxies have larger $\Delta m$. However, the main drivers for the difference are the ratio $R$, which depends on the magnitudes of the galaxies (panels (b)), and the assumed Sérsic index. In panels (e), we show for galaxies brighter than 23 mag $\Delta m$ as a function of $n_{\text{Sersic}}$. The points are color-coded for $R$ larger (orange) or smaller (blue) than 3. The simulations follow the expected dependency established by Graham & Driver, and shown on the figure. To further illustrate the dependency on both $R$ and $n_{\text{Sersic}}$, panels (f) show the effect as $\Delta m$ versus the ratio $R$, color-coded for $n_{\text{Sersic}}$. Based on our simulations for five clusters, we conclude that there are no significant differences in $\Delta m$ due to differences in filters, image quality, or redshift of the clusters. In summary, the median $\Delta m$ for galaxies brighter than 23 mag and with $R \geq 3$ is 0.06, 0.13, and 0.21 for $n_{\text{Sersic}} \leq 2$, 2–3.5, and $\geq 3.5$, respectively. The galaxies included in our spectroscopic samples and our investigation of the red sequence (Section 7) typically have $R \geq 3$. In practice, we do not know $n_{\text{Sersic}}$ from our ground-based data. However, we expect that galaxies on the red sequence have $n_{\text{Sersic}} \geq 2$, and therefore will have $\Delta m \approx 0.1$–0.2 mag.

In panels (g)–(h), we show the simulation results for the main color for the two clusters. In both cases, colors based on $\text{mag\_auto}$ reproduce the input colors better than colors based on aperture magnitudes, even when aperture sizes are chosen to match the seeing; cf. Equation (3). However, when evaluating which to use to investigate the colors of the real galaxies, it should also be kept in mind that the aperture magnitudes usually have lower uncertainties due to background noise. The simulations assumed no internal color gradients in the galaxies. Color gradients in the real galaxies will of course cause differences between aperture colors and colors using $\text{mag\_auto}$. In our discussion of the color–magnitude relation for the clusters, Section 7, we show both colors.

4. Photometric Calibration

4.1. Initial Calibration

The photometry from GMOS-N observations has been calibrated using magnitude zero-points and color terms established in Jørgensen (2009). As described in that paper, the expected absolute accuracy of the calibrations is $\approx 0.05$ mag. For convenience, the specific relations used for the color terms are reproduced in Table 8 with the original calibration numbers from Jørgensen (2009) noted. The $i'$-band observations were calibrated using the $(r'-i')$ color terms, except for the three highest-redshift clusters for which the $i'$ band was calibrated using the $(i'-z')$ color terms. This is done to avoid color terms spanning the 4000 Å break at the redshifts of the clusters. Ideally, the
Figure 14. Color–magnitude diagrams showing the aperture colors used for the rest-frame $B$-band calibration vs. the total magnitudes. Small gray squares—aperture colors for all galaxies in the field; red squares—aperture colors for confirmed members from our spectroscopy; magenta squares—aperture colors for clusters without processed spectroscopy, the spectroscopic sample members selected for the red sequence fitting, see text; green triangles—aperture colors for either confirmed non-members from our spectroscopy or galaxies omitted in the fitting of the red sequence, see text. Red and magenta lines—best-fit red sequence to the red or magenta points, iteratively determined as described in the text. Dashed black lines are offset from the best-fit color–magnitude relations with $\pm 3$ times the scatter. Black open squares—colors from mag_auto for confirmed members or for clusters without processed spectroscopy the the spectroscopic sample members selected for the red sequence fitting.
calibration based on the \((i' - z')\) color term should also have been used for RX J1716.6+6708. However, the \(z'\)-band observation of this cluster is too shallow for the \((i' - z')\) color term to provide a good calibration of the \(i'\)-band magnitudes.

RX J1347.5–1147 was observed with GMOS-S. We determined the calibration from standard stars observed the same night (UT 2005 January 11). Color terms were adopted from the Gemini Web site. The calibrations are summarized in Table 9. For completeness, we also list the magnitude zero point for the \(z'\) band, though not used for our photometry.

All observed magnitudes are calibrated to AB magnitudes. We adopted the mean atmospheric extinction for Maunakea as listed in Jørgensen (2009), \(k_g = 0.14\), \(k_r = 0.11\), \(k_i = 0.10\), and \(k_z = 0.05\). For Cerro Pachón, we adopted the extinction listed on the Gemini Web site: \(k_g = 0.18\), \(k_r = 0.10\), \(k_i = 0.08\), and \(k_z = 0.05\).

4.2. Comparison with SDSS Photometry

We compared our photometry to that of the SDSS data release 12 (DR12). For objects that from our observations are classified as stars, we use SDSS psfMag, while for objects classified as galaxies we use the SDSS magnitude cmodel-Mag, which is the magnitude from a linear combination of the best-fit exponential and \(r^{1/4}\) profiles. In all cases, we compare to our standard-calibrated magnitudes mag_auto.

We used two methods in the comparison: (1) a direct comparison of magnitudes of objects in the 10 clusters with available SDSS photometry, and (2) a comparison of star colors to the northern SDSS standard stars (Smith et al. 2002). The second method enables us to evaluate the accuracy of the photometry of all the clusters.

Based on the comparison of SDSS photometry with our photometry calibrated using the initial calibrations (Section 4.1), magnitude zero-point offsets were applied as detailed in Table 10. Figures 10–11 and Table 11 summarize the comparisons after these offsets were applied. Figure 10 shows comparisons for the lowest- and the highest-redshift clusters only, as all other comparisons look similar. The resulting offsets and scatter of the comparisons listed in Table 11 were derived from objects with SDSS magnitude uncertainties less than 0.2 mag, and excluding saturated objects and objects for which our photometry deviates from the SDSS photometry by more than 0.7 mag. The resulting scatter in the comparisons is typically 0.15–0.30 mag, lower for the stars than the galaxies.
The adopted magnitude zero-point offsets (Table 10) represent a compromise between offsets derived from the direct comparisons and achieving colors in the stars in the fields consistent with the locus of the SDSS standard stars in the color–color diagrams shown in Figure 11. In addition, the direct comparisons show systematic differences between the photometry for stars and that for galaxies in the fields. These differences likely originate from differences between methods used in the SDSS and those used in this paper to determine total magnitudes. Based on our simulations presented in Section 3.4, we expect the differences to depend on the distribution of $n_{\text{gal}}$ for the galaxies included in the comparisons. If the comparisons are dominated by disk galaxies, then the differences should be close to zero, while for a mix of disk and bulge-dominated galaxies, the differences are expected to be $\pm 0.07$ mag, increasing to $0.15$ mag for a sample of only bulge-dominated galaxies. The median value of the differences between $g^\prime$, $r^\prime$, and $i^\prime$ is $-0.03$ mag, with 73% of the fields and filters within $\pm 0.07$ mag. The median of the differences for four $z^\prime$-band comparisons is $0.12$ mag. For three of the four fields with available SDSS $z^\prime$-band photometry, we adjusted the magnitude zero-points based primarily on the photometry of the stars in the fields. Thus, it is unlikely that this magnitude offset for the galaxies is related to problem with our zero-points. Finally, the $z^\prime$-band comparisons for the galaxies show no dependences on the magnitudes, colors, or sizes of the galaxies. For our purpose, we conclude that absolute calibrations of $g^\prime$, $r^\prime$, and $i^\prime$ are consistent with the expected calibration consistency of $\approx 0.05$ mag obtainable with GMOS when using standard methods for calibration; cf. Jørgensen (2009). The $z^\prime$-band magnitudes may only be consistent to $\approx 0.12$ mag. We discuss this further when establishing the color–magnitude relations for the clusters; see Section 7.

4.3. Calibration Notes for Individual Clusters

This section contains information on the calibration corrections made for the individual clusters as well as any differences with previously published photometry in Jørgensen et al. (2005), Barr et al. (2005), and Jørgensen & Chiboucas (2013). The photometry in Jørgensen et al. (2017) originates from the consistently calibrated photometric catalog included in the present paper. Only the 10 fields with special considerations for the calibration and/or previously published photometry are listed.

Abell 1689: This cluster was covered with two GMOS-N pointings. Magnitudes from the two fields are internally consistent. The observations in the $i^\prime$ band were obtained on UT 2001 December 24 during which no standard stars were observed. We adopted the zero point from UT 2001 December 25. However, comparison with SDSS photometry shows a significant offset for both the $r^\prime$ band and the $i^\prime$ band. The photometry was corrected for these offsets; cf. Table 10. Photometric parameters for objects covered by both fields observed of this cluster were averaged.

RX J0056.2+2622: The cluster was covered by two GMOS-N pointings. Since no standard stars were observed the night of the observations of RX J0056.2+2622 F1, we first adopted the average of the zero-points for the preceding and following night. Comparison of the photometry of the 31 objects brighter than $i^\prime \approx 22.5$ mag and included in both fields show offsets of $< 0.01$ mag for the $g^\prime$ and $r^\prime$ bands. However, we find a significant offset for the $i^\prime$ band, and offset the zero point for the RX J0056.2+2622 F1 $i^\prime$ band to be consistent with the $i^\prime$-band photometry of RX J0056.2+2622 F2; cf. Table 10. Photometric parameters for objects covered by both fields observed of this cluster were averaged.

RX J0142.0+2131: We use magnitude zero-points corresponding to the night of the observations, UT 2001 October 22. These are $0.02$–$0.04$ mag different from those adopted by

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Table 7

Aperture Corrections for Point Sources

| Cluster        | $g^\prime$ Band | $r^\prime$ Band | $i^\prime$ Band | $z^\prime$ Band |
|----------------|-----------------|-----------------|-----------------|-----------------|
|                | $\Delta m_{\text{aper}}$ | $\Delta m_{2.5}$ | $\Delta m_{\text{aper}}$ | $\Delta m_{2.5}$ | $\Delta m_{\text{aper}}$ | $\Delta m_{2.5}$ | $\Delta m_{\text{aper}}$ | $\Delta m_{2.5}$ |
| Abell 1689 F1  | -0.024          | -0.060          | -0.039          | -0.166          | -0.044          | -0.163          | ...            | ...            |
| Abell 1689 F2  | -0.028          | -0.060          | -0.042          | -0.153          | -0.031          | -0.106          | ...            | ...            |
| RX J0056.2+2622 F1 | -0.043          | -0.131          | -0.040          | -0.111          | -0.036          | -0.096          | ...            | ...            |
| RX J0056.2+2622 F2 | -0.061          | -0.207          | -0.050          | -0.135          | -0.101          | -0.296          | ...            | ...            |
| RX J0142.0+2131 | -0.055          | -0.064          | -0.041          | -0.052          | -0.038          | -0.051          | ...            | ...            |
| RX J0056.2+2622 F1 | -0.091          | -0.099          | -0.074          | -0.079          | -0.051          | -0.052          | ...            | ...            |
| Abell 1689     | -0.088          | -0.097          | -0.064          | -0.067          | -0.064          | -0.071          | ...            | ...            |
| RX J1347.5−1145 | -0.178          | -0.280          | -0.117          | -0.121          | -0.123          | -0.124          | ...            | ...            |
| RX J2146.0+0423 | -0.094          | -0.076          | -0.075          | -0.057          | -0.071          | -0.054          | ...            | ...            |
| MS 0451.6−0305 | -0.142          | -0.135          | -0.067          | -0.064          | -0.138          | -0.131          | -0.134         | -0.129         |
| RX J0216.5−1747 | -0.114          | -0.096          | -0.094          | -0.079          | -0.076          | -0.062          | -0.085         | -0.075         |
| RX J1334.3+5030 | ...            | ...            | -0.215          | -0.258          | -0.133          | -0.174          | -0.098         | -0.079         |
| RX J1716.6+6708 | ...            | ...            | -0.158          | -0.116          | -0.173          | -0.130          | -0.174         | -0.132         |
| MS 1610.4+6616 | ...            | ...            | -0.112          | -0.094          | -0.113          | -0.094          | -0.139         | -0.118         |
| RX J0152.7−1357 | ...            | ...            | -0.093          | -0.071          | -0.112          | -0.089          | -0.108         | -0.090         |
| RX J1226.9−3332 | ...            | ...            | -0.148          | -0.116          | -0.179          | -0.132          | -0.131         | -0.104         |
| RX J1415.1+3612 | ...            | ...            | -0.107          | -0.080          | -0.200          | -0.139          | -0.120         | -0.089         |

Note. Column 1: galaxy cluster and field. Column 2: $g^\prime$-band aperture correction for adaptive aperture size. Typical uncertainties are 0.015 mag. Column 3: $g^\prime$-band aperture correction for an aperture diameter of 2.5 arcsec. Typical uncertainties are 0.015 mag. Columns 4–5: same information for the $r^\prime$ band. Columns 6–7: same information for the $i^\prime$ band. Columns 8–9: same information for the $z^\prime$-band.
Table 9
GMOS-S Photometric Calibration

| Filter | \(m_{0p}\) | Color Term \(m\) |
|--------|-------------|-----------------|
| \(g'\) | 28.638 | -0.08 (\(g'-r'\)) |
| \(r'\) | 28.587 | -0.02 (\(g'-r'\)) |
| \(i'\) | 28.088 | -0.02 (\(i'-z'\)) |
| \(z'\) | 27.011 | 0.0 |

Note.

* From the Gemini Web site.

Barr et al. (2005). This has no significant effect on our results in that paper. We note that the direct comparison to the SDSS photometry (Table 11) show offsets of the galaxy magnitudes of 0.03–0.10 mag. However, the colors of the stars follow the sequence of the SDSS standard stars (Figure 11). Thus, no additional offsets were applied to the magnitude zero-points.

**RX J1347.5–1145.** This cluster was observed with GMOS-S; see Table 9 for the photometric calibration. The \(g'\)-band imaging was obtained in non-photometric conditions in dark time. The photometry was calibrated by means of a single exposure obtained in photometric conditions in bright time.

**MS 0451.6-0305.** No standard stars were observed during the night of the \(z'\)-band observations. Based on the \(z'\)-band magnitude zero-points from UT 2001 November 22 and UT 2002 February 17, and assuming the degradation of the zero point is similar to that of the \(i'\) band during the period, we adopted a zero point of 26.686. Jørgensen & Chiboucas (2013) used 26.66. This offset has no effect on our previous results, as the \(z'\) band is not used in the calibration to the \(B\)-band rest frame.

**RX J0216.5–1747.** The \(z'\)-band imaging was obtained on UT 2004 July 20, which is not covered in Jørgensen (2009). We derived the magnitude zero-points for the night in the same way as done in Jørgensen (2009), and find zero-points of \((z_p, z_i, z_r) = (28.223, 27.959, 26.819)\) for the \(r'\), \(i'\), and \(z'\) bands, respectively.

**RX J1334.5+3030.** The \(r'\) and \(i'\)-band observations were obtained on nights without observations of standard stars. We derived the photometry from the co-added images scaled to the images obtained on UT 2001 December 26, which is noted in the observing log as being photometric. We then adopt the UT 2001 December 25 magnitude zero-points. The comparison with the SDSS photometry of the field shows that the \(r'\)- and \(i'\)-band photometries are in good agreement with SDSS, while the \(z'\)-band photometry shows a significant offset; cf. Table 10. The photometry was corrected for this offset.

**RX J0152.7–1357.** In Jørgensen & Chiboucas (2013), we confirmed that the \(i'\)-band photometry is in agreement with the HST/ACS photometry. This field has no SDSS photometry. However, comparison with SDSS stellar colors indicate that \((i'–z')\) is too small by \(\approx 0.1\) mag. We therefore offset the nominal \(z'\)-band zero point with \(-0.1\); cf. Table 10. The effect of this offset on our previous results is minimal, affecting the \(B\)-band rest-frame magnitudes by \(\approx 0.05\) mag.

**RX J1226.9+3332.** The photometry was corrected with the offsets determined from the SDSS comparison; cf. Table 10. The effect of this offset on our previous results is minimal, affecting the \(B\)-band rest-frame magnitudes by \(\approx 0.05\) mag.

**RX J1415.1+3612.** Offsets were applied based on both the direct comparison with the SDSS photometry, and, for the \(z'\) band, to optimize the match with the stellar colors; cf. Table 10.

### 5. Fully Calibrated Photometric Parameters

Table 12 shows the content of the available machine-readable table of the final calibrated photometric parameters. For each cluster, objects classified as galaxies are listed first, followed by those classified as stars. The columns are as follows:

1. Cluster—cluster name.
2. ID—GCP ID number for the galaxy.
3. and 4. R.A. (J2000), decl. (J2000)—right ascension and declination calibrated to be consistent with USNO (Monet et al. 1998) with an rms scatter of \(\approx 0.7\) arcsec.
4. to 12. \(g'_{\text{total}}, r'_{\text{total}}, i'_{\text{total}}, z'_{\text{total}}\)—total magnitude in \(g', r', i', \) and \(z'\) determined from SExtractor mag auto and associated uncertainties using the corrections from Table 6.
13. to 20. \(g'_{\text{aper}}, r'_{\text{aper}}, i'_{\text{aper}}, z'_{\text{aper}}\)—aperture magnitudes derived using the aperture sizes defined in Equation (3), and associated uncertainties.
21. to 28. \(g'_{S5}, r'_{S5}, i'_{S5}, z'_{S5}\)—aperture magnitudes derived using an aperture with diameter 2.5 arcsec, and associated uncertainties.
29. \(P = P(\text{class star})\) product of class star for the available passbands; cf. Equation (4).
Table 10
Offsets Added to Photometric Zero-points

| Cluster     | g' | r' | i' | z' | Comments            |
|------------|----|----|----|----|---------------------|
| Abell 1689 | 0.00 | −0.147 | −0.117 | ... | SDSS comparison     |
| RX J0056.2+2622 F1 | 0.00 | 0.000 | 0.095 | ... | Internal comparison |
| RX J1347.5−1347 | ... | 0.000 | 0.000 | −0.065 | SDSS comparison     |
| RX J1226.9+3332 | ... | −0.139 | −0.049 | −0.060 | SDSS comparison     |
| RX J1415.1+3612 | ... | −0.092 | −0.159 | −0.095 | SDSS comparison     |

Note. Clusters not listed in the table were standard-calibrated with the nominal zero-points.

30. \( M - M_{\text{class star}} \) median of class star for the available passbands.

For those objects classified as galaxies, the table also contains the following columns:

31. \( \log r_{\text{iso}} \)—the logarithm (base 10) of the isophotal circularized radius in arcseconds in the detection band;

cf. Equation (7). See Table 5 for the surface brightness limit at the isophote.

32. to 35. \( g'_{\text{iso}}, r'_{\text{iso}}, i'_{\text{iso}}, z'_{\text{iso}} \)—isophotal magnitudes derived using the surface brightness limits listed in Table 5.

36. \( \epsilon \)—ellipticity in the detection band, as derived from the semimajor and semiminor axes using SExtractor, \( \epsilon = 1 - a/b \).

37. PA—position angle in the detection band in degrees measured north through east.

All magnitudes and colors in the table are AB magnitudes. Magnitude measurements with uncertainties larger than 1 mag are omitted from the table. Galactic extinction for each field and filter are listed in Table 16 in Appendix A. The data in Table 12 have not been corrected for Galactic extinction.
Figure 19. (a)–(b) Rest-frame colors ($U - B$ and $B - V$) of the red sequence as a function of redshift. Passive evolution models based on Bruzual & Charlot (2003) are overlaid: blue solid, blue dashed, green solid, red dashed, and red solid lines—$[\text{M}/\text{H}]=0$ and formation redshifts of $z_{\text{form}}=1.2$, 1.4, 1.8, 2.2, and 4.0, respectively. Dotted–dashed green lines show models for $z_{\text{form}}=1.8$ with $[\text{M}/\text{H}]=−0.4$ or 0.4, with lower metallicity leading to bluer colors. (c)–(d) Slopes of the rest-frame color–magnitude relations. Dashed lines—predicted slopes as a function of redshift, assuming passive evolution and relations between age, metallicity, and velocity dispersions as found by Thomas et al. (2005) at low redshift; see text. Dotted–dashed lines—predicted slopes adopting only the metallicity–velocity dispersion relation from Thomas et al. (2005) and no age variation with velocity dispersion. (e)–(f) Internal scatter of the rest-frame color–magnitude relations. In panel (f), the four clusters shown at 0.01 formally has color–magnitude relations with no internal scatter. In all panels: solid circles—our data; unfilled squares—Mei et al. (2009); unfilled circles—Foltz et al. (2015); unfilled triangles—Cerulo et al. (2016).

Table 11

| Field & objects | $g'$ Band | $r'$ Band | $i'$ Band | $z'$ Band |
|-----------------|----------|----------|----------|----------|
|                 | $N$     | $\Delta$ | rms      | $N$     | $\Delta$ | rms      | $N$     | $\Delta$ | rms      |
| Abell 1689 galaxies | 360     | −0.013  | 0.28     | 405     | −0.091  | 0.26     | 393     | −0.051  | 0.28     |
| Abell 1689 stars   | 62      | 0.052   | 0.21     | 67      | 0.097   | 0.19     | 63      | 0.051   | 0.20     |
| RX J0056.2+2622 galaxies | 332 | −0.049  | 0.27     | 400     | 0.002   | 0.22     | 390     | 0.022   | 0.22     |
| RX J0056.2+2622 stars | 87    | −0.021  | 0.16     | 98      | 0.014   | 0.18     | 102     | 0.070   | 0.14     |
| RX J0142.0+2131 galaxies | 99   | −0.103  | 0.24     | 109     | −0.059  | 0.28     | 180     | 0.026   | 0.21     |
| RX J0142.0+2131 stars | 21    | 0.018   | 0.12     | 20      | −0.220  | 0.22     | 29      | 0.057   | 0.13     |
| RX J0027.6+2616 galaxies | 91   | 0.084   | 0.31     | 153     | 0.003   | 0.24     | 156     | −0.072  | 0.24     |
| RX J0027.6+2616 stars | 34    | 0.132   | 0.13     | 40      | 0.142   | 0.15     | 44      | 0.020   | 0.12     |
| Abell 851 galaxies | 202     | 0.042   | 0.27     | 302     | 0.027   | 0.22     | 323     | −0.003  | 0.22     |
| Abell 851 stars    | 27      | 0.107   | 0.16     | 35      | 0.055   | 0.17     | 36      | 0.043   | 0.12     |
| RX J2146.0+0423 galaxies | 80   | 0.061   | 0.28     | 112     | −0.017  | 0.26     | 104     | 0.026   | 0.23     |
| RX J2146.0+0423 stars | 89    | 0.033   | 0.17     | 98      | 0.015   | 0.16     | 98      | −0.004  | 0.14     |
| RX J1334.3+5030 galaxies | 144  | ...     | ...      | ...     | 178     | 0.012   | 0.29     | 99      | 0.124   | 0.29     |
| RX J1334.3+5030 stars | ...    | 0.047   | 0.30     | ...     | 32      | −0.030  | 0.21     | 33      | −0.006  | 0.19     |
| RX J1716.6+6708 galaxies | 37   | 0.087   | 0.27     | 48      | −0.026  | 0.27     | 24      | 0.178   | 0.32     |
| RX J1716.6+6708 stars | ...    | 0.059   | 0.15     | 45      | −0.010  | 0.10     | 43      | 0.053   | 0.13     |
| RX J2269.9+3332 galaxies | 100  | 0.021   | 0.31     | 111     | 0.016   | 0.28     | 30      | 0.308   | 0.27     |
| RX J2269.9+3332 stars | ...    | −0.012  | 0.15     | 39      | −0.010  | 0.13     | 35      | 0.001   | 0.12     |
| RX J1415.1+3612 galaxies | 104  | 0.042   | 0.24     | 101     | −0.018  | 0.26     | 32      | 0.128   | 0.26     |
| RX J1415.1+3612 stars | ...    | 0.007   | 0.15     | 44      | 0.019   | 0.19     | 33      | 0.065   | 0.13     |

Note. Differences are "GMOS"−"SDSS." *Zero-point offsets were applied to one of more passbands before final comparison; see Table 10.

Uncertainties are included for total magnitudes and colors. Uncertainties on the isophotal magnitudes are similar to those on the total magnitudes. The typical uncertainties on the logarithm of the isophotal radii are 0.003 with the largest uncertainties 0.01−0.015. For completeness, we list the isophotal radii even when they are smaller than the seeing of
Table 12
GCP Photometric Catalog

| Cluster ID | R.A. (J2000) | Decl. (J2000) | g$_{\text{total}}$ | σ$_g$ | r$_{\text{total}}$ | σ$_r$ | i$_{\text{total}}$ | σ$_i$ | z$_{\text{total}}$ | σ$_z$ | g$_{\text{aper}}$ | σ$_g$ | r$_{\text{aper}}$ | σ$_r$ | i$_{\text{aper}}$ | σ$_i$ | z$_{\text{aper}}$ | σ$_z$ |
|------------|--------------|---------------|--------------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|
| A1689 1    | 13:11:12.96  | −1:20:31.8    | 25.234             | 0.251 | 24.274         | 0.191 | 23.725         | 0.191 | ...            | ...   | 24.342         | 0.738 | 23.666         | 0.576 | ...            | ...   | 23.478         | 0.738 | 23.666         | 0.576 |
| A1689 2    | 13:11:12.99  | −1:20:38.7    | 20.614             | 0.027 | 20.106         | 0.035 | 19.828         | 0.038 | ...            | ...   | 20.770         | 0.014 | 20.277         | 0.018 | 19.994         | 0.020 | ...            | ...   | 20.532         | 0.020 |
| A1689 3    | 13:11:13.03  | −1:19:27.3    | 23.832             | 0.162 | 24.255         | 0.419 | 23.021         | 0.201 | ...            | ...   | 23.387         | 0.181 | ...            | ...   | ...            | ...   | 23.387         | 0.181 | ...            | ...   |
| A1689 4    | 13:11:13.10  | −1:21:45.2    | 23.356             | 0.101 | 22.362         | 0.079 | 21.741         | 0.067 | ...            | ...   | 23.189         | 0.128 | 22.177         | 0.100 | 21.510         | 0.079 | ...            | ...   | 22.177         | 0.100 |
| A1689 5    | 13:11:13.16  | −1:19:44.1    | 23.814             | 0.182 | 23.800         | 0.329 | 22.840         | 0.202 | ...            | ...   | 23.624         | 0.206 | 23.905         | 0.484 | 22.701         | 0.230 | ...            | ...   | 23.714         | 0.484 |
| A1689 6    | 13:11:13.36  | −1:21:02.3    | 23.358             | 0.053 | 23.103         | 0.075 | 22.494         | 0.069 | ...            | ...   | 23.318         | 0.151 | 23.116         | 0.236 | 22.177         | 0.144 | ...            | ...   | 23.116         | 0.236 |
| A1689 7    | 13:11:13.47  | −1:22:05.6    | 23.260             | 0.085 | 22.049         | 0.057 | 22.159         | 0.096 | ...            | ...   | 23.118         | 0.117 | 21.744         | 0.070 | 21.964         | 0.127 | ...            | ...   | 21.744         | 0.070 |
| A1689 8    | 13:11:13.54  | −1:22:23.9    | 20.523             | 0.016 | 19.151         | 0.010 | 18.764         | 0.010 | ...            | ...   | 20.584         | 0.011 | 19.270         | 0.007 | 18.860         | 0.007 | ...            | ...   | 19.270         | 0.007 |
| A1689 9    | 13:11:13.54  | −1:35:51.1    | 18.772             | 0.028 | 17.715         | 0.023 | 17.174         | 0.018 | ...            | ...   | 19.531         | 0.004 | 18.353         | 0.003 | 17.860         | 0.003 | ...            | ...   | 18.353         | 0.003 |
| A1689 10   | 13:11:13.64  | −1:19:41.9    | 21.918             | 0.081 | 21.395         | 0.095 | 20.776         | 0.073 | ...            | ...   | 22.226         | 0.054 | 21.598         | 0.059 | 21.101         | 0.055 | ...            | ...   | 21.598         | 0.059 |

Note. Columns are explained in Section 5.
(This table is available in its entirety in machine-readable form.)
the image in the detection filter. The uncertainties on the ellipticities are typically of similar size to the magnitude uncertainties in the detection band. The ellipticities have not been corrected for the effect of the image quality, thus they are expected to be affected by systematic errors, especially for galaxies smaller than about twice the seeing of the images.

Based on internal comparisons, we evaluate that the uncertainties on the position angles are <3° for galaxies with \( \epsilon \geq 0.3 \) and total magnitude in the detection band of 23 mag or brighter. Uncertainties are <5° for galaxies with \( \epsilon = 0.1 \)–0.3 and total magnitude in the detection band of 22 mag or brighter. Position angles of fainter or less elliptical galaxies are subject to higher uncertainties.

6. Calibration of the Photometry to the Rest Frames of the Galaxies

We calibrate the photometry, total magnitudes, and colors to the rest frames of the galaxies using calibrations based on stellar population models from Bruzual & Charlot (2003). We first described our method in Jørgensen et al. (2005). Here we generalize the method to calibrate the total magnitudes to the rest-frame B band for all clusters and also establish the calibration of the colors to rest-frame \((U - B)\) and \((B - V)\). The rest-frame B magnitudes, \((U - B)\) and \((B - V)\) used here are Vega magnitudes.

We use single stellar population (SSP) models from Bruzual & Charlot for a Chabrier (2003) initial mass function, ages of 2–13 Gyr, metallicities of \( Z = 0.004, 0.008, 0.02 \) (solar), and 0.04, and Padova 1994 evolutionary tracks; see Bruzual & Charlot for original references to the tracks. In our previous calibrations (Jørgensen et al. 2005; Jørgensen & Chiboucas 2013), we used filter functions included in the software distributed by Bruzual & Charlot. The filter functions for the SDSS filters \( g', r', i' \), and \( z' \) are identical to those supplied by the SDSS. Thus, we maintained use of these filter functions. However, the filter functions for \( U, B, \) and \( V \) are from Buser & Kurucz (1978). Filter functions for these filters were shown by Maíz Apellániz (2006) to give inaccurate descriptions of data. Maíz Apellániz derived better filter functions and also eliminated the internally inconsistent use of two filter functions for the \( B \) filter. We have here adopted these newer filter functions for \( U, B, \) and \( V \). Below we comment on the effect of this compared to our previously used calibrations.

The Bruzual & Charlot SSP models were used to derive rest-frame \( B \), \((U - B)\), and \((B - V)\) (Vega magnitudes), as well as the observed AB magnitudes \( g', r', i', \) and \( z' \), and colors. This was done in steps of 0.025 in redshift and for the redshift range spanning our observations. For each of these redshifts, we

| Cluster | Redshift | \( \lambda_{	ext{ref}} \) in Cluster Rest Frame | DM(z) | \( B_{	ext{rest}} \) | \((U - B)\) | \((B - V)\) |
|---------|----------|---------------------------------|--------|----------------|----------------|----------------|
| Reference | 0.0000 | 475 630 780 925 | ... | ... | ... | ... |
| Abell 1689 | 0.1865 | 400 531 657 ... | ... | ... | ... | ... |
| RX J0056.2+2622 | 0.1922 | 398 528 654 ... | ... | ... | ... | ... |
| RX J0124.0+2131 | 0.2794 | 371 492 610 ... | ... | ... | ... | ... |
| RX J0027.6+2616 | 0.3650 | 348 462 571 ... | ... | ... | ... | ... |
| Abell 851 | 0.4050 | 338 448 555 ... | ... | ... | ... | ... |
| RX J1347.5–1145 | 0.4506 | 327 434 538 ... | ... | ... | ... | ... |
| RX J2146.0+0423 | 0.532 | 310 411 509 ... | ... | ... | ... | ... |
| MS 0451.6–0305 | 0.5398 | 308 409 507 601 | 42.46 | ... | ... | ... |
| RX J0216.5–1747 | 0.578 | 301 399 494 586 | 42.64 | ... | ... | ... |
| RX J1334.3+5030 | 0.620 | ... 389 481 571 | 42.83 | ... | ... | ... |
| RX J1716.6+1608 | 0.809 | ... 348 431 511 | 43.53 | ... | ... | ... |
| MS 1610.4+6616 | 0.8300 | ... 344 426 505 | 43.60 | ... | ... | ... |
| RX J0152.7–1357 | 0.8350 | ... 343 425 504 | 43.62 | ... | ... | ... |
| RX J1226.9+3332 | 0.8908 | ... 333 413 489 | 43.79 | ... | ... | ... |
| RX J1415.1+3612 | 1.0269 | ... 311 385 456 | 44.17 | ... | ... | ... |

Note. The second line for each cluster lists the uncertainties on the calibration coefficients.

* Wavelengths noted only for the passbands that were obtained for each of the clusters.
established the calibration to rest-frame $B$ as

$$B_{\text{rest}} = m_{\text{obs}} + \alpha_1 \cdot \text{color}_{\text{obs},1} + \beta_1,$$

(11)

where $m_{\text{obs}}$ is the magnitude in the observed band most closely matching the rest-frame $B$ at the redshift and color$_{\text{obs}}$ is the observed color best complementing $m_{\text{obs}}$, to achieve coverage of the full rest-frame $B$ band. Inclusion of a second-order color term, as we did in Jørgensen et al. (2005) and Jørgensen & Chiboucas (2013), does not significantly improve the calibrations, when using the Maíz Apellániz (2006) $U$, $B$, and $V$ filter functions. From $B_{\text{rest}}$, the absolute $B$-band magnitude is derived as

$$M_B = B_{\text{rest}} - DM(z),$$

(12)

where $DM(z)$ is the distance modulus for a given redshift. Similarly, we establish calibrations to rest-frame $(U - B)$ and $(B - V)$ at each of the redshifts as

$$(U - B) = \alpha_2 \cdot \text{color}_{\text{obs},2} + \beta_2,$$

(13)

and

$$(B - V) = \alpha_3 \cdot \text{color}_{\text{obs},3} + \beta_3,$$

(14)

where color$_{\text{obs},2}$ and color$_{\text{obs},3}$ are the observed colors from the passbands most closely matching the passbands for rest-frame $(U - B)$ and $(B - V)$, respectively.

The calibrations to rest-frame $B$, $(U - B)$, and $(B - V)$ are applied to the data by interpolating the calibration coefficients to the exact redshift of each of the galaxies. It is important to note that the validity of the calibrations do not rely on the models being successful at modeling the ages and metallicities of the stellar populations in the observed galaxies. Rather, the models only have to provide correct relative color information over the wavelength range spanned by the desired rest-frame passbands and the observed passbands used in the calibration. As long as extrapolations from the observed passbands to the desired rest-frame passbands are kept to a minimum and the available models do span the observed colors, any shortcomings of the models to reproduce the exact colors of galaxies for physically believable ages and metallicities are less important. Additional information on how to calibrate the photometry to a “fixed-frame” system, i.e., rest-frame $B$, can be found in Blanton et al. (2003).

Figure 12 shows our previous $B$-band calibration compared with the one established here using the filter functions from Maíz Apellániz (2006). The calibrations are shown at the model redshifts closest to the redshifts of the three clusters analyzed in Jørgensen & Chiboucas (2013). The difference between two calibrations is typically 0.05 mag in rest-frame $B$ magnitudes, with the new calibration leading to fainter magnitudes. This change has no significant effect on our previously published results. Future analysis of the GCP data will use the calibrations established in the present paper. Figure 13 shows the color calibrations for three typical redshifts spanning the GCP cluster sample, demonstrating that linear calibrations are sufficient to fit the model data and provide reliable calibrations.

In Table 13 we provide the calibrations matching the cluster redshifts, as well as the distance moduli for the clusters. For guidance on how the optimal calibrations were chosen, we also list the effective wavelength of each of the observed bands in the cluster rest frames. In most cases, the observed colors used in the calibrations match the optimal redshift intervals, except for RX J2146.0+0423 for which no $z'$ imaging was obtained. For the highest-redshift clusters, the calibrations to $(B - V)$ in all cases rely on the same photometry as the calibrations to $(U - B)$ and $B$. Thus, they rely on extrapolation of the data using the SSP models.

7. Spectroscopic Samples and Color–Magnitude Relations

The spectroscopic samples for the GCP were selected based on magnitudes and colors, and when available at the time of sample selection, redshift information from the literature. The aim was to include the maximum number of galaxies on the red sequence. Our previous papers describe the sample selection for the clusters for which we have published the spectroscopic data; see Barr et al. (2005) for RX J0142.0+2131, Jørgensen et al. (2005) for RX J0152.7–1357, Jørgensen & Chiboucas (2013) for MS 0451.6–0305 and RX J1226.9+3332, and Jørgensen et al. (2017) for Abell 1689, RX J0056.2+2622, RX J0027.6+2616, and RX J1347.5–1145. These papers also include grayscale images of the clusters with the spectroscopic samples labeled. For the remainder of the clusters, we summarize the sample selection in Table 17 in Appendix B, and in Appendix C provide grayscale images with the spectroscopic samples marked, Figures 20–27. The grayscale image of RX J0142.0+2131 is included in the present paper, as the X-ray data were not available at the time of publication of our previous paper on the cluster (Barr et al. 2005).

Figure 14 shows the color–magnitude relations for the clusters, using the colors for the $B$-band rest-frame calibration. For galaxies on the red sequence, the figure shows both aperture colors from aperture sizes defined in Equation (3) and total colors. We fit the color–magnitude relations, using aperture colors, for the members iteratively (red symbols on Figure 14), rejecting galaxies deviating by more than three times the scatter relative to the relation. The rejection was iterated four times to reach a stable fit of the red sequence. The best fits to the cluster members are shown as red solid lines and summarized in Table 14. For clusters for which our spectroscopic data have not yet been processed, we instead fit the relations to the spectroscopic sample, excluding those galaxies with blue colors in at least one of the available colors. The fits for these clusters were also determined iteratively with rejection. The difference between using aperture colors and colors based on $\text{mag}_{\text{auto}}$ has a median of 0.03 on the zero-points (total colors being bluer), with an rms scatter of 0.05. The slopes and scatter of the relations are not significantly different for the two sets of colors. Thus, we proceed using only the aperture colors.

We then evaluate the completeness of the spectroscopic samples along the red sequence, including galaxies within $\pm 3$ times the scatter for the color–magnitude relations as marked on Figure 14. Figure 15 shows the distribution of the absolute $B$-band magnitudes, $M_{B,\text{abs}}$, of the spectroscopic samples, together with the completeness. In general, the samples are at least 80% complete for galaxies brighter than $M_{B,\text{abs}} \lesssim -22$ mag, except when the spatial distribution of these galaxies made it impossible to include all of them in the mask designs for the spectroscopic observations. This was the case for RX J0027.6+2616 and RX J1226.9+3332. For $-22 < M_{B,\text{abs}} \lesssim -19.5$ mag, the samples for clusters at $z < 0.5$ typically include 20%–50% of the red sequence galaxies. For higher-redshift clusters, the samples are limited at $M_{B,\text{abs}} \approx -20$ mag, but reach the same completeness.
### 8. Red-sequence Color–Magnitude Relations as a Function of Redshift

While the main purpose of this paper is to present the consistently calibrated X-ray measurements for the GCP clusters and the full photometric catalog from the optical imaging, we take this opportunity to briefly discuss the changes in the color–magnitude relations as a function of redshift.

Figure 16 shows the observed mean colors of the red sequence as a function of cluster redshift. The colors are the zero-points listed for the color–magnitude relations in Table 14 and correspond to the colors at $M_{B,\text{abs}} \approx -21$ mag. Models from Bruzual & Charlot (2003) are overlaid for ages of 2.5, 5, and 10 Gyr, and solar metallicity $[M/H] = 0$. The $(g' - r')$ and $(r' - i')$ colors follow the expected variation with redshift, consistent with mean ages of 2.5–10 Gyr and solar metallicity.

The $(i' - z')$ colors are systematically bluer than predicted by the models. Figure 16(c) includes a low-metallicity model with $[M/H] = -0.7$ and age $= 2.5$ Gyr. Comparing with the models from Vazdekis et al. (2012) and available from the MILES Web site, we find that the MILES models for a Chabrier IMF and the BaSTI isochrones are 0.05–0.10 bluer in $(i' - z')$ than in the Bruzual & Charlot models. Further, Mei et al. (2009) find the red sequence of RX J0152.7–1357 to have $(r_{0.25} - z_{0.50}) = 1.93$ at $i_{775} = 22.5$ in AB magnitudes. We find $(r' - z') = 2.04$ at $i' = 22.5$ for this cluster. While the two photometric systems are not completely identical, we take the comparison as an indication that it is unlikely that our colors are significantly too blue. Our $z'$-band mag_auto for the galaxies may be too faint at the 0.12 mag level; cf., Section 4.2. However, the $(i' - z')$ aperture colors for the stars are consistent with SDSS; see Figure 11. In conclusion, it is possible that the Bruzual & Charlot (2003) models do not correctly model the $z'$-band magnitudes.

To further investigate the changes in the color–magnitude relations with redshift, we establish the relations based on the absolute $B$-band magnitudes, and $(U - B)$ and $(B - V)$ colors in the rest frames of the clusters. Figures 17–18 and Table 15 summarize the slopes, zero points, and scatter of the color–magnitude relations. The fits are based on confirmed members for those clusters with fully processed spectroscopy. For clusters without processed spectroscopy, the fits are based on the same selection of spectroscopic samples as used for establishing the color–magnitude relations in the observed frames; cf., Section 7. The unusually positive slope for the RX J1334.3+5030 $(B - V)$-magnitude relation may be a result of the inclusion of faint non-members. However, the zero point at $M_{B,\text{abs}} = -21$ appears to be affected by less than 0.05 mag, so

### Table 14

| Cluster      | Relations                                                                 | rms | $N$ |
|--------------|---------------------------------------------------------------------------|-----|-----|
| Abell 1689   | $(g' - r') = (-0.027 \pm 0.009)(g' - 19) + (1.233 \pm 0.010)$             | 0.059 | 61  |
|              | $(r' - i') = (-0.015 \pm 0.005)(r' - 19) + (0.476 \pm 0.006)$             | 0.032 | 64  |
| RX J0056.2+2622 | $(g' - r') = (-0.034 \pm 0.008)(g' - 19) + (1.161 \pm 0.013)$         | 0.063 | 52  |
|              | $(r' - i') = (-0.010 \pm 0.004)(r' - 19) + (0.412 \pm 0.005)$             | 0.027 | 51  |
| RX J0142.0+2131 | $(g' - r') = (-0.046 \pm 0.015)(r' - 20) + (1.374 \pm 0.017)$        | 0.074 | 24  |
|              | $(r' - i') = (-0.016 \pm 0.005)(r' - 20) + (0.549 \pm 0.006)$             | 0.027 | 25  |
| RX J0027.6+2616 | $(g' - r') = (-0.062 \pm 0.011)(r' - 20) + (1.750 \pm 0.009)$       | 0.046 | 28  |
|              | $(r' - i') = (-0.008 \pm 0.005)(r' - 20) + (0.650 \pm 0.004)$             | 0.022 | 30  |
| Abell 851    | $(g' - r') = (0.001 \pm 0.027)(r' - 20) + (1.718 \pm 0.027)$            | 0.137 | 41  |
|              | $(r' - i') = (0.007 \pm 0.013)(r' - 20) + (0.575 \pm 0.013)$             | 0.070 | 44  |
| RX J1347.5–1145 | $(g' - r') = (-0.028 \pm 0.025)(r' - 20) + (1.540 \pm 0.041)$       | 0.136 | 41  |
|              | $(r' - i') = (-0.001 \pm 0.007)(r' - 20) + (0.734 \pm 0.011)$             | 0.055 | 40  |
| RX J2146.0+0423 | $(g' - r') = (-0.063 \pm 0.015)(r' - 21) + (1.725 \pm 0.020)$        | 0.076 | 20  |
|              | $(r' - i') = (-0.014 \pm 0.014)(r' - 21) + (0.894 \pm 0.019)$             | 0.073 | 20  |
| MS 0451.6–0305 | $(g' - r') = (-0.059 \pm 0.031)(r' - 21) + (1.686 \pm 0.024)$         | 0.121 | 39  |
|              | $(r' - i') = (-0.027 \pm 0.012)(r' - 21) + (0.892 \pm 0.009)$             | 0.047 | 36  |
| RX J0216.5–1747 | $(i' - z') = (-0.001 \pm 0.009)(r' - 21) + (0.381 \pm 0.007)$        | 0.036 | 42  |
|              | $(i' - z') = (-0.015 \pm 0.013)(r' - 21) + (1.813 \pm 0.023)$             | 0.118 | 30  |
| RX J1334.3+5030 | $(i' - z') = (-0.057 \pm 0.013)(r' - 21) + (1.021 \pm 0.010)$        | 0.048 | 28  |
|              | $(i' - z') = (-0.071 \pm 0.011)(r' - 21) + (0.386 \pm 0.008)$             | 0.043 | 33  |
| RX J1716.6+6708 | $(i' - z') = (-0.005 \pm 0.015)(r' - 22) + (1.115 \pm 0.027)$       | 0.050 | 18  |
|              | $(i' - z') = (0.020 \pm 0.012)(r' - 22) + (0.441 \pm 0.022)$             | 0.033 | 18  |
| MS 1610.4+6616* | $(i' - z') = (-0.002 \pm 0.021)(r' - 22) + (1.271 \pm 0.020)$       | 0.060 | 27  |
|              | $(i' - z') = (-0.002 \pm 0.010)(r' - 22) + (0.645 \pm 0.009)$             | 0.027 | 24  |

Note.
* Median colors of the four passive galaxies in the $z = 0.83$ group.
we make no attempt here to exclude additional galaxies from the fit. In Figure 19 we show the colors at $M_{B,abs} = -21$, the slopes, and internal scatter of the relations as a function of cluster redshift. The internal scatter was derived by subtracting off in quadrature the median uncertainty at the observed magnitude corresponding to $M_{B,abs} = -21$. We do not include any contribution from the calibration to the rest frame, as random errors from the observations dominate over random errors from the rest-frame calibration. The figure also includes data from Cerulo et al. (2016), Foltz et al. (2015), and Mei et al. (2009) covering redshifts from 0.8 to 1.5. The literature data have been calibrated to also show colors at $M_{B,abs} = -21$ (Vega magnitudes) and slopes of the relations relative to the absolute $B$-band magnitude.

In Figures 19(a) and (b), passive evolution models based on Bruzual & Charlot (2003) are shown for formation redshifts of $z_{form} = 1.4-4.0$ and solar metallicity. For $z_{form} = 1.8$, we also show low- and high-metallicity models to illustrate how the assumed metallicity affects the predicted colors. Our results are generally in agreement with passive evolution and a formation redshift of 1.5–2.0, consistent with our results based on the absorption line indices (Jørgensen et al. 2017). At redshifts $z = 0.8–1.0$, where our coverage overlaps with that in Cerulo et al. (2016), our $(U - B)$ results are in agreement, while our $(B - V)$ colors are $\approx 0.15$ bluer than that found by Cerulo et al. We caution that our wavelength coverage for the highest-redshift clusters does not overlap with the $V$ band and therefore the $(B - V)$ colors rely on extrapolation based on the Bruzual & Charlot models. The $(U - B)$ colors from Mei et al. and Foltz et al. are $\approx 0.1–0.15$ redder than our results and those from Cerulo et al. In general, the zero-points of the color–magnitude relations provide a much less stringent constraint on the ages of intermediate-redshift cluster galaxies than the absorption line indices (e.g., Jørgensen & Chiboucas 2013; Jørgensen et al. 2017). However, the results still serve as a consistency check of the results.

We find no change in the slope of the color–magnitude relations as a function of redshift; see Figures 19(c) and (d). This is in agreement with results from Cerulo et al. (2016), Foltz et al. (2015), and Mei et al. (2009). Thomas et al. (2005) established age–velocity dispersion and metallicity–velocity dispersion relations at $z \approx 0$. We use those relations and the Faber-Jackson relation (Faber & Jackson 1976; luminosity–velocity dispersion relation) established for the joint sample of Abell 1689 and RX J0056.2+2622 members to derive the expected slopes of the color–magnitude relations, under the assumption of passive evolution. The predictions are shown as the dashed lines in Figures 19(c) and (d). Assuming no age variation with velocity dispersion and adopting the metallicity–velocity dispersion relation from Thomas et al. give predicted slopes of the color–magnitude relations indicated by the dotted–dashed lines in Figures 19(c) and (d). The joint data from the GCP (this paper), Cerulo et al. (2016), Foltz et al. (2015), and Mei et al. (2009) are inconsistent with the low-redshift age–velocity dispersion relation seen simply as a consequence of passive evolution. This limits the allowable age change along the color–magnitude relation from the brightest cluster galaxies to galaxies four magnitudes fainter to $<0.05$ dex. Alternatively, a steep slope of the low-redshift age–velocity dispersion relation must be maintained by adding younger galaxies to the red sequence, possibly primarily at low masses; cf., McDermid et al. (2015).

We also find no change in the internal scatter of the color–magnitude relations as a function of redshift; see Figures 19(e) and (f). One might expect that the addition of younger galaxies to the red sequence at later epochs would lead to a higher scatter at lower redshifts. However, the samples used for establishing the color–magnitude relations are incomplete at low luminosities and also biased against galaxies far from the red sequence, as they are simply our spectroscopic samples aimed at galaxies on the red sequence. In addition, the transition from blue star-forming galaxy to passive red galaxy may be too fast to result in significantly higher scatter. Only Abell 851 in the GCP sample contains a significant number of post-starburst bulge-dominated galaxies (P. Hibon et al. 2018, in preparation). The color–magnitude relations for this cluster does have a significantly higher scatter than found for the other GCP clusters. The results from Cerulo et al. (2016), Foltz et al. (2015), and Mei et al. (2009) are based on larger photometric samples. However, these authors also use sigma clipping when fitting the color–magnitude relations, most likely affecting the estimates of the scatter.

9. Summary

In this paper, we have given an overview of the science goals for the Gemini/HST Galaxy Cluster Project (GCP), summarized the cluster selection, and assembled consistently calibrated
X-ray measurements for the clusters. We present the photometric catalog based on the ground-based imaging of the GCP clusters in the g', r', i', and z' bands. The photometry has been calibrated to be consistent with the SDSS photometric system. The sample selection for the spectroscopic observations are summarized and provided for those clusters not included in prior publications.

We established the calibration of the photometry to rest-frame magnitudes and colors, and provide calibration coefficients at the relevant cluster redshifts.

Finally, we have derived the color–magnitude relations for all clusters and briefly discussed the redshift dependence on the red sequence mean color and scatter, and compare our results to results from the literature for higher-redshift clusters and to stellar population models. The absence of change in the slopes of the rest-frame color–magnitude relations with redshifts limits the allowable age differences along the color–magnitude relation to <0.05 dex from the brightest cluster galaxies to those four magnitudes fainter. The data add evidence to the need for younger, low-mass galaxies to be added to the red sequence between z ≈ 1 and the present in order to obtain a relatively steep age–velocity dispersion relation at low redshift.

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The data presented in this paper originate from the following Gemini programs: GN-2001B-Q-10, GN-2001B-DD-3, GN-2002A-Q-34, GN-2002B-Q-29, GN-2002B-DD-4, GN-2003A-DD-4, GN-2003B-Q-21, GN-2003B-DD-3, GS-2003B-Q-26, GN-2004A-Q-45, and GS-2005A-Q-27, System Verification program GN-2001B-SV-51, and engineering programs GN-2002B-SV-90 and GN-2003A-SV-80. The data were processed using the Gemini IRAF package.

Photometry from SDSS is used for comparison purposes. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS web site is http://www.sdss.org/.

Observations that were obtained with XMM-Newton, an ESA science mission funded by ESA member states and NASA; the Chandra X-ray Observatory; and the ROSAT Mission have been used. The observations were obtained from these missions’ data archives.

Appendix A
Log of Available Observations

Table 16 gives detailed information on the available observations, exposure times, image quality, and sky brightness. The table also lists the adopted Galactic extinction for each field and filter.

| Cluster          | Program ID* | Dates (UT) | Filter | Exposure time (s) | FWHM (arcsec) | Sky brightness (mag arcsec^{-2}) | A_v (mag) |
|------------------|-------------|------------|--------|-------------------|---------------|----------------------------------|-----------|
| Abell 1689 F1d   | GN-2003B-DD-3 | 2003 Dec 24 | g'     | 4 × 180           | 0.54          | 21.55                            | 0.089     |
|                  | GN-2001B-Q-10 | 2001 Dec 24 | r'     | 5 × 300           | 1.05          | 20.32                            | 0.062     |
|                  | GN-2001B-Q-10 | 2001 Dec 25 | i'     | 3 × 300           | 1.04          | 19.49                            | 0.046     |
| Abell 1689 F2d   | GN-2003B-DD-3 | 2003 Dec 24 | g'     | 4 × 180           | 0.57          | 21.54                            | 0.089     |
|                  | GN-2001B-Q-10 | 2001 Dec 24 | r'     | 6 × 300           | 1.05          | 19.80                            | 0.062     |
|                  | GN-2001B-Q-10 | 2001 Dec 25 | i'     | 3 × 300           | 0.81          | 19.51                            | 0.046     |
| RX J0056.2+2622 F1i | GN-2003B-Q-21 | 2003 Jul 2  | g'     | 4 × 120           | 0.79          | 21.94                            | 0.192     |
|                  | GN-2003B-Q-21 | 2003 Jul 2  | r'     | 4 × 120           | 0.70          | 21.24                            | 0.133     |
|                  | GN-2003B-Q-21 | 2003 Jul 2  | i'     | 4 × 120           | 0.62          | 20.34                            | 0.099     |
| RX J0056.2+2622 F2i | GN-2003B-Q-21 | 2003 Jul 30 | g'     | 4 × 120           | 1.04          | 22.06                            | 0.192     |
|                  | GN-2003B-Q-21 | 2003 Jul 30 | r'     | 4 × 120           | 0.85          | 21.20                            | 0.133     |
|                  | GN-2003B-Q-21 | 2003 Jul 30 | i'     | 5 × 120           | 1.05          | 19.98                            | 0.099     |
| RX J0142.0+2131  | GN-2001B-SV-51 | 2001 Oct 22 | g'     | 6 × 600           | 0.67          | 21.58                            | 0.225     |
|                  | GN-2001B-SV-51 | 2001 Oct 22 | r'     | 8 × 300           | 0.52          | 20.65                            | 0.156     |
|                  | GN-2001B-SV-51 | 2001 Oct 22 | i'     | 8 × 300           | 0.53          | 19.90                            | 0.116     |
| RX J0027.6+2616  | GN-2003B-Q-21 | 2003 Jul 1, 2003 Jul 2 | g'     | 4 × 360           | 0.60          | 21.97                            | 0.134     |
|                  | GN-2003B-Q-21 | 2003 Jul 1, 2003 Jul 2 | r'     | 4 × 300           | 0.47          | 21.22                            | 0.099     |
|                  | GN-2002B-SV-90, 3B-Q-21 | 2002 Sep 30, 2003 Jul 1 | i'     | 32 × 120          | 0.65          | 20.19                            | 0.069     |
Table 16  
(Continued)

| Cluster | Program IDa | Dates (UT) | Filter | Exposure time (s) | FWHMb (arcsec) | Sky brightness (mag arcsec−2) | Aνc (mag) |
|---------|-------------|------------|--------|-------------------|----------------|-------------------------------|-----------|
| Abell 851 | GN-2001B-Q-10 | 2001 Nov 21 | g′ | 6 × 600 | 0.73 | 21.65 | 0.055 |
| GN-2001B-Q-10 | 2001 Nov 17 | r′ | 6 × 300 | 0.69 | 20.97 | 0.038 |
| RX J1347.5−1145 | GS-2005A-Q-27 | 2005 Apr 13 | g′ | 4 × 450 | 1.16 | 22.15 | 0.204 |
| GS-2005A-Q-27 | 2005 Jan 11 | g′ | 1 × 450 | 0.99 | 19.58 | 0.204 |
| MS 0451.6−0305 | GN-2003B-Q-21 | 2003 Jul 1 | g′ | 6 × 600 | 0.55 | 22.17 | 0.197 |
| RX J2146.0+0423 | 2003 Jul 1 | r′ | 6 × 300 | 0.49 | 21.18 | 0.136 |
| RX J0152.7 | 2003 Jul 1 | r′ | 7 × 300 | 0.46 | 20.25 | 0.101 |
| MS 0451.6−0305 | GN-2003B-Q-21 | 2003 Dec 24 | g′ | 6 × 600 | 0.80 | 22.28 | 0.127 |
| GN-2002B-Q-29 | 2002 Sep 12–16 | r′ | 15 × 600 | 0.57 | 20.82 | 0.099 |
| GN-2001B-DD-3, 2B-Q-29 | 2001 Dec 26, 2002 Sep 15 | r′ | 6 × 600, 2 × 300 | 0.71 | 18.38 | 0.078 |
| RX J0216.5−1747 | GN-2001B-DD-3 | 2001 Dec 26 | z′ | 19 × 600 | 0.72 | 18.54 | 0.064 |
| GN-2003B-Q-21 | 2003 Aug 1–5 | g′ | 11 × 300 | 0.67 | 21.68 | 0.119 |
| GN-2003B-Q-21 | 2003 Aug 27–28 | r′ | 5 × 300 | 0.62 | 20.78 | 0.083 |
| RX J1334.3+5030 | GN-2001B-DD-3, 2A-Q-34 | 2001 Dec 26, 2002 Feb 11 | r′ | 11 × 600 | 1.06 | 21.12 | 0.022 |
| MS 1610.4+6616 | GN-2003B-Q-21 | 2003 May 3 | 6 × 600 | 0.72 | 19.92 | 0.080 |
| GN-2003A-Q-27 | 2003 May 3, 2003 May 8 | r′ | 11 × 420 | 0.72 | 19.58 | 0.059 |
| MS 1610.4+6616 | GN-2003A-Q-27 | 2003 May 3–8 | z′ | 19 × 210 | 0.73 | 18.54 | 0.044 |
| GN-2003B-Q-21 | 2003 Apr 25 | r′ | 6 × 450 | 0.73 | 21.00 | 0.068 |
| GN-2003A-Q-27 | 2003 Apr 25 | r′ | 6 × 450 | 0.69 | 19.80 | 0.050 |
| GN-2003A-Q-27 | 2003 Apr 26 | r′ | 12 × 210 | 0.76 | 18.81 | 0.038 |
| RX J0152.7−1357 | GN-2002B-Q-29 | 2002 Sep 14–15 | r′ | 12 × 600 | 0.68 | 20.59 | 0.033 |
| GN-2002B-Q-29, SV-90 | 2002 Jul 17–19, 2002 | r′ | 7 × 450, 100 × 120 | 0.56 | 19.31 | 0.024 |
| RX J1226.9+3332 | 2002 Jul 19, 2002 Sep 14–17 | z′ | 25 × 450 | 0.59 | 19.03 | 0.018 |
| GN-2003A-Q-27 | 2003 Apr 26 | r′ | 9 × 600 | 0.75 | 21.16 | 0.044 |
| GN-2003A-Q-27, SV-80 | 2003 Jan 31–Feb 1, 2003 | r′ | 7 × 300, 3 × 360 | 0.78 | 20.53 | 0.033 |
| RX J1415.1+3612 | GN-2003A-Q-27, SV-80 | 2003 Mar 13, 2003 May 6 | z′ | 29 × 120 | 0.68 | 18.80 | 0.024 |
| GN-2003A-Q-27 | 2003 Apr 27, 2003 May 5 | r′ | 11 × 600 | 0.63 | 20.82 | 0.023 |
| GN-2003A-Q-27, SV-80 | 2003 Apr 27, 2003 May 5 | r′ | 94 × 120 | 0.71 | 19.51 | 0.017 |
| GN-2003A-Q-27 | 2003 Apr 27, 2003 May 5 | z′ | 13 × 210 | 0.62 | 18.78 | 0.013 |

Notes.

a Observations with program IDs starting with GN and GS were obtained with GMOS-N and GMOS-S, respectively.
b Image quality measured as the average FWHM of 7–10 stars in the field from the final stacked images.
c Galactic extinction at cluster center (Schlafly & Finkbeiner 2011) as available through the NASA/IPAC Extragalactic Database.
d F1 pointing eastern field (R.A., Decl.)J2000 = (13 11 37.0, −1 20 29), F2 pointing western field (R.A., Decl.)J2000 = (13 11 23.5, −1 20 29).
e F1 pointing southern field (R.A., Decl.)J2000 = (0 55 59.0, 26 20 30), F2 pointing northern field (R.A., Decl.)J2000 = (0 56 00.5, 26 25 10).
f Observation obtained in twilight, used for photometric calibration only.
g Observations in r′ band (12 × 240 s) obtained under GS-2003B-Q-26 were not used as the images have significantly worse image quality than those from GN-2003B-Q-21.

Appendix B  
Spectroscopic Sample Selection

The sample selection for the GCP spectroscopic observations is based on the color–magnitude diagrams and any redshift information available in the literature at the time of sample selection. Table 17 summarizes the sample selection for those clusters not included in our previous papers. Objects in classes 1 and 2 have highest priority, and span the brighter 2–2.5 magnitude of the red sequence. Available redshifts were used to give higher priority to members and if possible excluded non-members from this selection. We used redshifts from Gioia et al. (1999) for RX J1716.6+6708 and from Dressler et al. (1999) for Abell 851. Objects in class 3 are typically fainter galaxies on the red sequence. However, for clusters with some prior redshift information, brighter red sequence galaxies without prior redshift determinations are included in class 3. Objects in class 4 are only added to fill available space in the...
mask design. They are typically fainter and/or bluer than the objects in classes 1–3. For the field of MS 1610.4+6616, the sample selection was aimed at the published cluster redshift of 0.65 (Luppino & Gioia 1995). Objects in class 1 were assigned to targets with colors that could match this redshift and with a limit of $i^\prime = 21.8$ mag. However, because the field does not contain a rich cluster, there is no well-defined red sequence at the expected colors. Redder and bluer, or fainter, objects were assigned object class 2, and given lower priority in the mask design. The redder objects turned out to be part of the poor group that we identified at $z = 0.83$. The sample in RX J1334.3+5030 was selected without a blue limit on the colors and using only two intervals of the total magnitude to ensure coverage in luminosities. Thus, the sample contains a much larger fraction of blue galaxies than the samples in the other fields.

**Appendix C**

**Cluster Properties and Grayscale Images**

Here we summarize the properties of the clusters, with reference to the original discovery papers, results regarding cluster structure (evidence for subclusters or merging), and the star formation history.

In the descriptions, we make use of Figures 20–27, showing the grayscale images of the clusters for which such information was not included in our previous papers. The images include overlaid contours of X-ray data from either *XMM-Newton* or *Chandra*, or in the case of the field MS 1610.4+6616, X-ray data from *ROSAT*. We also show the grayscale image for RX J0142.0+2131 since at the time of the original publication (Barr et al. 2005), the *Chandra* X-ray data were not available. Grayscale images of the remaining GCP clusters are available in Jørgensen et al. (2005, RX J0152.7–1357), Jørgensen & Chiboucas (2013, MS 0451.6–0305, RX J1226.9+3332), and Jørgensen et al. (2017, Abell 1689, RX J0056.2+2622, RX J0027.6+2626, RX J1347.5–1145).

For the clusters RX J0142.0+2131, Abell 851, RX J0216.5–1747, and RX J1415.1+3612, our spectroscopic samples are marked with information about cluster membership. For MS 1610.4+6616, we show the spectroscopic sample with the 12 members of the poor group indicated. The processing of the spectroscopic data for RX J2146.0+0423, RX J1334.3+5060, and RX J1716.6+6708 is pending. Thus, for these clusters, we show the spectroscopic sample divided into galaxies on the red sequence and those bluer than the red sequence. The labeling matches our selection for the fits to the red sequence; see Section 7.

*Abell 1689/RX J1311.4–0120.* This cluster is included in the Abell catalog of northern clusters (Abell et al. 1989), and has been observed with *XMM-Newton* and *Chandra*; see Jørgensen et al. (2017) for the X-ray data overlaid on our imaging data. The cluster velocity dispersion is very high, $\approx 2100$ km s$^{-1}$ (Jørgensen et al. 2017; Czoske 2004). Analysis of the cluster kinematic data and lensing data (Lemze et al. 2009; Umetsu et al. 2015) shows that the central structure is complex and that the X-ray mass estimate is likely too low. The cluster may be a merger; see discussion in Andersson & Madejski (2004). The cluster is included in our spectroscopic analysis of GCP data (Jørgensen et al. 2017) where we find that the stellar populations of the bulge-dominated galaxies are consistent
with the median metallicities and abundance ratios for the GCP clusters.

**RX J0056.2+2622/Abell 115.** This cluster is also included in the Abell catalog of northern clusters (Abell et al. 1989). This is a binary cluster; see the grayscale image in our analysis in the paper Jørgensen et al. (2017). Barrena et al. (2007) found that the two subclusters are in the plane of the sky as based on the kinematic structure of the cluster. The northern subcluster brightest galaxy is the powerful radio galaxy 3C 28 and hosts an active galactic nucleus (AGN); see, e.g., Hardcastle et al. (2009). The galaxy is ID 1054 in our spectroscopic sample. The cluster X-ray emission is quite diffuse, showing the presence of the two subclusters; see the overlay of XMM-Newton data on our optical imaging in Jørgensen et al. (2017).

We find that the stellar populations of the bulge-dominated galaxies in the cluster are consistent with the median metallicities and abundance ratios for the GCP clusters (Jørgensen et al. 2017).

**RX J0142.0+2131.** This cluster is included in the northern ROSAT All-Sky Galaxy Cluster Survey (NORAS; Böhringer et al. 2000) and the extended ROSAT Brightest Cluster Sample (eBCS; Ebeling et al. 2000a). A bright foreground galaxy is superimposed on the cluster near the center. This led Böhringer et al. to mistakenly list the cluster redshift as 0.0696, the redshift of the foreground galaxy, although the correct cluster redshift is $z = 0.28$. At the time of the publication of our spectroscopic study of this cluster, Barr et al. (2005), XMM-Newton and Chandra data were not available. Chandra data have since been obtained. Figure 20 shows the X-ray data overlaid on our optical imaging. The morphological appearance is that of a relaxed cluster, with X-ray point sources associated with optical counterparts. No detailed analysis of the X-ray data seems to be available in the literature.

**RX J0027.6+2616.** This cluster was discovered in ROSAT observations and first listed in NORAS by Böhringer et al. (2000) and also included in the eBCS (Ebeling et al. 2000a). Later observations with Chandra show little substructure, except for possibly some X-ray emission associated with members of the foreground group at $z = 0.34$, which we identified from our optical spectroscopy Jørgensen et al. (2017). The full spectroscopic analysis is included in Jørgensen et al.

**Abell 851.** This cluster is included in the Abell catalog of northern clusters (Abell et al. 1989). The cluster is very massive and contains substantial substructure. Based on XMM-Newton observations, De Filippis et al. (2003) identified two main subclusters with internal structure; see also Figure 21 for the X-ray data overlaid on our optical imaging. This cluster contains a large fraction of disk galaxies as well as post-starburst galaxies (Andreon et al. 1997; Oemler et al. 2009), and as such is quite atypical for a massive cluster at this redshift. Andreon et al. find the spiral fraction to be close to 50% and hypothesize that the reason may be that the relatively
Figure 21. GMOS-N $r'$-band image of Abell 851 with the spectroscopic samples marked. Contours of the XMM-Newton X-ray data are overlaid. Red circles—confirmed bulge-dominated members with EW[O II] $\leq$ 5 Å. Blue circles—confirmed bulge-dominated members with EW[O II] $>$ 5 Å. Blue triangles—confirmed disk-dominated members. Dark green triangles—confirmed non-members. Purple triangles—targets for which the spectra do not allow redshift determination. The approximate location of the HST/ACS field observed in F814W is marked with dashed lines. Most of the GMOS-N field is also covered by HST/WFPC2 observations (P. Hibon et al. 2018, in preparation). The X-ray image is the sum of the images from the two XMM-Newton EPIC-MOS cameras. The X-ray image was smoothed; any structure seen is significant at the 3σ level or higher. The spacing between the contours is logarithmic with a factor of 1.5 between each contour.

Figure 22. GMOS-N $r'$-band image of RX J2146.0+0423 with the spectroscopic samples marked. Contours of the XMM-Newton X-ray data are overlaid. Red circles—galaxies used to fit the red sequence $(r' - i') > 1.0$ and $(i' - z') > 0.5$. Blue circles—blue galaxies in the spectroscopic sample. Green diamonds—blue stars included in the mask to facilitate correction for telluric absorption lines. The approximate location of the HST/ACS field observed in F814W is marked with dashed lines. The X-ray image is the sum of the images from the two XMM-Newton EPIC-MOS cameras. The X-ray image was smoothed; any structure seen is significant at the 3σ level or higher. The spacing between the contours is logarithmic with a factor of 1.5 between each contour.
Figure 23. GMOS-S $i'$-band image of RX J0216.5–1747 with the spectroscopic samples marked. Contours of the Chandra X-ray data are overlaid. Red circles—confirmed members on the red sequence, $(i'-r') > 0.7$. Blue circles—confirmed blue members with $(r'-i') < 0.7$. Dark green triangles—confirmed non-members. Green diamonds—blue stars included in the mask to facilitate correction for telluric absorption lines. The approximate locations of the HST/ACS fields observed in F775W are marked with dashed lines. The southern HST/ACS field was observed at two different roll angles of HST. The vignetting of the GMOS-S OIWFS is marked. The X-ray image is from the Chandra ACIS camera and is the sum of Chandra ObsId 5760 and Chandra ObsId 6393. The X-ray image was smoothed; any structure seen is significant at the $3\sigma$ level or higher. The spacing between the contours is logarithmic with a factor of 1.5 between each contour.

Figure 24. GMOS-N $i'$-band image of RX J1334.3+5030 with the spectroscopic samples marked. Contours of the XMM-Newton X-ray data are overlaid. Red circles—galaxies used to fit the red sequence $(i'-r') > 0.9$ and $(i'-z') > 0.3$. Blue circles—blue galaxies in the spectroscopic sample. The vignetting of the GMOS-N OIWFS is marked. The approximate location of the HST/ACS field was observed in F775W is marked with dashed lines. The locations of the HST/ACS fields were chosen to avoid the three bright foreground stars (one of which is vignetted by the OIWFS on this image) and to optimize the inclusion of the red galaxies in the spectroscopic sample. The X-ray image is the sum of the images from the two XMM-Newton EPIC-MOS cameras. The X-ray image was smoothed; any structure seen is significant at the $3\sigma$ level or higher. The spacing between the contours is logarithmic with a factor of 1.5 between each contour.
low density intercluster gas failed to stop the star formation in the cluster members. Oemler et al. focus on starburst and post-starburst galaxies in the cluster, and in particular find that the youngest starburst galaxies reside in the center of the cluster. Our spectral analysis of the GCP data will be presented in a future paper.

**RX J1347.5–1147.** This cluster was discovered as the most X-ray luminous of the ROSAT clusters (Schindler et al. 1997). It has been studied extensively in both the optical and X-ray. Weak- and strong-lensing studies have been conducted in an attempt to better estimate the cluster mass and understand the dynamical structure of the cluster; see, e.g., Bradač et al. (2008). As discussed in Jørgensen et al. (2017), there is evidence that the cluster contains an infalling substructure to the southeast of the cluster center (Ettori et al. 2004; Kreisch et al. 2016). We also found that the velocity dispersion of the cluster is in agreement with expectations from the X-ray luminosity, once corrected for the diffuse emission from the substructure. The cluster is included in the analysis in Jørgensen et al.

**RX J2146.0+0423.** The cluster was first mentioned by Gunn et al. (1986) in their photographic survey for intermediate-redshift clusters. The cluster appeared in the 160 square degree ROSAT survey (Vikhlinin et al. 1998), with the cluster redshift listed by Mullis et al. (2003). The cluster was also included in the Wide Angle ROSAT Pointed Survey (WARPS; Perlman et al. 2002). Figure 22 shows our optical image of the cluster overlaid with the X-ray data from XMM-Newton. The cluster is one of the lowest-mass clusters included in the GCP and appears relatively compact, with the majority of the red galaxies in our spectroscopic sample within one arcminute of the cluster center. Our spectroscopic analysis of the cluster will be presented in a future paper.

**MS 0451.6–0305.** This cluster was the most X-ray-luminous cluster included in the Einstein Extended Medium Sensitive Survey (EMSS; Gioia & Luppino 1994). Based on ROSAT data, it was estimated to be among the most X-ray-luminous clusters above redshift 0.5 (Ebeling et al. 2007). The CNO survey found a very large cluster velocity dispersion, 1330 ± 100 km s⁻¹, confirming the large mass of the cluster (Ellingson et al. 1998; Borgani et al. 1999). This is in agreement with our result for the velocity dispersion, 1450 ± 150 km s⁻¹ (Jørgensen & Chiboucas 2013). Strong-lensing modeling by Zitrin et al. (2011) shows that the central mass distribution may be elliptical, while weak-lensing studies show that the brightest cluster galaxy is slightly offset from the peak of the X-ray emission (Comerford et al. 2010; Hoekstra et al. 2012; Soucail et al. 2015). Thus, the cluster is most likely not relaxed. Moran et al. (2007a, 2007b) used wide-field HST/ACS data and optical spectroscopy to study the morphological evolution and star formation history. These authors concluded that the star formation history is truncated, and that star formation stopped at an epoch corresponding to a formation redshift of ≈2. The cluster is included in our analysis in
Based on the absorption line strengths, we find that the bulge-dominated galaxies in this cluster on average have \( \approx 0.1 \) dex lower metallicity than found for other GCP clusters.

**RX J0216.5–1747.** The cluster was included in WARPS (Perlman et al. 2002). Together with RX J2146.0+0423, RX J1334.3+5030, and RX J1716.6+6708, this cluster is among the four lowest-mass clusters in the GCP. Figure 23 shows our optical image of the cluster overlaid with the X-ray data from Chandra. The cluster appears less compact than RX J2146.0+0423 and RX J1716.6+6708. Our spectroscopic analysis of the cluster will be presented in a future paper.

**RX J1334.3+5030.** This cluster was included in the Bright Serendipitous High-Redshift Archival Cluster (SHARC) survey (Romer et al. 2000). The cluster is characterized as non-relaxed by Parekh et al. (2015) based on the morphology of the X-ray emission. Figure 24 shows our optical image of the cluster overlaid with the X-ray data from XMM-Newton. Our spectroscopic analysis of the cluster will be presented in a future paper.

**RX J1716.6+6708.** This cluster was discovered as part of the ROSAT North Ecliptic Pole Survey (Henry et al. 1997). At the time of discovery, this cluster was among only four known \( z > 0.75 \) X-ray clusters. Gioia et al. (1999) found from 37 member galaxies a cluster velocity dispersion of \( \approx 1500 \) km s\(^{-1}\), which is significantly higher than expected given the X-ray luminosity of the cluster. Figure 25 shows our optical image of the cluster overlaid with the X-ray data from Chandra. The X-ray morphology shows some substructure possibly associated with two concentrations of red galaxies about 1.5 arcminute from the otherwise compact core of the cluster. The cluster was included, together with the two higher-redshift GCP clusters RX J0152.7–1357 and RX J1226.9+3332, in the investigation of the \( K \)-band luminosity function for \( z = 0.6-1.3 \) clusters by De Propris et al. (2007), who found the luminosity functions to be consistent with massive galaxies being fully in place by \( z \approx 1.3 \), but also that the epoch of major star formation was as recent as \( z \approx 1.5-2 \). Our spectroscopic analysis of the cluster will be presented in a future paper.

**MS 1610.4+6616.** The EMSS (Gioia & Luppino 1994) included MS 1610.4+6616 as a cluster at redshift larger than 0.5, while Luppino & Gioia (1995) gives a redshift of 0.65. However, subsequent observations have shown that this is not a rich cluster. Donahue et al. (1999) state that the X-ray source is a point source and possibly originates from an AGN. Our spectroscopic observations confirm that the field does not contain a rich cluster. Our sample contains 27 galaxies with redshifts of \( z = 0.60-0.86 \), 12 of which are clustered at \( z = 0.83 \). However, there is no clear clustering of these galaxies and no obvious extended X-ray emission associated with them; see Figure 26. For completeness, we include the photometry obtained of this field in the present paper.

**RX J0152.7–1357.** This cluster was originally discovered from ROSAT data and is included in three different ROSAT surveys: the ROSAT Deep Cluster Survey, the Bright SHARC survey (Nichol et al. 1999), and WARPS (Ebeling et al. 2000b). The
XMM-Newton and Chandra X-ray observations show that the cluster consists of two subclusters, probably in the process of merging (Maughan et al. 2003). See also Jørgensen et al. (2005) for the XMM-Newton X-ray data overlaid on our optical imaging. Nantais et al. (2013) studied the morphologies of the member galaxies and put forward the hypothesis that infalling galaxies are transformed directly from peculiar systems into bulge-dominated galaxies. The cluster is included in our analysis in Jørgensen et al. (2005, 2006, 2007, 2017) and Jørgensen & Chiboucas (2013).

The steep slope of the FP for the cluster relative to that of our low-redshift reference sample supports that low-mass bulge-dominated galaxies contain younger stellar populations than the higher-mass galaxies. This is also supported by the analysis of the spectroscopic and photometric data presented by Demarco et al. (2010). In addition, we find that the average of the abundance ratios \([\alpha/Fe]\) derived from our spectra are \(\approx 0.2\) dex higher than that of the other GCP clusters.

**RX J11226.9+3332.** This cluster was discovered in WARPS (Ebeling et al. 2001). The X-ray structure is due to AGNs. However, Maughan et al. (2007) analyzed the temperature map of the X-ray gas and concluded that it showed evidence of a recent merger event, which is associated with the overdensity of the galaxies southwest of the cluster center; see the grayscale image of the cluster in our analysis paper, Jørgensen & Chiboucas (2013). Recent analysis based on the Sunyaev-Zel’dovich effect of the cluster supports this view (Adam et al. 2015). The cluster is included in our analysis in Jørgensen et al. (2006, 2007, 2017) and Jørgensen & Chiboucas (2013). The FP for this cluster is consistent with our results for RX J0152.7–1357 and indicates the presence of stellar populations in the lower-mass galaxies that are younger than those in higher-mass galaxies.

**RX J1415.1+3612.** The highest-redshift cluster in our \(z = 0.2–1.0\) GCP sample was first listed in WARPS (Perlman et al. 2002), with the note added in proof giving the spectroscopic confirmation of \(z = 1.013\) for the brightest cluster galaxy. Huang et al. (2009) studied strong lensing created by the cluster. These authors find the cluster redshift to be \(z = 1.026\) and cluster velocity dispersion of \(\sigma_{cl} = 807 \pm 185\) km s\(^{-1}\), in agreement with our measurements; cf., Table 1. Figure 27 shows our optical image of the cluster overlaid with the X-ray data from Chandra. Our spectroscopic analysis of the cluster will be presented in a future paper.

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