The Gemini/Hubble Space Telescope Galaxy Cluster Project: Stellar Populations in the Low-redshift Reference Cluster Galaxies

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Abstract

In order to study stellar populations and galaxy structures at intermediate and high redshift (z = 0.2–2.0) and link these properties to those of low-redshift galaxies, there is a need for well-defined local reference samples. Especially for galaxies in massive clusters, such samples are often limited to the Coma cluster galaxies. We present a cluster-to-cluster velocity dispersion study of four massive clusters at z < 0.1: Abell 426/Perseus, Abell 1656/Coma, Abell 2029, and Abell 2142. The measurements are based on data from the Gemini Observatory, McDonald Observatory, and Sloan Digital Sky Survey. For bulge-dominated galaxies, the samples are 95% complete in Perseus and Coma and 74% complete in A2029 and A2142, to a limit of MB,abs ≤ −18.5 mag. The data serve as the local reference for our studies of galaxy populations in the higher-redshift clusters that are part of the Gemini/HST Galaxy Cluster Project (GCP). We establish the scaling relations between line indices and velocity dispersions as a reference for the GCP. We derive stellar population parameters, ages, metallicities [M/H], and abundance ratios from line indices, both averaged in bins of velocity dispersion and from individual measurements for galaxies in Perseus and Coma. The zero points of relations between the stellar population parameters and the velocity dispersions limit the allowed cluster-to-cluster variation of the four clusters to ±0.08 dex in age, ±0.06 dex in [M/H], ±0.07 dex in [CN/Fe], and ±0.03 dex in [Mg/Fe].

Key words: galaxies: clusters: individual (Abell 1656/Coma, Abell 426/Perseus, Abell 2029, Abell 2142) – galaxies: evolution – galaxies: stellar content

Supporting material: machine-readable tables

1. Introduction

Massive galaxy clusters with masses of 10^{14} M_☉ or larger are major building blocks of the large-scale structure of the universe. The precursors of these and the galaxies residing in them can be traced back to z ≈ 2 (e.g., Stanford et al. 2012; Gobat et al. 2013; Andreon et al. 2014; Newman et al. 2014; Daddi et al. 2017) at a time when the age of the universe was about 25% of its current age. As such, these galaxies are valuable time posts for studying galaxy evolution over a large fraction of the history of the universe. The techniques used in investigations of galaxy evolution include photometric studies of luminosity functions and color–magnitude diagrams (e.g., Ellis & Jones 2004; Faber et al. 2007; Foltz et al. 2015; Cerulo et al. 2016) and investigations of morphological mixtures and galaxy sizes (e.g., Dressler et al. 1997; Huertas-Company et al. 2013, 2016; Delaye et al. 2014). Detailed studies of the stellar populations using scaling relations for the spectroscopy, the fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987), and in some cases, determinations of ages, metallicities, and abundance ratios cover many clusters at z ≈ 0.2–1.0 (e.g., Jørgensen et al. 2005, 2006, 2007; Moran et al. 2005, 2007; Kelson et al. 2006; van Dokkum & van der Marel 2007; Sánchez-Blázquez et al. 2009; Saglia et al. 2010; Leethochawalit et al. 2018). At z > 1, the Lynx W cluster (z = 1.3) has been studied by our group (Jørgensen et al. 2014) using data for 13 bulge-dominated galaxies, while three z = 1.4–1.6 clusters were studied by Beifiori et al. (2017) using data for a total of 19 galaxies on the red sequence. All of these investigations rely on reference samples defining the end product of the galaxy evolution. To the extent that the cluster environment affects the evolution of the galaxies, the reference samples should match the cluster environment into which the higher-redshift clusters will evolve. There has been a lack of such data sets, exemplified by the fact that many researchers use the data for the Coma cluster (Jørgensen et al. 1995a, 1995b, 1996; Jørgensen 1999) as their main or only low-redshift reference (e.g., van Dokkum & Franx 1996; Ziegler et al. 2001; Wuyts et al. 2004; Jørgensen et al. 2005, 2006, 2007, 2017; van Dokkum & van der Marel 2007; Cappellari et al. 2009; Saglia et al. 2010; Saracco et al. 2014; Beifiori et al. 2017). Limiting the low-redshift reference to one cluster does not take into account the possible cluster-to-cluster differences in the galaxy populations and their star formation histories. In addition, the Coma cluster is in fact not massive enough to be the end product of some of the massive z = 0.2–1.0 clusters. In our project, the Gemini/HST Galaxy Cluster Project (GCP), we study clusters whose masses are expected by z = 0 to reach close to M_500 = 10^{15} M_☉, which is more than double that of the Coma cluster; cf. Jørgensen et al. (2017, 2018). Other researchers have studied similarly massive clusters, e.g., Kelson et al. (2006), Moran et al. (2007), and Beifiori et al. (2017). The ongoing project Gemini Observations of Galaxies in Rich Early Environments (Balogh et al. 2017) includes three clusters at z = 1.0–1.5 with masses above
5 × 10^{14} M_☉ and will also benefit from access to better reference data at low redshift.

In order to address this lack of in-depth studies of very massive clusters at z < 0.1, we selected for study the two most massive clusters within this redshift, Abell 2029 at z = 0.077 and Abell 2142 at z = 0.089. Together with Coma and Perseus, these clusters will be used as our low-redshift reference sample for future investigations of the GCP clusters. In the present paper, we present and analyze the spectroscopic data for the four clusters based on measurements of velocity dispersions and absorption-line indices. Our analysis includes determination of ages, metallicities, and abundance ratios. Full-spectrum fitting may be pursued in future analysis but is beyond the scope of the current paper. A companion paper (I. Jørgensen et al. 2018, in preparation) will present photometry for the galaxies, enabling studies of galaxy sizes and the fundamental plane.

In Section 2, we provide the context for selecting the four clusters as our low-redshift reference, and we summarize the properties of the clusters. The parent galaxy samples are described in Section 3. Section 4 gives an overview of the various data sources used to compile the most complete samples with measurements of velocity dispersions and absorption-line indices. The section also details the calibration of parameters. Appendix A.1 contains additional detail.

Section 5 presents the color–magnitude diagrams and defines the subsamples of the passive bulge-dominated galaxies used in the remainder of the paper. Then we establish the scaling relations between the line indices and the velocity dispersions in Section 6. We determine ages, metallicities, and abundance ratios from line indices. These measurements are used to study their correlations with the velocity dispersions and set limits on the cluster-to-cluster variations of the stellar populations in Section 7.

In Section 8, we compare our results with other results for low-redshift cluster galaxies and discuss these in the context of using the samples as reference samples for studies of higher-redshift bulge-dominated galaxies and in the context of galaxy evolution in general. The conclusions are summarized in Section 9.

Throughout this paper, we adopt a ΛCDM cosmology with H_0 = 70 km s^{-1} Mpc^{-1}, Ω_M = 0.3, and Ω_λ = 0.7. Magnitudes are given in the AB system, except where noted.

2. Cluster Sample and Cluster Properties

Massive clusters at intermediate and high redshifts (z = 0.2–2.0) continue to grow in mass as they evolve (e.g., van den Bosch 2002; Fakhouri et al. 2010). Therefore, the descendants of such clusters at z ~ 0 will be significantly more massive. If we want to ensure that we are comparing the galaxies in z = 0.2–2.0 massive clusters to galaxies in z ~ 0 clusters that can be their descendants, then that low-redshift reference sample needs to contain the most massive known low-redshift clusters. We illustrate this in Figure 1, which shows mass versus redshift for the GCP clusters at z = 0.2–1.0 and, for reference, all X-ray clusters from Piffaretti et al. (2011). The solid and dashed lines in the figure represent example models for the mass evolution of clusters as a function of redshift; cf. van den Bosch (2002). The most massive GCP clusters at all redshifts are expected by z ~ 0 to evolve into clusters significantly more massive than the Coma cluster and even the Perseus cluster. Massive clusters at z > 1, e.g., Khullar et al. (2018) and references therein, can also be expected to evolve into clusters more massive than the Perseus cluster. The most massive clusters at z < 0.1 are A2029 and A2142, and they may be more suitable as the low-redshift reference clusters for studies of these high-mass z > 0.2 clusters. We therefore selected these two clusters to use as local reference clusters for the GCP, together with the more well-studied Coma and Perseus clusters. All four clusters were included in the northern Abell catalog (Abell et al. 1989). Table 1 summarizes the cluster masses, radii, and luminosities based on X-ray observations. The clusters have masses of M_{500} = (4.3–8.1) × 10^{14} M_☉. The Piffaretti et al. catalog contains a total of 20 clusters with M_{500} > M_{500} (Coma) and z ≤ 0.1. Perseus and Coma are the two lowest-redshift clusters of these, and A2029 and A2142 are the two most massive.

The large masses of the four selected clusters are also reflected in their high cluster velocity dispersions. In Figure 2, we show the distributions of the radial velocities of member galaxies included in the parent samples (see Section 3) and the distributions of the passive bulge-dominated members (see Section 5). Kolmogorov–Smirnov tests give probabilities of 45%–93% that for each cluster, the distributions of the radial velocities of parent sample galaxies and the passive bulge-dominated galaxies are drawn from the same parent distribution. Thus, there are no significant differences in these distributions. Using the biweight method from Beers et al. (1990), we determine the cluster velocity dispersions, σ_{cl}, from the member galaxies in the parent samples. The results are listed in Table 1. We find somewhat larger cluster velocity dispersions than found by other studies. In the classical study by Zabludoff et al. (1990), velocity dispersions of 1277 and 1010 km s^{-1} are found for Perseus and Coma, respectively, based on samples of 114 and 234 galaxies, respectively. Sohn...
Table 1
Cluster Properties and Parent Samples

| Cluster     | Redshift | \(\sigma_{\text{cluster}}\) (km s\(^{-1}\)) | \(\Delta z\) | \(L_{\text{X}}\) (10\(^{44}\) erg s\(^{-1}\)) | \(M_{\text{500}}\) (10\(^{14}\) M\(_{\odot}\)) | \(R_{\text{500}}\) (Mpc) | Sample area (arcmin \(\times\) arcmin) | \(A_g\) | \(k_g\) |
|-------------|----------|-----------------------------------------|------------|---------------------------------|----------------------|-----------------|---------------------------------|------|------|
| Perseus/Abell 426 | 0.0179   | 1368\(^{+74}_{-66}\)                    | 0.006–0.030 | 6.217                           | 6.151                | 1.286           | 120 \(\times\) 124              | 15.5 | 0.555 | 0.03 |
| Coma/Abell 1656 | 0.0231   | 1154\(^{+56}_{-56}\)                    | 0.011–0.035 | 3.456                           | 4.285                | 1.138           | 64 \(\times\) 70                | 16.1 | 0.023 | 0.04 |
| Abell 2029    | 0.0780   | 1181\(^{+42}_{-42}\)                    | 0.066–0.090 | 8.727                           | 7.271                | 1.334           | 30 \(\times\) 30                | 18.7 | 0.134 | 0.17 |
| Abell 2142    | 0.0903   | 1190\(^{+48}_{-48}\)                    | 0.078–0.103 | 10.676                          | 8.149                | 1.380           | 30 \(\times\) 30                | 19.1 | 0.143 | 0.19 |

Notes. Column 1: galaxy cluster. Column 2: cluster redshift. Column 3: cluster velocity dispersion, determined from the available redshifts for the parent samples; see Section 3. Column 4: redshift limits used for definition of cluster membership. Column 5: 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). Column 6: cluster mass within the radius \(R_{\text{500}}\). Column 7: radius within which the mean overdensity of the cluster is 500 times the critical density at the cluster redshift. Column 8: sample area, covering approximately 2\(R_{\text{500}}\) \(\times\) 2\(R_{\text{500}}\). Column 9: magnitude limit of the sample in the rest-frame \(g'\) band, corresponding to \(M_{B,\text{abs}} = -18.5\) mag (Vega magnitudes). Column 10: average Galactic extinction in the \(g'\) band. Column 11: average \(k\)-correction for member galaxies on the red sequence, i.e., for galaxies with \((g' - r') = 0.8\).

Figure 2. Distribution of the radial velocities (in the rest frames of the clusters) relative to the cluster redshifts for cluster members, \(v_r \approx c(z - z_{\text{cluster}})/(1 + z_{\text{cluster}})\). Blue hatched histograms correspond to passive bulge-dominated members brighter than the adopted analysis limits. For reference, the gray histograms show all members in the parent samples. The parent samples have been limited at magnitudes just below the adopted limits for the final samples; see Section 3.

et al. (2017) found \(\sigma_3 = 947 \pm 31\) km s\(^{-1}\) for Coma and 973 \(\pm\) 31 km s\(^{-1}\) for A2029, both based on samples of \(\approx\)1000 galaxies. Owers et al. (2011) found a similar velocity dispersion, 995 \(\pm\) 21 km s\(^{-1}\), for A2142 based on almost 1000 member galaxies. It is possible that our larger values are due to a selection effect of our smaller samples in Coma, A2029, and A2142. However, the differences are not significant for our analysis and results.

Below, we briefly summarize the global properties of each of the clusters. These summaries are by no means intended to be complete reviews of the substantial literature on each of these clusters but serve to put in context the role of the clusters as references for studies of higher-redshift massive clusters.

**Perseus.** The cluster is included in the catalog by Zwicky (1942) and the original Abell (1958) catalog. The brightest cluster galaxy, NGC 1275, hosts a powerful active galactic nucleus (Conselice et al. 2001 and references therein). The cluster’s X-ray emission shows that the cluster is a cooling flow cluster (Fabian 1994), though more recent X-ray data indicate that the initial cooling rates were overestimated; see Rafferty et al. (2008) and references therein. The cluster is generally considered relaxed and has no significant optical substructure (cf. Girardi et al. 1997). However, earlier X-ray observations indicated that substructure may be present (Mohr et al. 1993). Most recently, Chandra data were used to investigate the “sloshing” of the intracluster gas (Walker et al. 2017). The properties and star formation history of NGC 1275 have been studied extensively; see, e.g., Canning et al. (2014) for a recent investigation of the young star clusters in the galaxy. Penny et al. (2009) investigated the dwarf galaxy population of the cluster based on HST imaging and argued that a large dark matter content of these was needed to avoid disruption by the cluster potential. No recent detailed studies based on spectroscopy and line indices exist of the stellar populations of the member galaxies. Friaux-Burnet et al. (2010) included the Perseus cluster in their study of the fundamental plane for the early-type galaxies, though their analysis contains no specific comments on differences among the clusters in the study.

**Coma.** The cluster was first mentioned in the Curtis (1918) cluster catalog. It was included in the catalog by Zwicky (1942) and the original Abell (1958) catalog and has been studied intensively since. ROSAT X-ray observations (White et al. 1993) show that the Coma cluster has significant substructure, most notably the large substructure associated with NGC 4939 to the southwest of the cluster center. Recent weak-lensing studies and new X-ray observations confirm the presence of several subhalos within the cluster (Okabe et al. 2014; Sasaki et al. 2016). Pimbblet et al. (2014) compared the Coma cluster to other massive low-redshift clusters and concluded that kinematically, the cluster is comparable to others, and that subclustering in low-redshift clusters is not unusual. However, the authors concluded that Coma cluster galaxies have higher star formation rates for a given stellar mass than found for other clusters, but see also Tyler et al. (2013). In our discussion, we will return to the question of cluster-to-cluster differences of the stellar populations in the member galaxies. Of the many studies of the stellar populations in the Coma cluster galaxies, most relevant for our analysis are the results by Harrison et al. (2011), who established scaling relations between line strengths and velocity dispersions and investigated the ages, [M/H], and \([\alpha/Fe]\) as a function of velocity dispersions and environment. These authors found no significant dependency of the environment, reaching much larger cluster-center distances.
than covered in our analysis. We compare their other results with ours in the discussion (Section 8).

Abell 2029. The cluster has been known since the original Abell (1958) catalog. It is a cooling flow cluster, with cooling time comparable to that of the Perseus cluster (Allen 2000; Rafferty et al. 2008). Parekh et al. (2015) used Chandra data to study the X-ray morphology of several low-redshift clusters. They classified A2029 as “strong relaxed,” in agreement with the classification from Vikhlinin et al. (2009). Sohn et al. (2017) investigated the luminosity function, stellar mass function, and velocity dispersion function for both A2029 and the Coma cluster. They found no significant differences between these two clusters. Tyler et al. (2013) focused on the star-forming galaxies and determined that A2029 contains star-forming galaxies resembling those in the field, while the Coma cluster contains a population of star-forming galaxies with significantly lower star formation rates for their stellar mass.

Abell 2142. The cluster has been known since the original Abell (1958) catalog. This is another cooling flow cluster (Allen 2000). Parekh et al. (2015) classified this cluster as “nonrelaxed” based on their study of the X-ray morphology, while Vikhlinin et al. (2009) regarded the cluster as relaxed. Owers et al. (2011) identified substructures in the cluster based on extensive redshift data and argued that these are the remnants of minor merging of groups into the cluster. Two of the identified substructures lie within the area we study in the present paper. The earlier study of the Chandra data by Markevitch et al. (2000) also supports the presence of substructure in the central part of the cluster. The spatial distribution of the galaxy types may be related to the infalling groups. In particular, Einasto et al. (2018) found that the central part within 0.7 Mpc of the cluster center is dominated by the passive older galaxies, while the star-forming and recently quenched galaxies dominate at cluster-center distances larger than 2.6 Mpc.

3. Parent Samples

For each cluster, we construct a parent sample of confirmed members within a square area centered on the cluster and with a side length of approximately 2 R500. Here R500 is the radius within which the mean overdensity of the cluster is 500 times the critical density at the cluster redshift. In our analysis, we use samples that are magnitude-limited in the g′ band to a magnitude equivalent to an absolute B-band magnitude of $M_{B,\text{abs}} = -18.5$ mag (Vega magnitudes). This limit corresponds to a dynamical mass of $M_{\text{dyn}} \approx 10^{13.3} M_\odot$ and a velocity dispersion of approximately 100 km s$^{-1}$ for galaxies on the fundamental plane. With current 8 m class telescopes and instrumentation, $M_{B,\text{abs}} = -18.5$ mag is a practical limit for obtaining spectra of such galaxies to $z \approx 1$ and with a sufficient signal-to-noise ratio (S/N) to study the stellar populations, e.g., Jørgensen et al. (2017). Thus, our local sample is a suitable reference for such studies.

The parent samples are described in the following, while Section 4 details the spectroscopy. Table 1 summarizes the sample limits, areas, and sizes. Our sample selection is based on the Sloan Digital Sky Survey (SDSS) photometry, which we correct for Galactic extinction using the values for the individual galaxies provided in SDSS. This originate from the calibration by Schlafly et al. (2011). We calibrate the photometry for the cluster members to rest-frame magnitudes using the k-corrections with color terms as described in Chilingarian et al. (2010). Table 1 includes the mean Galactic extinction for the cluster members and the average k-correction for the g′ band for galaxies on the red sequence. As part of the SDSS data processing, the galaxy profiles were fit with a linear combination of the best-fit radial r$^{1/4}$ profile and exponential profile. The magnitude from this fit is cmodelmag, which we use as the measure of the total magnitudes of the galaxies. As recommended on the SDSS website, we use colors based on modelmag (the total magnitude from the best-fit r$^{1/4}$ profile or exponential profile), as these are consistent across the SDSS passbands.

Perseus/Abell 426. The sample is based on the catalog by Paturel et al. (2003), in the following referred to using the catalog prefix for the galaxies as the Primary Galaxy Catalog (PGC). We cross-match galaxies from the catalog with SDSS Data Release 14 (DR14) photometry. The area R.A.-123000 = 49°.8381−50°.025, decl.-123000 = 41°.597−41°.48 is not covered by DR14. Thus, we used Data Release 7 (DR7) photometry for sample selection in this area. For the analysis, the parent sample was then limited to a rest-frame magnitude of $g'_{\text{rest}} = 15.5$ mag or brighter. The SDSS DR14 contains objects in the Perseus field typed as “galaxies” but not included in the PGC. Visual inspection of the SDSS images shows that these are saturated stars. Our inspection confirms that the PGC provides a complete catalog to the magnitude limit relevant for our study. The selected sample covers an area of 120′ × 124′.

Redshift data from SDSS, the NASA/IPAC Extragalactic Database (NED), and our own observations were used to identify cluster members. Only eight galaxies with $g'_{\text{rest}} < 15.5$ mag do not have spectroscopic redshifts. The parent sample contains 166 spectroscopically confirmed members, 153 of which are brighter than the adopted magnitude limit for the analysis.

Coma/Abell 1656. The sample is based on the catalog from Godwin et al. (1983; GMP). We cross-match galaxies from this catalog with SDSS DR14 photometry and use for the analysis the sample of confirmed members with $g'_{\text{rest}} < 16.1$ mag. The sample covers the same area as used in our previous publications on the cluster, 64′ × 70′ (Jørgensen & Franx 1994; Jørgensen 1999). Redshift data from SDSS, NED, and our own observations were used to identify cluster members. The parent sample contains 185 spectroscopically confirmed members, 152 of which are brighter than the adopted magnitude limit. Only one galaxy brighter than the sample limit does not have a spectroscopic redshift.

Abell 2029. The sample is based on the SDSS DR14 supplemented with DR7 for a small area at the very center of the cluster, where the photometry from DR14 appears to be systematically incorrect for many of the galaxies and other galaxies are missing. While we do not know the origin of this issue, it is possible that it is due to the presence of the very large central cD galaxy. The area covers R.A.-123000 = 227°715−227°751 and decl.-123000 = 5°73417−5°78394. Data from DR7 were also used in the area R.A.-123000 = 227°625−227°765, decl.-123000 = 5°841−5°95, which is not included in DR14. This was also noted by Sohn et al. (2017) in their use of DR12 for the cluster. The SDSS type designation as “galaxy” was adopted for the initial selection. With the sample limited to $g' \leq 20$ mag (including all objects with possible useful spectroscopy), all objects were visually inspected on the SDSS images. A few artifacts and one saturated star were removed from the sample. The selected sample covers an area of 30′ × 30′. The sample for the analysis was then limited to
$, g'_{\text{rest}} \leq 18.7$ mag. Redshifts from SDSS, Sohn et al. (2017), and our own observations were used to assign membership. Twenty-two galaxies with $g'_{\text{rest}} \leq 18.7$ mag have no available redshift. Of these, seven have photometric redshifts from SDSS of 0.06–0.1 and may be cluster members. The parent sample contains 282 spectroscopically confirmed members, 189 of which are brighter than the adopted magnitude limit.

Abell 2142. The sample is based on the SDSS DR14. The SDSS type designation as “galaxy” was adopted for the initial selection. With the sample limited to $g' \leq 20$ mag, all objects were visually inspected on the SDSS images to ensure that they were galaxies. The selected sample covers an area of $30' \times 30'$. The sample for the analysis was then limited to $g'_{\text{rest}} \leq 19.1$ mag. Redshifts from SDSS, NED, and our own observations were used to assign membership. Nine galaxies with $g'_{\text{rest}} \leq 19.1$ mag have no available redshift. None of them are expected to be cluster members based on their SDSS photometric redshifts. The parent sample contains 313 spectroscopically confirmed members, 251 of which are brighter than the adopted magnitude limit.

4. Spectroscopy

4.1. Data Sources

The spectroscopic data were assembled from four main sources.

1. We previously published spectroscopic data for 116 Coma cluster members (Jørgensen 1999). These data were assembled from our own observations with the Large Cassegrain Spectrograph (LCS) and the Fiber Multi-Object Spectrograph (FMOS) on the McDonald Observatory 2.7 m telescope. The derived spectroscopic parameters were supplemented with literature data available at the time and calibrated to consistency. The reader is referred to Jørgensen (1999) for full details on the observations, processing, and calibration to consistency.

2. Observations of 61 Perseus cluster members were obtained with the LCS on the McDonald Observatory 2.7 m telescope. These data were previously used as part of the reference sample in our GCP analysis papers (Barr et al. 2005; Jørgensen et al. 2005, 2014, 2017; Jørgensen & Chiboucas 2013). However, the data have not previously been published.

3. Observations of A2029 and A2142 cluster members were obtained with the Gemini Multi-Object Spectrograph (GMOS-N; Hook et al. 2004) on Gemini North. The observations cover 69 and 63 galaxies in A2029 and A2142, respectively.

4. We use SDSS spectra for all four clusters and derive the relevant spectroscopic parameters from these spectra. The data cover 336 member galaxies with no data from the other data sources; 222 of these are passive bulge-dominated galaxies brighter than our analysis limit of $M_{B,\text{abs}} = -18.5$ mag (Vega magnitudes). The SDSS spectra also provide all line indices blueward of H$\beta$ for the Coma cluster galaxies.

We refer to the previous data for the Coma and Perseus cluster galaxies, items (1) and (2), as the legacy data. In the following sections we describe the processing of the data and the derivation of the spectral parameters. Appendix A.1 contains additional information.

4.2. Perseus Observations

Observations of galaxies in Perseus were carried out with the LCS on the McDonald Observatory 2.7 m telescope in the periods 1994 October 27–November 2 and 1995 October 25–30. Spectra were obtained in two configurations (see Table 2) such that the full wavelength coverage is 3500–5600 Å. The spectra obtained with grating 47 had sufficient spectral resolution for determination of velocity dispersions, as well as line indices. The spectra obtained with grating 43 had lower spectral resolution and were used for determination of line indices in the blue. The slit was aligned with the major axis of the galaxies.

The LCS spectroscopic observations were processed using the methods described in Jørgensen (1999). The processing involved the standard steps of bias and dark subtraction, correction for scattered light, flat fielding, correction for the slit function, wavelength calibration using argon lamp spectra, and sky subtraction. The spectra were cleaned for signal from cosmic-ray events using the technique originally described in Jørgensen et al. (1995b). Observations of the spectrophotometric standard stars BD +284211, Feige 110, and Hiltner 600 were used to calibrate the spectra to a relative flux scale. One-dimensional spectra were extracted with a resulting aperture size of $2'' \times 6''35$; see Table 3.

4.3. A2029 and A2142 Observations

Galaxies in A2029 and A2142 were observed with GMOS-N during semester 2014A using either the long-slit (LS) or the multi-object spectroscopy (MOS) mode. The main purposes of the observations were to obtain deeper spectroscopy for faint cluster members without SDSS spectra and provide sufficient overlap with brighter galaxies with SDSS spectra to facilitate consistent calibration of parameters derived from the two data sources.
Table 3
Summary of Spectroscopic Data

| Cluster | Telescope, Spectrograph | Grating | Exposure Time | FWHM | \( \sigma_{\text{inst}} \) | Aperture | \( N_{\text{member}} \) | S/N |
|---------|------------------------|---------|---------------|-------|----------------|----------|----------------|-----|
| Perseus | McD. 2.7 m, LCS        | #43     | 600–1800      | 1.2–2.5 | 2.35 Å, 134 km s\(^{-1}\) | 2.0 × 6.35, 2.07 | 52 | 21.6 |
| Perseus | McD. 2.7 m, LCS        | #47     | 900–3600      | 2.5–3.0 | 1.03 Å, 59 km s\(^{-1}\) | 2.0 × 6.35, 2.07 | 61 | 28.9 |
| Perseus | SDSS, SDSS spec        |         |               |       | 1.12 Å, 62 km s\(^{-1}\) | 1.5 | 119 | 80.2 |
| Coma   | McD. 2.7 m, LCS        | #47     | 900–3600      | 0.97 Å, 56 km s\(^{-1}\) | 2.0 × 6.35, 2.07 | 44 | 28.3 |
| Coma   | McD. 2.7 m, FMOS       | 3001 mm\(^{-1}\) | 1800–3600 | 4.25 Å, 246 km s\(^{-1}\) | 1.3 | 38 | 33.0 |
| Coma   | Literature             |         |               |       |                      |          | 80 |      |
| A2029  | Gemini North, GMOS-N (MOS) | B600   | 2640          | 0.55–1.20 | 2.07 Å, 111 km s\(^{-1}\) | 1.0 × 2.4, 0.90 | 49 | 36.8 |
| A2029  | Gemini North, GMOS-N (LS) | B600   | 3600          | 0.52–2.17 | 1.66 Å, 89 km s\(^{-1}\) | 0.75 × 2.4, 0.78 | 25 | 17.2 |
| A2029  | SDSS, SDSS Boss spec   |         |               |       | 1.18 Å, 62 km s\(^{-1}\) | 1.5, 1.0 | 117 | 29.0 |
| A2142  | Gemini North, GMOS-N (MOS) | B600   | 2640          | 0.66–1.20 | 2.07 Å, 110 km s\(^{-1}\) | 1.0 × 2.4, 0.90 | 57 | 29.4 |
| A2142  | Gemini North, GMOS-N (LS) | B600   | 3600          | 0.58–1.39 | 1.66 Å, 88 km s\(^{-1}\) | 0.75 × 2.4, 0.78 | 11 | 17.6 |
| A2142  | SDSS, SDSS Boss spec   |         |               |       | 1.19 Å, 62 km s\(^{-1}\) | 1.5, 1.0 | 140 | 18.4 |

Notes. Column 1: cluster name. Column 2: telescope and spectrograph used for the observations. The Gemini North data were obtained under Gemini program IDs GN-2014A-Q-27 (MOS data) and GN-2014A-Q-104 (LS data). The SDSS data were obtained from the SDSS data archive. Column 3: grating. Column 4: exposure times in seconds. Column 5: instrumental resolution derived as \( \sigma \) in Gaussian fits to the sky lines of the stacked LCS and GMOS-N spectra. For the SDSS spectra, we list the resolution of the convolved spectra; see text. The second entry is the equivalent resolution in km s\(^{-1}\) at 5175 Å in the rest frame of the cluster. Column 7: aperture size in arcsec. The LCS and GMOS-N spectra, the first entry is the rectangular extraction aperture (slit width × extraction length). The second entry is the radius in an equivalent circular aperture, \( \alpha_{\text{circ}} = 1.025 (\text{length} \times \text{width})^{1/2} \). Column 8: number of member galaxies with data from this mode, including galaxies fainter than the adopted magnitude limits for the analysis. Column 9: median S/N per Å for the cluster members in the rest frame of the clusters. The S/N for the GMOS-N and SDSS data were derived in the wavelength interval 4100–5250 Å. For the LCS data, 4100–4750 and 4900–5400 Å were used for gratings 43 and 47, respectively.

Table 2 summarizes the instrumentation, while Table 3 summarizes the observations. All observations were obtained with the detector binned by two in both the spatial and spectral direction. Four MOS fields were observed in each cluster, covering 11–18 galaxies each. Each LS pointing covered two or three sample galaxies.

The data were processed in a standard fashion using tasks from the Gemini GMOS package. The processing includes bias subtraction, flat fielding, sky subtraction, and wavelength calibration using CuAr lamp spectra. Observations of the spectrophotometric standard star Wolf 1346 and HZ 44 were used to calibrate the spectra to a relative flux scale. One-dimensional spectra were extracted with a resulting aperture size of 1″0 × 2″4 and 0″75 × 2″4 for the MOS and LS observations, respectively; see Table 3.

4.4. SDSS Spectra

We primarily use SDSS spectra from DR14. As described in Section 3, some areas of the Perseus cluster and A2029 are missing in DR14. For these, we used spectra from DR10. The majority of the spectra were obtained with the original SDSS spectrograph, while a few were obtained with the Baryon Oscillation Spectroscopic Survey (BOSS) spectrograph. Table 3 summarizes the available data relevant for our samples. The wavelength scale of the spectra was first transformed from vacuum wavelengths, \( \lambda_{\text{vac}} \), to air wavelengths, \( \lambda_{\text{air}} \), using the transformation provided on the SDSS DR13 website (cf. Morton 1991):

\[
\lambda_{\text{air}} = \lambda_{\text{vac}} (1.0 + 2.735182 \cdot 10^{-4} + 131.4182 \lambda_{\text{vac}}^2 + 2.76249 \cdot 10^8 \lambda_{\text{vac}}^4)^{-1}.
\]  

The spectra were then resampled onto a linear wavelength scale and convolved with a variable kernel Gaussian to achieve spectra with a constant resolution. For determination of the velocity dispersions, we used minimal convolution to achieve a resolution of 1.0786 Å in the rest frame of the clusters. This matches the resolution of the single stellar population (SSP) models from Maraston & Strömbäck (2011), which we use in the determination of the velocity dispersions (see Section 4.5).

4.5. Spectroscopic Parameters

The spectroscopic parameters were determined using the same methods as described in Jørgensen et al. (2005, 2017) and Jørgensen & Chiboucas (2013). In particular, the redshifts and velocity dispersions were determined from the LCS, GMOS-N, and SDSS data by fitting the galaxy spectra with template spectra using software made available by Karl Gebhardt (Gebhardt et al. 2000, 2003).

The kinematics fitting of LCS grating 47 spectra obtained for the Perseus galaxies used only one template star, an observation of the K0 III star HD 52071, which was obtained with the same instrumental configuration as the galaxies. The velocity dispersions determined from these fits were used in the GCP papers (Barr et al. 2005; Jørgensen et al. 2005, 2014, 2017; Jørgensen & Chiboucas 2013). The spectra were fit in the wavelength range 4900–5400 Å in the rest frame. All galaxies observed with the LCS are passive galaxies dominated by metal lines in this wavelength interval. The fits have \( \chi^2 \approx 1 \). See Table 13 in Appendix A.3, showing that any template mismatch from using only one template spectrum for these fits is minimal.
For the GMOS-N and SDSS data, the fits were limited to a wavelength range of 3750–5500 Å, as for our $z = 0.2–0.5$ GCP spectra (cf. Jørgensen et al. 2017). We use three SSP models from Maraston & Strömbäck (2011) as template spectra. The models have $(\text{age}, \, Z) = (1 \, \text{Gyr}, \, 0.01)$, $(5 \, \text{Gyr}, \, 0.02)$, and $(15 \, \text{Gyr}, \, 0.04)$ and a Salpeter (1955) initial mass function (IMF). The choice of IMF is not critical for the fits, as the lines in the fitted wavelength range are not sensitive to the IMF. These three models adequately span the spectral types of the galaxies and lead to velocity dispersions unaffected by template mismatch. This is similar to the situation for our $z = 0.2–0.9$ GCP data, for which we used three template stars spanning similar spectral properties; see Jørgensen & Chiboucas (2013) for discussion. The Maraston & Strömbäck SSP models are based on the Medium-resolution Isaac Newton Telescope Library of Empirical Spectra (MILES; Vazdekis et al. 2010) library, and we adopt a spectral resolution of $\sigma = 1.0786$ Å, as found by Maraston & Strömbäck.

Absorption-line indices were determined using the Lick/IDS passband definitions (Worthey et al. 1994). In addition, we derive the indices CN3883 and CaHK (Davidge & Clark 1994) and D4000 (Bruzual 1983), the higher-order Balmer line indices H$_{6\lambda}$ and H$_{7\lambda}$ ( Worthey & Ottaviani 1997), the H$_{\beta}G$ index defined by Jørgensen (1997), and the higher-order Balmer line index H$_{\lambda\alpha}$ (Nantais et al. 2013). In all cases, we first convolve the spectra to the Lick/IDS resolution in the rest frame of the galaxies; cf. Worthey & Ottaviani (1997).

At the redshift of A2029, the 5577 Å skyline falls within the passband for the Mgb index. The SDSS spectra have very strong residuals from inadequate subtraction of this skyline. In order to obtain reliable Mgb indices for as many of the A2029 galaxies as possible, we first interpolate across the residuals from the 5577 Å skyline. We evaluate the effect of this on the resulting measurements by interpolating the SDSS spectra of Coma cluster galaxies in the same way, affecting the same wavelengths in the rest frame as affected in the A2029 spectra. We then compare Mgb measured from the interpolated galaxy spectra with the values from the original Coma spectra. As expected, the Mgb measurements are strongly affected if the interpolation is done across the center of the strongest of the magnesium triplet lines, weakening the measurement by more than 0.2 dex. However, only eight out of the 118 A2029 members with SDSS spectra are affected to this extent. For these, we choose not to measure Mgb. For the remainder of the galaxies, our test shows that the interpolation contributes about 0.03 to the uncertainty on log Mgb, which is only half of the typical internal uncertainties.

The line indices were corrected to zero velocity dispersion; see Jørgensen et al. (2005) for details and typical sizes of these corrections. The velocity dispersions and absorption-line indices were then aperture-corrected to a standard aperture diameter of 3′′4 at the distance of the Coma cluster. Correction coefficients are listed in Jørgensen et al. (2005), except for H$_{\lambda\alpha}$, for which we adopt a zero correction (cf. Jørgensen et al. 2014). The aperture sizes for the various data used are listed in Table 3. Velocity dispersions were also corrected for systematic effects based on simulations; see Appendix A.1.

Duplicate GMOS-N observations of the A2029 and A2142 galaxies and duplicate SDSS observations of galaxies in the Perseus and Coma clusters were used to assess the uncertainties on the derived parameters. The details are provided in Appendix A.2. In general, the Monte Carlo simulations used in the kinematics fitting to obtain uncertainty estimates give reliable estimates. The uncertainties on the line indices are in general larger than estimated from the S/N of the spectra. Tables 11 and 12 in Appendix A.2 list the scaling factors for the uncertainties and adopted typical uncertainties on the final measurements. Measurements from repeat observations with GMOS-N or repeat SDSS spectra were averaged. Only the average values are used in the following.

The spectra were inspected for emission in [O II], [O III], and/or H$\beta$, and significant emission was noted. Measurements of emission-line equivalent widths are available through the Portsmouth group’s work (Thomas et al. 2013) and were not repeated here. We use our emission-line flags to omit galaxies with strong emission lines from the analysis. Our flags correspond to equivalent widths of approximately 5 and 2 Å for [O II] and H$\beta$, respectively.

Tables 13–15 in Appendix A.3 list the results from the template fitting and the measured absorption-line indices for each of the data sets.

4.6. Calibration of the Spectroscopic Parameters

The main purpose of this section is to establish consistently calibrated velocity dispersions and absorption-line indices, such that the samples can reliably be used as the low-redshift reference samples for studies of higher-redshift galaxies. As described in Section 1, our previous Coma cluster data (Jørgensen et al. 1995a, 1995b, 1996; Jørgensen 1999) have been used widely in the literature as the low-redshift reference sample. We have used the legacy data for the Coma and Perseus clusters in our previous analysis of $z = 0.2–1.3$ cluster galaxies as part of the GCP (Jørgensen et al. 2005, 2014, 2017; Jørgensen & Chiboucas 2013). We know from our previous work with these data that the two samples are consistent, as will also be confirmed in the following. For these reasons, we aim to calibrate all other data to consistency with the legacy data and proceed as follows.

1. We first establish offsets between our measurements from the SDSS spectra and the legacy data.
2. We then establish offsets between our measurements from the SDSS spectra and the GMOS-N data for A2029 and A2142.
3. We apply the adopted offsets to our measurements from the SDSS spectra and measurements from the GMOS-N spectra such that all individual measurements are consistent with the legacy data.
4. We then average available measurements for each galaxy to obtain the best average parameters consistent with the legacy data.

Figure 3 and Table 4 summarize the comparisons for items (1) and (2). For the redshift and velocity dispersion comparisons, only observations with S/N $\geq 10$ Å$^{-1}$ were included, while for the line index comparisons, we required S/N $\geq 20$ Å$^{-1}$. We estimate the uncertainties on the median offsets as $\sigma_\Delta \approx \text{rms}N^{-0.5}$, where rms is the scatter of the comparisons and $N$ is the number of measurements in the comparisons. We apply an offset to those parameters where at least one of the comparisons has an offset with 3$\sigma$ or larger significance. Those offsets are shown in italics in Table 4. The apparently large and disparate offsets for H$\delta$ and H$\gamma$ are not
statistically significant and only amount to \( \approx 5\% \) of the range of these indices for low-redshift passive galaxies. The comparisons also showed that offsets between the velocity dispersions determined from the SDSS spectra and the legacy data for Coma and Perseus are the same within the uncertainties for the two clusters, confirming the consistency of these two sets of legacy data.

Final average measurements are listed in Table 16 in Appendix A.3. This table also lists the effective S/N Å\(^{-1}\) in the rest frame of the galaxies. Where two measurements were averaged, we list S/N values added in quadrature. Complete S/N information for the Coma legacy data does not exist, as part of the data were compiled from the literature without such information (Jørgensen 1999). We adopted the median S/N = 28 Å\(^{-1}\) for our own data as the typical for all Coma legacy data.

In the analysis, we use the Balmer line indices \( H\beta_G \) and \( (H\delta_A + H\gamma_A)/2 \equiv -2.5 \log (1-(H\delta_A + H\gamma_A)/43.75 + 38.75)) \) (Kuntschner 2000), the iron indices Fe4383 and \( (Fe5270 + Fe5335)/2 \), and the indices Mg\(b \), CN3883, and C4668. These indices can generally be reliably measured from spectra with S/N \( \gtrsim 20 \) Å\(^{-1}\) and are therefore realistic to use for studies of \( z \gtrsim 0.2 \) galaxies. According to stellar population models (e.g., Thomas et al. 2011), the indices are also sufficient to derive ages, [M/H], and abundance ratios, making studies of the variation and evolution of these parameters possible. Calibrated values for other Lick/IDS indices are included Table 16 but not used in the present analysis.

Figure 3. Comparison of previous data with measurements from the SDSS spectra. Panels (a)–(h) show the legacy data for Perseus and Coma. Blue squares are for Perseus, and green triangles are for Coma. The legacy data are on the X-axis, and our SDSS-based determinations are on the Y-axis. Panels (i)–(p) show the GMOS-N data for A2029 and A2142. Yellow squares are for A2029, and red triangles are for A2142. Gray points show data from spectra with S/N < 20 Å\(^{-1}\). Dashed lines mark the one-to-one relations. The GMOS-N data are on the X-axis, and our SDSS-based determinations are on the Y-axis. Only comparisons for the velocity dispersions and line indices used in the analysis are included in the figure. Table 4 summarizes all the comparisons.
Table 4
Comparisons of Legacy, GMOS-N, and SDSS Data

| Parameter     | Legacy Data | GMOS-N Data |
|---------------|-------------|-------------|
|               | N (2)       | Δ (3)       | rms (4) | N (5) | Δ (6) | rms (7) |
| Redshift      | 147         | 0.00002     | 0.00007 | 62    | 0.00008 | 0.00009 |
| log σ         | 147         | 0.056       | 0.052   | 62    | −0.044  | 0.117  |
| CN3883        | 27          | 0.005       | 0.038   | 34    | −0.012  | 0.035  |
| log HCN       | 18          | −0.048      | 0.197   | 33    | −0.032  | 0.285  |
| log CaHK      | 27          | −0.017      | 0.027   | 38    | 0.016   | 0.042  |
| D4000         | 26          | −0.026      | 0.108   | 34    | −0.013  | 0.113  |
| log Fe4383    | 27          | −0.110      | 0.980   | 38    | −0.349  | 1.326  |
| log σ         | 27          | −0.243      | 0.543   | 38    | 0.253   | 0.833  |
| (Hα + Hγ) /λ  | 27          | −0.002      | 0.014   | 38    | −0.001  | 0.020  |
| CN2           | 27          | 0.013       | 0.017   | 38    | −0.008  | 0.028  |
| log G4300     | 27          | 0.017       | 0.043   | 36    | −0.017  | 0.078  |
| log Fe4383    | 27          | 0.016       | 0.062   | 37    | 0.017   | 0.152  |
| log C4668     | 27          | 0.016       | 0.038   | 38    | −0.006  | 0.169  |
| log Hα        | 123         | 0.028       | 0.053   | 35    | 0.018   | 0.061  |
| log Hβ        | 34          | 0.036       | 0.091   | 35    | 0.020   | 0.088  |
| log Mg        | 146         | 0.021       | 0.031   | 38    | 0.017   | 0.037  |
| log Fe5270    | 103         | 0.006       | 0.044   | 35    | 0.017   | 0.180  |
| log Fe5355    | 103         | 0.038       | 0.060   | 34    | 0.033   | 0.090  |
| log(Fc)       | 103         | 0.024       | 0.041   | 34    | 0.023   | 0.076  |

Notes. Column 1: spectroscopic parameter. Column 2: number of galaxies included in the comparisons between the legacy data and our SDSS measurements. Column 3: median of differences derived as “legacy data”−“SDSS measurements.” Offsets in italics are applied to reach consistent calibration; see text. Column 4: scatter of the comparison between the legacy data and the SDSS measurements. Columns 5–7: same information for the comparisons between the GMOS-N data and the SDSS measurements. Differences are derived as “GMOS-N data”−“SDSS measurements.” Comparisons for redshift and log σ include data for which the SDSS S/N ≥ 10 Å−1. Comparisons for line indices include data for which the SDSS S/N ≥ 20 Å−1.

4.7. Comparison with SDSS, Portsmouth, and MPA–JHU Measurements

We compare the final calibrated measurements with (1) redshifts from SDSS DR14, (2) the Portsmouth group’s measurements of velocity dispersions (Thomas et al. 2013), and (3) the Max Planck Institute for Astrophysics and the Johns Hopkins University (MPA–JHU) group’s measurements of line indices. The methods for the various measurements from the MPA–JHU group are described in Kauffmann et al. (2003), Brinchmann et al. (2004), and Tremonti et al. (2004). All measurements are available through the SDSS DR14, though the Portsmouth group used DR12, and the MPA–JHU group’s methods were last run on DR8 spectra. The Portsmouth velocity dispersions were not aperture-corrected (D. Thomas 2018, personal communication). Thus, we first aperture-correct these measurements to our standard size aperture. It is not clear if the MPA–JHU measurements were aperture-corrected or corrected to zero velocity dispersion. Since it is stated on the SDSS DR14 website that the measurements are on the Lick system, we assume that they have been corrected to zero velocity dispersion. We apply our aperture correction to the MPA–JHU measurements before comparing them to our fully calibrated measurements. The comparisons are summarized in Figure 4 and Table 5.

As expected, the redshift measurements are in agreement with the SDSS DR14 values. The comparisons of the velocity dispersions show offsets of 0.005–0.022 in log σ for each of the clusters. These are all within our previous estimates of internal consistency of 0.026 (Jørgensen et al. 2005). Assuming that the data from Thomas et al. are internally consistent, these comparisons confirm that the final measurements of log σ are consistent between the four clusters. We note that small offsets between measurements performed using different techniques are not unusual. Thomas et al. performed more extensive comparisons with previous velocity dispersion measurements based on SDSS spectra and found offsets of 4%–7%, with scatter of 16%–19%.

The comparisons of the line indices show significant offsets at the 5σ or larger level only for D4000, CN2, log Fe4383, and log Hβ (shown in italics in Table 5). In absolute terms, these offsets are quite small. They may originate from small differences in the flux calibration applied by SDSS in the earlier data releases compared to DR14. As can be seen from the error bars in the figures, the scatter in all comparisons is within expectations based on the uncertainties, with the exception of the comparison of Mg b for the A2029 galaxies. The larger scatter in this comparison most likely originates from our corrections for the 5577 Å skyline residuals in these spectra, as we assume that such a correction was not done by the MPA–JHU group.

5. The Galaxy Samples and Methods

Our aim is to characterize the stellar populations in the passive bulge-dominated cluster galaxies by (1) establishing the scaling relations between the velocity dispersions and the absorption-line indices and (2) establishing the relations between the velocity dispersions and the ages, metallicities, and abundance ratios of the galaxies. To achieve the latter, we use the individual measurements for the Perseus and Coma galaxies from spectra with S/N ≥ 50 Å−1, as well as luminosity-weighted averages of the absorption-line indices and the velocity dispersions for all four clusters.

In this section, we establish the samples of passive bulge-dominated cluster galaxies and the completeness of these samples in each cluster and describe the determination of the luminosity-weighted parameters. We briefly recap the adopted methods and stellar population models, all consistent with our approach in our recent GCP publications for z = 0.2–0.9 clusters (Jørgensen & Chiboucas 2013; Jørgensen et al. 2017).

5.1. The Samples

We base our selection of the passive bulge-dominated galaxies on a combination of colors in (g′ − r′) and the modeling parameter fracdev from SDSS. This parameter is the fraction of the luminosity modeled by the r′1/4 profile. In practice, the measurements of fracdev are quite noisy, especially for galaxies at the distances of A2029 and A2142, where comparison of fracdev in the g′, r′, and i′ bands indicates an uncertainty of about 0.07. The measurements for galaxies in Perseus and Coma have uncertainties of about 0.03. Using similar comparisons, we estimate that the uncertainties on fracdev in the u′ and z′ bands are approximately a factor of four and two larger, respectively. To identify
bulge-dominated galaxies, we use the product of \( \text{fracdev} \) in the \( g' \), \( r' \), and \( i' \) bands, \( f_g \times f_r \times f_i \).

We establish the best fit to the red sequence in the \( g'_{\text{rest}} \) versus \( (g' - r') \) color–magnitude diagrams. The relations for the four clusters are shown in Figure 5 and summarized in Table 6. The total \( g'_{\text{rest}} \) magnitude is \( \text{modelmag} \) in the \( g' \) band from SDSS, corrected for galactic extinction and \( k \)-corrected to the rest frame of the galaxies. The \( k \)-correction was done using the calibration from Chilingarian et al. (2010) available through their web interface. The colors are based on \( \text{modelmag} \) from SDSS and have also been corrected to the rest frames. All four clusters have tight red sequences, though the scatter of the Perseus and A2029 galaxies is almost a factor of two larger than that found for Coma and A2142. In Figure 6, we show the residuals \( \Delta(g' - r') \) relative to the red-sequence fits offset to the zero points listed in Table 6 versus \( f_g \times f_r \times f_i \). To identify the galaxies that can be considered passive and bulge-dominated, we proceed as follows. We consider galaxies with \( f_g \times f_r \times f_i < 0.125 \) disk-dominated, corresponding to the exponential disk contributing at least 50% of the flux in all three filters. Galaxies with \( (g' - r') \) more than 3.5\( \sigma \) below the red sequence are also considered disk-dominated, independent
Table 5
Comparisons of Final Data with SDSS Data

| Parameter | All Clusters | Perseus | Coma | A2029 | A2142 |
|-----------|--------------|---------|------|-------|-------|
|           | N            | Δ       | rms  | N     | Δ     | rms  | N    | Δ    | rms  | N    | Δ    | rms  |
| Redshift  | 457          | −0.00002| 0.0002| 119   | −0.00003| 0.0004| 179   | −0.00002| 0.0001| 107   | −0.00003| 0.0001| 52    | −0.00002| 0.0001|
| log σ     | 456          | 0.014   | 0.139 | 119   | 0.013   | 0.104 | 178   | 0.022   | 0.165 | 107   | 0.005   | 0.146 | 52    | 0.010   | 0.064 |
| D4000     | 353          | 0.018   | 0.033 | 84    | 0.074   | 0.030 | 119   | 0.002   | 0.002 | 99    | 0.018   | 0.026 | 51    | 0.022   | 0.024 |
| (HδA + HγA)' | 376       | 0.003   | 0.017 | 98    | 0.003   | 0.012 | 128   | 0.003   | 0.009 | 99    | 0.002   | 0.015 | 51    | 0.001   | 0.034 |
| CN2       | 376          | −0.014  | 0.023 | 98    | −0.016  | 0.065 | 128   | −0.014  | 0.044 | 97    | −0.012  | 0.197 | 51    | 0.001   | 0.057 |
| log G4300 | 372          | −0.013  | 0.111 | 98    | −0.016  | 0.065 | 126   | −0.014  | 0.044 | 97    | −0.012  | 0.197 | 51    | 0.001   | 0.057 |
| log Fe4383| 375          | −0.065  | 0.044 | 97    | −0.066  | 0.025 | 128   | −0.067  | 0.052 | 99    | −0.065  | 0.047 | 51    | −0.055  | 0.041 |
| log C4668 | 374          | 0.004   | 0.036 | 98    | 0.005   | 0.054 | 126   | 0.003   | 0.015 | 99    | 0.004   | 0.037 | 51    | 0.009   | 0.028 |
| log HδG   | 350          | 0.018   | 0.049 | 91    | 0.020   | 0.035 | 118   | 0.015   | 0.041 | 92    | 0.017   | 0.068 | 49    | 0.023   | 0.048 |
| log Mgb    | 371          | 0.010   | 0.058 | 98    | 0.009   | 0.010 | 128   | 0.010   | 0.018 | 95    | −0.004  | 0.109 | 50    | 0.023   | 0.029 |
| log (Fe)  | 375          | −0.008  | 0.035 | 98    | −0.016  | 0.028 | 127   | −0.016  | 0.029 | 99    | −0.007  | 0.042 | 51    | 0.028   | 0.035 |

Notes. Column 1: spectral parameter. Column 2: total number of measurements in comparison. Column 3: median difference. All differences are derived as “this paper”–“SDSS data,” where SDSS data refer to redshifts from DR14, velocity dispersions from the Portsmouth group (Thomas et al. 2013), and line indices from the MPA–JHU group. Differences significant at the 5σ level or higher are shown in italics. Column 4: scatter of the comparison. Columns 5–7: number of measurements, median difference, and scatter of comparison for Perseus galaxies. Columns 8–10: number of measurements, median difference, and scatter of comparison for Coma galaxies. Columns 11–13: number of measurements, median difference, and scatter of comparison for A2029 galaxies. Columns 14–16: number of measurements, median difference, and scatter of comparison for A2142 galaxies.
of the value of $f_g \times f_r \times f_i$. The remainder are considered bulge-dominated. We then visually inspected images of all the galaxies using the SDSS interface to false-color images of the galaxies. This resulted in 38 galaxies (4% of the parent sample) being reclassified from bulge-dominated to disk-dominated or vice versa; see Table 7.

As is common for studies of intermediate- and high-redshift galaxies, our sample selection in Jørgensen et al. (2017) relied on the Sérsic (1968) index, adopting $n_{ser} \geq 1.5$ as bulge-dominated galaxies. Profile fitting of the galaxies in the present low-redshift reference sample will be covered in our companion photometry paper (I. Jørgensen et al. 2018, in preparation). However, for the ≈170 Coma and Perseus galaxies for which we have completed the fitting, the preliminary results

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**Table 6**

| Cluster | Relation                        | $N$  | rms |
|---------|---------------------------------|------|-----|
| Perseus | $(g' - r') = (-0.026 \pm 0.007)(g' - 14.0) + (0.815 \pm 0.007)$ | 148  | 0.058 |
| Coma    | $(g' - r') = (-0.028 \pm 0.003)(g' - 14.6) + (0.765 \pm 0.003)$ | 162  | 0.033 |
| A2029   | $(g' - r') = (-0.023 \pm 0.004)(g' - 17.2) + (0.769 \pm 0.005)$ | 240  | 0.059 |
| A2142   | $(g' - r') = (-0.029 \pm 0.003)(g' - 17.6) + (0.796 \pm 0.003)$ | 259  | 0.036 |

**Notes.** Column 1: cluster. Column 2: best-fit relation. Column 3: number of galaxies included in the fit. Column 4: scatter of the fit.

**Table 7**

| Cluster | From Disk- to Bulge-dominated | From Bulge- to Disk-dominated |
|---------|-------------------------------|-------------------------------|
|         | (1)                           | (2)                          | (3)                          |
| Perseus | 12253, 12290, 12474, 12193,   | 12081, 12497, 12537, 12627,   |                          |
|         | 12287, 12434                 | 12392, 12780, 2197137,       |                          |
|         |                               | 2185837, 2174899, 12119      |                          |
| Coma    | 2940, 4679, 3664, 4156        | 2555, 2374, 2431, 2441,      |                          |
|         |                               | 3238, 4522, 4597, 4933,      |                          |
|         |                               | 5038                          |                          |
| A2029   | 2555, 968, 189               | 4252                          |                          |
| A2142   | 447, 1514, 2661, 326, 2788   | ---                           |                          |

**Notes.** Column 1: cluster. Column 2: IDs for galaxies reclassified from disk- to bulge-dominated. Column 3: IDs for galaxies reclassified from bulge- to disk-dominated.

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Figure 5. Color–magnitude diagrams for the four clusters shown as rest frame ($g' - r'$) vs. $g'_\text{rest}$. Filled black squares indicate the known members of Perseus, A2029, and A2142. Open black squares (panels c and d) show the galaxies in A2029 and A2142 with photometric redshifts that indicate possible membership of the clusters. In panel (b), the filled red squares are the bulge-dominated members and the filled blue squares are the disk-dominated members of Coma with classifications from Dressler (1980). Blue circles indicate emission-line galaxies. Solid red lines show the best fits to the red sequences (Table 6). Dashed black lines mark the location of $\approx 3.5$, the scatter relative to the best-fit red sequence. Dashed blue lines show the adopted limit of the main samples, corresponding to $M_{B,\text{abs}} = -18.5$ mag (Vega magnitudes).

Figure 6. Color residuals $\Delta(g' - r')$ offset to the zero points listed in Table 6, vs. $f_g \times f_r \times f_i$. Symbols and lines are the same as in Figure 5, except the dashed blue lines mark the adopted limit of $f_g \times f_r \times f_i = 0.125$ between the disk- and bulge-dominated galaxies; see text.
show disagreements between the two methods for only four galaxies for which $f_f \times f_e \times f_1 < 0.125$ and $n_{ter} \geq 1.5$. All four of these were reclassified as bulge-dominated as a result of our visual inspection of the SDSS images. Additional discussion of the consistency of the sample selection methods will be included in the photometry paper.

Finally, we divide the samples according to the target-limiting magnitude and divide the bulge-dominated sample into passive and emission-line galaxies. Table 8 summarizes the number of galaxies in each subsample. Our main sample for the analysis consists of the passive bulge-dominated galaxies, the number of which is listed in column (7) in Table 8. In Figure 7, we show the distributions of $g^\prime_{\text{rest}}$ for the four clusters. The blue hatched histograms in the figure compare the distribution of the bulge-dominated galaxies with spectroscopy to all bulge-dominated members of the clusters (blue open histograms). The completeness of the spectroscopy for the bulge-dominated galaxies is 92% and 99% for Perseus and Coma, respectively. A2029 and A2142 have lower completeness, reaching 77% and 71%, respectively.

5.2. Average Parameters

In our determination of ages, metallicities, and abundance ratios, we use line indices averaged in bins of 0.05 in log $\sigma$. The averages are luminosity-weighted, and only measurements from spectra with $S/N \geq 20$ Å$^{-1}$ are included. For a few bins in A2029 and A2142, neighboring bins were merged to ensure that all bins contain at least four galaxies. The median number of galaxies in each bin is 11. The velocity dispersions for the galaxies in each bin were averaged the same way. Average parameters are listed in Appendix A.3, Table 18.

5.3. The Methods and Stellar Population Models

Our technique for establishing the scaling relations and associated uncertainties on slopes and zero points is the same as we used in Jørgensen et al. (2005) and Jørgensen & Chiboucas (2013). Briefly, we establish the scaling relations using a fitting technique that minimizes the sum of the absolute residuals and determines the zero points as the median and the uncertainties on the slopes using a bootstrap method. The technique is very robust to the effect of outliers. In the discussion of the zero-point differences, we use both the random uncertainties as established from the scatter relative to the relations and the systematic uncertainties on the zero-point differences. The latter is expected to be dominated by the possible inconsistency in the calibration of the velocity dispersions. Based on the comparison of the velocity dispersions with data from Thomas et al. (2013), we adopt an upper limit on the systematic differences of 0.022 in log $\sigma$.

For determination of luminosity-weighted mean ages, metallicities, and abundance ratios, we use the SSP models from Thomas et al. (2011) for a Salpeter (1955) IMF and adopt the methods used in Jørgensen et al. (2017). The models assume that the abundance ratios for carbon and nitrogen track those of the $\alpha$-elements, specifically the magnesium abundance ratios.

6. Scaling Relations for Absorption Lines

In Figures 8 and 9, we show the absorption-line indices versus the velocity dispersions for the passive bulge-dominated galaxies. We concentrate on those absorption-line indices that we use in our analysis of the $z = 0.2–0.9$ GCP clusters (Jørgensen et al. 2017), specifically the indices at blue wavelengths ($H\delta_A + H\gamma_A \beta^\prime$, C4668, Fe4383, and CN3883) and visible wavelengths ($H\beta$, Mg$b$, and $Fe$). In the following, we refer to these indices as the “blue” and “visible” indices, respectively.

We first fit the relations to each cluster separately. Measurements originating from spectra with $S/N < 20$ Å$^{-1}$ are omitted. This affects only A2029 and A2142. Within the uncertainties, the slopes of these fits are the same for the four clusters. Thus, we determined the best-fit relations using all four cluster samples together, requiring common slopes but allowing different zero points for the clusters. Table 9 lists the relations shown on the figures, including the zero points and the scatter for each of the cluster samples. The residuals were
minimized perpendicular to the relations, except for
\((H_\delta + H_\gamma)A' = (-0.064 \pm 0.006) \log \sigma + \gamma\), for which the residuals were minimized in the
direction of the \(Y\)-axis.

The larger scatter seen for the galaxies in A2029 and A2142
compared to those in Perseus and Coma is completely
explained by the larger measurement uncertainties. Subtracting
off the measurement uncertainties in quadrature, we
find that the internal scatter is \(\approx 0.015\) for the
\((H_\delta + H_\gamma)A' - \log \sigma\) relation and 0.02–0.03 for all other relations.

| Table 9 Scaling Relations |
|---------------------------|
| Relation                  | Perseus |                | Coma |                | A2029 |                | A2142 |
| (1)                       | \(\gamma\) | \(N_{\text{gal}}\) | rms  | \(\gamma\) | \(N_{\text{gal}}\) | rms  | \(\gamma\) | \(N_{\text{gal}}\) | rms  |
| \((H_\delta + H_\gamma)A' = (-0.064 \pm 0.006) \log \sigma + \gamma\) | 0.053  | 102  | 0.015 | 0.049  | 119  | 0.014 | 0.059  | 102  | 0.024 | 0.055  | 83  | 0.019 |
| \(\log C4668 = (0.29 \pm 0.04) \log \sigma + \gamma\) | 0.204  | 103  | 0.052 | 0.174  | 119  | 0.055 | 0.207  | 103  | 0.073 | 0.158  | 84  | 0.093 |
| \(\log Fe_{4383} = (0.183 \pm 0.017) \log \sigma + \gamma\) | 0.265  | 103  | 0.052 | 0.256  | 119  | 0.042 | 0.235  | 103  | 0.084 | 0.254  | 84  | 0.122 |
| \(CN3883 = (0.198 \pm 0.012) \log \sigma + \gamma\) | -0.207 | 99   | 0.034 | -0.200 | 118  | 0.022 | -0.201 | 101  | 0.037 | -0.193 | 84  | 0.051 |
| \(\log H_\delta = (-0.194 \pm 0.026) \log \sigma + \gamma\) | 0.729  | 101  | 0.052 | 0.743  | 122  | 0.041 | 0.750  | 103  | 0.063 | 0.715  | 84  | 0.063 |
| \(\log Mg_b = (0.243 \pm 0.016) \log \sigma + \gamma\) | 0.109  | 105  | 0.038 | 0.104  | 123  | 0.030 | 0.107  | 98   | 0.055 | 0.117  | 84  | 0.043 |
| \(\log (Fe) = (0.097 \pm 0.018) \log \sigma + \gamma\) | 0.238  | 105  | 0.033 | 0.235  | 122  | 0.036 | 0.237  | 103  | 0.049 | 0.220  | 83  | 0.064 |

Notes. Column 1: scaling relation. Column 2: zero point for the Perseus sample. Column 3: number of galaxies included from the Perseus sample. Column 4: scatter (rms) in the \(Y\)-direction of the scaling relation for the Perseus sample. Columns 5–7: zero point, number of galaxies, rms in the \(Y\)-direction for the Coma sample. Columns 8–10: zero point, number of galaxies, rms in the \(Y\)-direction for the A2029 sample. Columns 11–13: zero point, number of galaxies, rms in the \(Y\)-direction for the A2142 sample.

Figure 8. Absorption lines in the blue, \((H_\delta + H_\gamma)A'\), CN3883, Fe4383, and C4668, vs. velocity dispersions. Blue squares are for Perseus, green triangles are for Coma, yellow squares are for A2029, and red triangles are for A2142. Gray points in panels (e)–(h) show measurements from spectra with \(S/N < 20 \text{ Å}^{-1}\). The best-fit relations offset to the median zero points for each cluster are overlaid, color-coded as the points. Typical uncertainties are shown in the lower right of each panel.

Figure 9. Absorption lines in the visible, \(H_\lambda, Mg_b,\) and \((Fe)\), vs. velocity dispersions. Symbols are the same as in Figure 8. The best-fit relations offset to the median zero points for each cluster are overlaid. Typical uncertainties are shown in the lower right of each panel.
The differences between the zero points are very small. In Figure 10, we illustrate this by showing the line index values for the fits at log $\sigma = 2.24$ for each of the clusters as a function of cluster redshift. The values at log $\sigma = 2.24$ are taken as representative for the clusters, following the convention from Jørgensen et al. (2017). No significant redshift dependence is expected; the choice of X-axis on the plot is purely to separate the clusters to visualize the zero-point differences. The random uncertainties are shown as error bars derived as rms $N_{\text{gal}}^{-0.5}$, where $N_{\text{gal}}$ is the number of galaxies included in each fit. The upper limit on systematic uncertainties due to the possible systematic differences of log $\sigma$ of 0.022 are shown as green dotted lines offset from the median values marked by black lines. We adopt these as marking the possible scatter due to systematic errors. In almost all cases, the clusters are within 2$\sigma$ of the lines marking scatter possible due to systematic errors, and no clusters deviate more than 3$\sigma$. The three cases of deviations of 2$\sigma$–3$\sigma$ are marked with blue circles. These very small zero-point differences set limits on the cluster-to-cluster variation of the ages, metallicities, and abundance ratios. However, since all the indices depend on all three physical quantities, we opt to proceed with determination of these parameters directly before discussing the possible cluster-to-cluster variation.

7. Ages, Metallicities, and Abundance Ratios

To determine ages, metallicities [M/H], and abundance ratios, we use the individual measurements for the Perseus and Coma cluster galaxies with S/N $\geq$ 50 Å$^{-1}$ and, for all four clusters, the luminosity-weighted average indices for subsamples binned in log $\sigma$.

Figure 11 shows the Balmer line index ($\text{H}_\delta + \text{H}_\gamma$)' versus the combination index [C4668 Fe4383] and the iron indices versus CN3883 and log Mg$b$. Model grids from Thomas et al. (2011) are overlaid. The model values for CN3883 are derived from CN2 as described in Jørgensen & Chiboucas (2013). The metal combination index is defined to minimize its dependence on the abundance ratios [\(\alpha/\text{Fe}\)].

$$[\text{C4668 Fe4383}] \equiv \text{C4668} \cdot (\text{Fe4383})^{1/3}$$

see Jørgensen & Chiboucas (2013).

We proceed as in Jørgensen & Chiboucas (2013) and Jørgensen et al. (2017). We determine (age, [M/H]) by linearly interpolating between the models from Thomas et al. in the ($\text{H}_\delta + \text{H}_\gamma$)'—log [C4668 Fe4383] space to identify the (age, [M/H]) value matching each galaxy’s line indices. The abundance ratios are derived from the iron indices versus CN3883 and log Mg$b$. This is done by fitting second-order polynomials to the $[\alpha/\text{Fe}] = 0.3$ models in the parameter spaces of (log Fe4383, CN3883) and (log [Fe], log Mg$b$). The abundance ratio is then determined from the distance between the polynomial fit and the measured parameters measured along the lines of the $[\alpha/\text{Fe}]$ change, as indicated by the purple arrows in the figure. In the following, we refer to these two determinations as [CN/Fe] and [Mg/Fe], respectively, or $[\alpha/\text{Fe}]$ collectively. Note that the Thomas et al. models assume that these abundance ratios are identical. Uncertainties are in all cases estimated from the extreme points of the uncertainties on the line indices.

We chose to use ($\text{H}_\delta + \text{H}_\gamma$)' versus [C4668 Fe4383] as age and metallicity indicators, because the uncertainties on the ages are a factor of 2–2.5 smaller than if determined from $\text{H}_\beta$ versus [MgFe] (see González 1993 for the original definition of the [MgFe] index). This is because the uncertainties on our $\text{H}_\beta$ measurements are higher relative to the index’s age dependency, compared to those of our ($\text{H}_\delta + \text{H}_\gamma$)' measurements. Further, to enable use of the results as a reference for higher-redshift studies, where measurements of the $\text{Mg}$ and $\text{Fe}$ indices are often impossible, we use [C4668 Fe4383] rather than [MgFe]. The uncertainties on [M/H] are also $\approx 30\%$ larger if we use the visible versus the blue indices.

In Figure 12, we show ages, [M/H], [CN/Fe], and [Mg/Fe] versus the velocity dispersions. Best-fit relations are determined as least-squares fits to the parameters derived from the average line indices. There are no significant differences in the slopes for the four clusters. Thus, the slopes are determined by fitting all four clusters together, requiring a common slope but allowing the zero points to vary. The residuals were minimized in the direction of the Y-axis. The best fits are shown in Figure 12 at the median zero point for the clusters (blue lines). We then determine median zero points for all four clusters relative to these fits. The results are summarized in Table 10. The individual measurements (Figures 12(a)–(d)) follow the same relations as the measurements based on the average line indices but with a higher scatter due to the measurement uncertainties. The correlation between the ages and the velocity dispersions is quite weak; a Spearman rank order correlation test gives a probability $P = 0.9\%$ that no correlation is present when using measurements from the average line indices. If
using the individual measurements, the probability of no correlation is $P = 6\%$. For the individual measurements of ages, $[\text{M/H}], [\text{CN/Fe}], \text{and } [\text{Mg/Fe}]$, we tested for possible dependencies on the cluster environment. We used the cluster-center distances, $R_{cl}/R_{500}$, and the radial velocity of the galaxies relative to the clusters, $v_{||}/\sigma_{cl}$, in this test but found no significant correlations between the residuals for the relations in Figures 12(a)–(d) and $R_{cl}/R_{500}$ or with the phase-space parameter $|v_{||}|/\sigma_{cl} \cdot R_{cl}/R_{500}$, which is expected to be related to the accretion epoch of a galaxy onto a cluster; cf. Haines et al. (2012, 2015). Since Smith et al. (2012) found environmental effects in the Coma cluster for the low-mass galaxies (equivalent to $\log \sigma < 1.9$), we repeated the tests by including only galaxies with velocity
To illustrate possible differences between the clusters, Figure 13 shows ages, [M/H], [CN/Fe], and [Mg/Fe] at log σ = 2.24 as determined by the relations. We use the redshift of the clusters as the X-axis of the plot only to separate the measurements. No significant dependence on redshift is expected to be detectable. The measurements for the Perseus and Coma clusters are generally consistent within 2σ and with the median for the four clusters. A2029 and A2142 exhibit differences at the 2σ–2.5σ level. Based on the maximum differences between the four clusters, we can quantify to what extent the data allow cluster-to-cluster variations in ages, [M/H], [CN/Fe], and [Mg/Fe]. For the four clusters, variations of ±0.08 dex in median ages are possible, while variations in [M/H] and [CN/Fe] are within ±0.06 and ±0.07 dex, respectively. The abundance ratio [Mg/Fe] is restricted to ±0.03 dex.

Figure 14 shows the scatter in ages, [M/H], [CN/Fe], and [Mg/Fe] at fixed velocity dispersions. The scatter determined from the relations based on average line indices should be understood as lower limits. More realistic estimates are achieved by using the individual measurements for the Perseus and Coma cluster galaxies (triangles in Figure 14). Subtracting off the measurement uncertainties in quadrature, we find an internal scatter of 0.15, 0.1, 0.09, and 0.06 dex in ages, [M/H], [CN/Fe], and [Mg/Fe], respectively.

Using the individual measurements for the Perseus and Coma galaxies, we find that the residuals for the [M/H]–velocity dispersion relation are correlated with the ages. Fitting all three parameters together gives

\[ \log[M/H] = (0.60 \pm 0.05)\log \sigma - (0.68 \pm 0.07)\log \text{age} - 0.53. \]  

(3)

The residuals were minimized in [M/H]. This relation is illustrated in Figure 15(a), where the points are color-coded in bins of age. The scatter of the relation is 0.092 in [M/H], while a fit to [M/H] as a function of only the velocity dispersion, requiring a common zero point for the Perseus and Coma samples, has a scatter of 0.14. The reduction in the scatter by including the age term is significant at the 5σ level, and the relation has no significant internal scatter. Figures 15(b) and (c) show similar age color-coded versions of [CN/Fe] and [Mg/Fe] versus the velocity dispersions for the Perseus and Coma galaxies. Only an insignificant reduction in scatter is achieved by inclusion of an age term in these relations, though formally, the age coefficients are significant at the 2.5σ–5σ level. We find

\[ \log[CN/Fe] = (0.51 \pm 0.06)\log \sigma - (0.26 \pm 0.05)\log \text{age} - 1.18 \]  

(4)

and

\[ \log[Mg/Fe] = (0.34 \pm 0.04)\log \sigma - (0.10 \pm 0.04)\log \text{age} - 0.57 \]  

(5)

with a scatter of 0.10 and 0.067, respectively. The scatter of the fits without the age term is 0.11 and 0.070 for the two relations.

8. Discussion

8.1. Comparison of Scaling Relations with Previous Results

We want to ensure that our results are consistent with previous results for massive low-redshift clusters. We used dispersions below the median of our sample. None of the tests showed any significant dependency on the cluster-center distance or the phase-space parameter. However, we note that our samples only reach cluster-center distances of \( \approx 1.2R_{500} \) (1.3–1.6 Mpc in Perseus and Coma) and do not include a significant number of galaxies with log σ < 1.9. Thus, we do not expect to see the environmental dependency detected by Smith et al. for low-mass galaxies.
smaller samples of galaxies in Perseus and Coma as our reference samples in previous GCP papers, e.g., Jørgensen & Chiboucas (2013) and Jørgensen et al. (2017). The scaling relations established in those papers agree with our results based on the larger samples in the present paper. Thus, using the larger low-redshift reference sample established in the present paper will not significantly affect our results for the $z = 0.2–0.9$ GCP clusters.

Nelan et al. (2005) and Smith et al. (2006) established scaling relations for clusters in the NOAO Fundamental Plane (FP) survey. The main emphasis of Smith et al. was an investigation of the possible effects of the cluster environment at very large cluster-center distances. Since Nelan et al. and Smith et al. determined the relations in the form $\text{index} = a_1 \log \sigma + a_2$, rather than using the logarithm of the indices, we overlay their relations on our results and compare the slope and zero points at $\log \sigma = 2.2$. We omit the cluster-center distance terms from the
| Relation                      | Perseus | Coma       | A2029 | A2142 |
|-------------------------------|---------|------------|-------|-------|
|                               | γ       | ms$_{avg}$ | ms$_{ind}$ | γ2.24 |     | γ       | ms$_{avg}$ | ms$_{ind}$ | γ2.24 |     | γ       | ms$_{avg}$ | ms$_{ind}$ | γ2.24 |
| log age = (0.40 ± 0.16) log $\sigma + \gamma$ | −0.045  | 0.072      | 0.178  | 0.848 |     | 0.044  | 0.058      | 0.161  | 0.938 | −0.123  | 0.136      | 0.771      | 0.011 |
| [M/H] = (0.56 ± 0.16) log $\sigma + \gamma$    | −1.010  | 0.055      | 0.135  | 0.251 |     | −1.098 | 0.038      | 0.139  | 0.163 | −1.104 | 0.083      | 0.247      | −1.120 |
| [CN/Fe] = (0.57 ± 0.09) log $\sigma + \gamma$  | −1.098  | 0.046      | 0.117  | 0.172 |     | −1.056 | 0.030      | 0.108  | 0.215 | −1.041 | 0.058      | 0.229      | −0.960 |
| [Mg/Fe] = (0.37 ± 0.06) log $\sigma + \gamma$  | −0.559  | 0.019      | 0.073  | 0.263 |     | −0.544 | 0.023      | 0.067  | 0.278 | −0.547 | 0.030      | 0.275      | −0.494 |

**Notes.** Column 1: scaling relation. Column 2: zero point for the Perseus sample. Column 3: scatter (rms) in the Y-direction of the scaling relation for the Perseus sample, based on average line indices. Column 4: rms in the Y-direction of the scaling relation for the Perseus sample, based on individual line indices. Column 5: value of the parameter (log age, [M/H], [CN/Fe], or [Mg/Fe]) at a velocity dispersion of log $\sigma = 2.24$ for the Perseus sample. Columns 6–9: values for the Coma sample. Columns 10–12: values for the A2029 sample; only rms values for measurements based on average line indices are listed. Columns 13–15: values for the A2142 sample; only rms values for measurements based on average line indices are listed.
Table 11
Comparison of Repeat Observations

| Parameter | SDSS Data | | | GMOS-N data | | |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|           | N         | rms       | Ratio     | σ_{int}   | N         | rms       | Ratio     | σ_{int}   |
| log σ     | 70        | 0.029     | 1.6       | 0.013     | 9         | 0.089     | 2.2       | 0.028     |
| CN3883    | 67        | 0.030     | 2.2       | 0.010     | 6         | 0.070     | 1.6       | 0.036     |
| log Hα    | 70        | 0.170     | 1.4       | 0.076     | 6         | 0.436     | 1.2       | 0.192     |
| log CaHK  | 70        | 0.034     | 2.6       | 0.009     | 6         | 0.056     | 1.4       | 0.034     |
| D4000     | 63        | 0.058     | 6.2       | 0.007     | 6         | 0.215     | 6.9       | 0.023     |
| (Hα+HγA)  | 70        | 0.016     | 3.3       | 0.003     | 8         | 0.022     | 1.5       | 0.010     |
| CN2       | 70        | 0.015     | 1.8       | 0.006     | 9         | 0.033     | 1.3       | 0.018     |
| log G4300 | 70        | 0.077     | 3.5       | 0.015     | 9         | 0.118     | 1.7       | 0.042     |
| log Fe4383| 70        | 0.090     | 2.4       | 0.024     | 9         | 0.111     | 1.1       | 0.072     |
| log C4668 | 70        | 0.110     | 3.9       | 0.020     | 9         | 0.114     | 2.2       | 0.038     |
| log Hβb   | 65        | 0.051     | 2.2       | 0.017     | 8         | 0.072     | 2.0       | 0.025     |
| log Mgβ   | 70        | 0.046     | 2.6       | 0.013     | 8         | 0.031     | 1.3       | 0.017     |
| log(Fe)   | 70        | 0.035     | 1.3       | 0.016     | 7         | 0.070     | 2.7       | 0.018     |

Notes. Column 1: spectroscopic parameter. Column 2: number of galaxies in comparisons of the SDSS data. Column 3: scatter of the comparisons for the SDSS data. Column 4: ratio between the scatter of the comparisons and the expected scatter based on the measurement uncertainties in the SDSS data. Column 5: median measurement uncertainties of the measurements included in the comparisons of the SDSS data. Columns 6–9: number of galaxies, scatter, ratio, and median measurement uncertainties for the GMOS-N data.

Smith et al. relations. Before comparison, we convert Hβ to Hβb using the transformation from Jørgensen (1997). We combine the literature relations for HδA and HγA to a relation for (HδA + HγA). Similarly, we combine the literature relations for Fe5270 and Fe5335 to a relation for (Fe). Our slopes agree within the uncertainties with those from Smith et al. The slopes from Nelan et al. are marginally steeper for (HδA + HγA) and C4668, Hβb, Mgβ, and (Fe) and marginally shallower for Fe4383. In all cases, the zero points agree with our zero point for the Coma cluster within ±0.03 dex at log σ = 2.2. This agreement is similar to the agreement in our results for the four clusters studied in the present paper; cf. Table 9.

Harrison et al. (2011) used data for four nearby clusters, including the Coma cluster, to establish scaling relations between line indices and velocity dispersions. These authors used indices converted to magnitudes. Thus, we compare our results to their cluster sample results by comparing slopes and zero points at log σ = 2.2. In all cases, the zero points agree with our zero point for the Coma cluster within ±0.03 dex. The slope from Harrison et al. (2011) for the Mgβ-velocity dispersion relation is marginally steeper at log σ = 2.2 than our result, but for higher velocity dispersion galaxies, it flattens to agreement with our determination.

8.2. Ages, Metallicities, and Abundance Ratios

There are numerous studies in the literature aimed at establishing the relations between the velocity dispersions (or masses) and the stellar population ages, metallicities, and abundance ratios; see Harrison et al. (2011) for an overview. Here we compare to a few selected studies spanning different techniques and sample sizes.

Thomas et al. (2005) used an earlier version (Thomas et al. 2003) of the same models used in the present paper. They based their study on available literature data for 124 galaxies and derived ages, [M/H], and [α/Fe] using the indices in the visible. The slopes of the relations established by Thomas et al. (2005; dashed lines in Figures 12(e), (f), and (h)) agree with our results. A later study by Thomas et al. (2010) uses the same techniques but a much larger sample of SDSS spectra and results in a slightly steeper age–velocity dispersion relation than the 2005 study. The Thomas et al. relations for age and [α/Fe] are offset from our results with approximately +0.1 and −0.1 dex, respectively, possibly due to small differences in the adopted models.

Nelan et al. (2005) stacked the NOAO FP survey spectra in five bins by velocity dispersion in order to achieve high-S/N spectra for their study of ages, [M/H], and [α/Fe]. They derived the parameters from the visible indices (H/β, Mgβ, Fe)) using the Thomas et al. (2003) models. We show their result in Figure 12 (panels (e), (f), and (h)) as purple lines. The slopes of their relations for [M/H] and [α/Fe] agree with ours, while they find an age–velocity dispersion relation slightly steeper than our result. The [α/Fe] is offset to slight lower values relative to ours, again presumably due to small differences in the assumed models.

Smith et al. (2009b) studied the stellar populations of massive galaxies in the Shapley concentration. They used the indices (Hγ, Mgβ, and Fe5015) combined with models from Thomas et al. (2003) to derive ages, metallicities and abundance ratios of the galaxies. We include their results in Figure 12 (panels (e), (f), and (h)) as light green lines. Their relations for [M/H] and [Mg/Fe] are slightly shallower than our results, while their results for the age–velocity dispersion relation agree with our results within the uncertainties. Smith et al. (2009a) listed shallower slopes for all the relations for the Shapley sample and found slightly steeper [M/H] and [Mg/Fe] relations for low-mass galaxies in the Coma cluster, though presumably these differences are due to the range of masses (velocity dispersions) sampled and not to a cluster-to-cluster difference.

Trager et al. (2008) studied a small sample of Coma cluster galaxies using high-S/N spectra. They determined ages, [M/H], and [α/Fe] using the visible indices (H/β, Mgβ, and Fe)). We show their results overlaid in Figure 12 (gray triangles in panels (e), (f), and (h)). In general, their results are in agreement with ours, except there is a systematic offset in [α/Fe] of about 0.15 dex, with the values from Trager et al. being smaller than ours. This offset can be traced back to the
difference in the adopted SSP models. Trager et al. used models from Worthey (1994) with revised response functions to model the nonsolar abundance ratios. Comparing their Figure 4 model grids for different [$\alpha$/Fe] with our Figure 11 model grids illustrates that the models give different abundance ratios. For a typical galaxy with (Mg$b$, Fe) ≈ (4.0, 2.8; GMP 3484 in the Trager et al. sample), Trager et al. found [$\alpha$/Fe] = 0.08, while we found 0.23, confirming an offset of 0.15 dex.

Harrison et al. (2011) derived ages, [M/H], and [$\alpha$/Fe] from several absorption-line indices. They used models from Thomas et al. (2003). We show their results overlaid in Figure 12 (orange lines on panels (e), (f), and (b)). Their age–velocity dispersion relation is slightly steeper than our result, while their [M/H]–velocity dispersion relation is slightly shallower than our result. At log $\sigma = 2.24$, this leads to ≈0.1 dex lower ages and ≈0.06 higher [M/H] than our results. Their results for [$\alpha$/Fe] agree with ours within the uncertainties.

Conroy et al. (2014) used very high S/N stacks of SDSS spectra for their investigation. They performed full-spectrum fitting with models that allowed variations in the individual abundance ratios. In order to compare their results with ours, we make the following assumptions. (1) Conroy et al. [Mg/Fe] can be used as a stand-in for [$\alpha$/Fe] determined from the (Mg$b$, Fe) diagram. (2) The average of Conroy et al. [C/Fe] and [N/Fe] can be used as a stand-in for [$\alpha$/Fe] determined from the (CN3883, Fe4383) diagram, keeping in mind that the underlying assumption for the SSP models we use is that carbon and nitrogen track the $\alpha$-element abundances. (3) We can convert Conroy et al. [Fe/H] to total metallicity [M/H] using the conversion from Thomas et al. (2003), [M/H] = [Fe/H] + 0.94 [$\alpha$/Fe]. With these assumptions and conversions, we then overlay the results from Conroy et al. in Figure 12 (gray lines in panels (e)–(h)). The ages from Conroy et al. are in agreement with our results. The metallicities from Conroy et al. are about 0.1 dex below our results. Our [CN/Fe] determinations are ≈0.05 dex higher than the average of [C/Fe] and [N/Fe] from Conroy et al., while our [Mg/Fe] values are about 0.15 dex higher than the [Mg/Fe] from Conroy. It is possible that the differences are due to differences in the models, though a direct comparison of index–index model grids is not possible.

Finally, we compare to our previous results for the $z = 0.2$–0.9 GCP clusters in Jørgensen et al. (2017), shown in cyan on Figures 12(e)–(g). The age–velocity dispersion relation presented in Jørgensen et al. (2017) was flat when all clusters were fit together. The data for the $z \approx 0.2$ clusters (A1689 and RX J0056.2+2622) give a slope of ≈0.2. In all cases, the correlation between age and velocity dispersion is very weak, as also found here for the four low-redshift clusters. The [M/H]–velocity dispersion relation for the $z = 0.2$–0.9 GCP clusters is almost identical to our result for the low-redshift clusters, while the [CN/Fe]–velocity dispersion relation is significantly steeper. This steeper relation also leads to the median [CN/Fe] value at log $\sigma = 2.24$ being 0.06 dex higher than we find for the low-redshift clusters, with the difference increasing with velocity dispersion. We augment the Jørgensen et al. (2017) results with the [Mg/Fe]–velocity dispersion relation for the $z = 0.2$–0.9 GCP clusters using the data from that paper. The result is shown in cyan in Figure 12(h). The relation is in fact identical to that of the four low-redshift clusters.

In summary, the slopes for the age–velocity dispersion relations established here are within the range found by other studies (Nelan et al. 2005; Thomas et al. 2005, 2010; Harrison et al. 2011; Conroy et al. 2014). However, as also noted by Harrison et al. (2011), there is substantial variation in the determinations of the slope of the age–velocity dispersion relation and, to a lesser extent, in the determinations of the slope of the [M/H]–velocity dispersion relation. It is possible that the steep relations found for some low-redshift samples are due to the inclusion of very young low-mass galaxies in some of the studies (e.g., McDermid et al. 2015). However, it does not fully explain the steep relation found by Nelan et al. (2005).

There is agreement in the literature and with our new results that the slope of the [$\alpha$/Fe]–velocity dispersion relation is 0.3–0.35 when the determinations are based on the visible indices, i.e., the
### Table 13
Abell 426/Perseus: LCS Data

| ID     | Redshift | log $\sigma$ | $\sigma_{\log \sigma}$ | $\chi^2$ | S/N43 | S/N47 | H$_{\alpha}$ | $\sigma_{H_{\alpha}}$ | CN3883 | $\sigma_{CN3883}$ | CaHK | $\sigma_{CaHK}$ | D4000 | $\sigma_{D4000}$ | H$_{\delta}$ | $\sigma_{H_{\delta}}$ |
|--------|----------|--------------|--------------------------|----------|-------|-------|-------------|------------------------|--------|------------------|------|----------------|-------|----------------|--------|------------------|
| 12074  | 0.01616  | 2.240        | 0.013                    | 0.8      | 23.0  |       |             |                        |        |                  |      |                |       |                |        |                  |
| 12098  | 0.02036  | 2.317        | 0.010                    | 1.0      | 21.9  | 30.7  | 0.05        | 0.93                   | 0.246  | 0.018           | 21.73| 0.85           | 2.212| 0.011           | -2.12 | 0.50            |
| 12141  | 0.01395  | 2.249        | 0.018                    | 1.0      | 22.2  |       |             |                        |        |                  |      |                |       |                |        |                  |
| 12152  | 0.02095  | 2.290        | 0.011                    | 1.2      | 24.8  | 29.5  | 1.66        | 0.73                   | 0.297  | 0.015           | 22.72| 0.71           | 2.140| 0.009           | -2.77 | 0.43            |
| 12157  | 0.01623  | 2.239        | 0.010                    | 1.2      | 25.7  | 32.0  | -0.99       | 0.79                   | 0.178  | 0.014           | 21.07| 0.70           | 2.180| 0.009           | -1.26 | 0.41            |
| 12171  | 0.01881  | 2.346        | 0.012                    | 1.2      | 27.5  | 28.6  | 1.51        | 0.46                   | 0.149  | 0.009           | 15.08| 0.55           | 1.554| 0.006           | -0.06 | 0.34            |
| 12176  | 0.01955  | 2.389        | 0.008                    | 1.1      | 28.0  |       |             |                        |        |                  |      |                |       |                |        |                  |
| 12193  | 0.02418  | 2.481        | 0.013                    | 1.4      | 24.3  | 30.3  | -0.47       | 0.86                   | 0.298  | 0.016           | 20.89| 0.77           | 2.212| 0.010           | -3.19 | 0.46            |
| 12203  | 0.02035  | 2.196        | 0.010                    | 1.0      | 23.5  | 28.2  | 1.27        | 0.74                   | 0.252  | 0.015           | 22.24| 0.75           | 2.050| 0.009           | -1.76 | 0.45            |
| 12208  | 0.01928  | 2.306        | 0.015                    | 1.1      | 16.4  | 23.4  | 1.40        | 0.99                   | 0.238  | 0.021           | 18.70| 1.09           | 1.760| 0.012           | -2.07 | 0.65            |

#### Notes
- Columns are explained in Table 17.
- This table is available in its entirety in machine-readable form.
| Cluster/ID | Redshift | log $\sigma$ | $\sigma_{\log \sigma}$ | $f_1$ Gyr | $f_5$ Gyr | $f_{15}$ Gyr | $\chi^2$ | S/N | $H_\alpha$ | $\sigma_{\log H_\alpha}$ | CN3883 | $\sigma_{\log CN3883}$ | CaHK | $\sigma_{\log CaHK}$ | D4000 | $\sigma_{\log D4000}$ | $H_\beta$ | $\sigma_{\log H_\beta}$ | A2029: |
|------------|----------|--------------|------------------------|-----------|-----------|-------------|---------|-----|-----------|------------------------|---------|------------------------|-------|------------------------|--------|------------------------|--------|------------------------|--------|------------------------|
| 9          | 0.08073  | 1.878        | 0.041                  | 0.16      | 0.84      | 0.00        | 0.07    | 20.4 | 0.70      | 0.97                   | 24.12   | 1.56                   | 20.12 | 1.56                   | 21.96  | 1.36                   |
| 16         | 0.07482  | 2.129        | 0.021                  | 0.32      | 0.23      | 0.46        | 1.0     | 37.1 | 0.70      | 0.97                   | 24.12   | 1.56                   | 20.12 | 1.56                   | 21.96  | 1.36                   |
| 17         | 0.08048  | 2.033        | 0.030                  | 0.15      | 0.82      | 0.03        | 1.1     | 30.9 | 0.74      | 1.14                   | 21.96   | 1.93                   | 20.12 | 1.56                   | 21.96  | 1.36                   |
| 43         | 0.07643  | 2.033        | 0.036                  | 0.01      | 0.81      | 0.18        | 0.6     | 16.8 | −0.71     | 1.91                   | 0.065   | 18.74                  | 3.35  | 1.722                  | 0.036  | 1.68                   |
| 62         | 0.08236  | 1.881        | 0.033                  | 0.29      | 0.39      | 0.33        | 0.7     | 21.5 | 0.46      | 1.0                    | 56.6    | 2.0                   | 1.97  | 0.63                   | 21.96  | 1.36                   |
| 92         | 0.07363  | 1.961        | 0.026                  | 0.39      | 0.54      | 2.0         | 55.7    | 1.39 | 0.58      | 0.240                 | 0.023   | 23.47                  | 0.98  | 2.208                  | 0.016  | 1.92                   |
| 115        | 0.08586  | 1.773        | 0.035                  | 0.34      | 0.00      | 0.66        | 23.2    | −0.25 | 1.80      | 0.093                 | 0.066   | 19.10                  | 2.92  | 2.337                  | 0.047  | 1.80                   |
| 131        | 0.08266  | 2.132        | 0.039                  | 0.00      | 0.90      | 1.10        | 30.9    | 0.22 | 1.16      | 0.044                 | 0.023   | 25.33                  | 1.88  | 2.151                  | 0.030  | 0.76                   |
| 135        | 0.08121  | 1.988        | 0.038                  | 0.21      | 0.00      | 0.79        | 22.5    | −0.21 | 1.62      | 0.297                 | 0.060   | 20.64                  | 2.73  | 2.051                  | 0.039  | 1.12                   |
| 137        | 0.08446  | 2.083        | 0.030                  | 0.41      | 0.10      | 0.49        | 1.0     | 33.7 | 2.82      | 0.80                   | 0.034   | 22.86                  | 1.54  | 1.981                  | 0.022  | 0.63                   |

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Table 15
Perseus, Coma, A2029, and A2142: Measurements from SDSS Spectra

| Cluster/ID | Redshift | log σ | σlog σ | f_s, Gyr | f_s, Gyr | f_s, Gyr | χ^2 | S/N | H_α | σ_H_α | CN3883 | σ_CN3883 | CaHK | σ_CaHK | D4000 | σ_D4000 | H_βA | σ_H_β |
|-----------|----------|-------|--------|---------|---------|---------|------|-----|------|-------|--------|----------|------|---------|------|----------|------|--------|
| Perseus:  |          |       |        |         |         |         |      |     |      |       |        |          |      |         |      |          |      |        |
| 12074     | 0.01621  | 2.069 | 0.017  | 0.10   | 0.62   | 0.28    | 3.0  | 137.2 | 0.95 | 0.10  | 0.203  | 0.004    | 19.60 | 0.18    | ...  | ...      | −1.57| 0.08  |
| 12097     | 0.01981  | 1.670 | 0.011  | 0.81   | 0.19   | 0.00    | 0.6  | 56.3  | 3.20 | 0.17  | 0.041  | 0.007    | 16.30 | 0.40    | 1.525| 0.004    | 2.57| 0.16  |
| 12119     | 0.01546  | 2.064 | 0.018  | 0.08   | 0.81   | 0.10    | 1.2  | 83.5  | −1.12| 0.17  | 0.023  | 0.006    | 5.95  | 0.32    | 1.968| 0.004    | −0.92| 0.12  |
| 12132     | 0.01563  | 1.888 | 0.021  | 1.00   | 0.00   | 0.00    | 0.4  | 42.3  | 2.05 | 0.24  | −0.011 | 0.000    | 11.74 | 0.62    | ...  | ...      | 3.05| 0.23  |
| 12133     | 0.01783  | 2.098 | 0.014  | 0.48   | 0.21   | 0.31    | 1.1  | 88.3  | 1.96 | 0.15  | 0.126  | 0.007    | 18.38 | 0.33    | 1.971| 0.004    | 0.42| 0.13  |
| 12160     | 0.01654  | 1.993 | 0.008  | 0.27   | 0.69   | 0.04    | 1.6  | 127.6 | 1.50 | 0.10  | 0.135  | 0.004    | 19.68 | 0.20    | 1.930| 0.003    | −0.11| 0.08  |
| 12166     | 0.01346  | 1.873 | 0.022  | 1.00   | 0.00   | 0.00    | 0.6  | 56.4  | 4.42 | 0.16  | ...    | ...      | 15.04 | 0.41    | ...  | ...      | 4.49| 0.16  |
| 12171     | 0.01882  | 2.266 | 0.007  | 0.49   | 0.11   | 0.40    | 1.4  | 112.7 | 1.67 | 0.08  | 0.128  | 0.003    | 13.73 | 0.19    | 1.650| 0.002    | 0.49| 0.08  |
| 12176     | 0.01971  | 2.319 | 0.011  | 0.00   | 0.72   | 0.28    | 2.3  | 91.9  | 0.59 | 0.13  | 0.294  | 0.005    | 22.28 | 0.23    | 2.293| 0.004    | −1.69| 0.10  |
| 12185     | 0.02097  | 2.260 | 0.010  | 0.11   | 0.61   | 0.28    | 2.5  | 106.1 | 1.08 | 0.14  | 0.285  | 0.005    | 22.48 | 0.24    | 2.321| 0.004    | −1.99| 0.10  |

CN2 (20) σ_CN2 (21) G4300 (22) σ_G4300 (23) H_A (24) σ_H_A (25) Fe4383 (26) σ_Fe4383 (27) C4668 (28) σ_C4668 (29) H_B (30) σ_H_B (31) H_A (32) σ_H_A (33) MgB (34) σ_MgB (35) Fe5270 (36) σ_Fe5270 (37) Fe5335 (38) σ_Fe5335 (39)

Note. Columns are explained in Table 17.
(This table is available in its entirety in machine-readable form.)
Table 16
Perseus, Coma, A2029, and A2142: Fully Calibrated Spectral Parameters

| Cluster/ID | R.A. (J2000) | decl. (J2000) | Sample | F (5) | $\log \sigma$ | Redshift | log $\sigma$ | S/N | $\log \sigma$ | $\log \sigma$ | $\log \sigma$ | CN3833 | CN3833 CaHK | D4000 | $\sigma_\Delta_{\text{CaHK}}$ | $\sigma_\Delta_{\text{D4000}}$ |
|------------|--------------|---------------|--------|-------|--------------|-----------|-------------|-----|--------------|--------------|--------------|--------|---------------|-------|-----------------|-----------------|
| Perseus:   |              |               |        |       |              |           |             |     |              |              |              |        |               |       |                 |                 |
| 12074      | 48.69888     | 42.22270      | 1      | 0.54  | 13.63       | 0.894     | 0.01619    | 2.182| 0.011        | 139.1        | 70            | 0.95   | 0.04          | 0.004| 18.85          | 0.17            |
| 12097      | 48.83565     | 41.61246      | 4      | 0.00  | 14.89       | 0.498     | 0.01981    | 1.726| 0.011        | 56.3         | 11            | 3.20   | 0.17          | 0.041| 0.07          | 15.67          | 0.39          | 1.525          | 0.004          |
| 12098      | 48.83789     | 41.35541      | 1      | 0.26  | 13.29       | 0.791     | 0.02036    | 2.317| 0.010        | 30.7         | 0            | ...   | ...           | 0.246| 0.018         | 21.73          | 0.86          | 2.212          | 0.011          |
| 12119      | 48.96732     | 41.85770      | 4      | 1.00  | 14.69       | 0.860     | 0.01546    | 2.120| 0.018        | 83.5         | 70            | ...   | ...           | 0.023| 0.006         | 5.72           | 0.31          | 1.968          | 0.004          |
| 12132      | 49.00324     | 40.88569      | 4      | 0.03  | 13.80       | 0.432     | 0.01563    | 1.944| 0.021        | 42.3         | 71            | 2.05   | 0.24          | -0.011| 0.000        | 11.29          | 0.60          | ...            | ...            |
| 12133      | 49.00412     | 42.07430      | 1      | 0.36  | 14.11       | 0.885     | 0.01783    | 2.154| 0.014        | 88.3         | 70            | 1.96   | 0.15          | 0.126| 0.007        | 17.67          | 0.32          | 1.971          | 0.004          |
| 12141      | 49.02619     | 40.80464      | 1      | 0.87  | 13.49       | 0.807     | 0.01395    | 2.249| 0.018        | 22.2         | 70            | ...   | ...           | ...  | ...           | ...            | ...            | ...            | ...            |
| 12152      | 49.06599     | 41.18074      | 1      | 1.00  | 14.12       | 0.809     | 0.02095    | 2.290| 0.011        | 29.5         | 0            | 1.66   | 0.73          | 0.297| 0.015        | 22.72          | 0.71          | 2.140          | 0.009          |
| 12157      | 49.10881     | 41.53037      | 1      | 0.67  | 14.09       | 0.815     | 0.01623    | 2.239| 0.010        | 32.0         | 0            | ...   | ...           | 0.178| 0.014        | 21.07          | 0.70          | 2.180          | 0.009          |
| 12160      | 49.11466     | 41.62702      | 1      | 0.37  | 14.33       | 0.770     | 0.01654    | 2.049| 0.008        | 127.6        | 70            | 1.50   | 0.10          | 0.135| 0.004        | 18.92          | 0.19          | 1.930          | 0.003          |

Note. Columns are explained in Table 17.
(This table is available in its entirety in machine-readable form.)
[Mg/Fe]–velocity dispersion relation. We find a somewhat steeper relation from the blue indices, i.e., the [CN/Fe]–velocity dispersion relation. The behavior is in general agreement with the results for carbon and nitrogen from Conroy et al. (2014), though the difference in slopes found by these authors is smaller than that seen from our data. The fact that the [Mg/Fe]–velocity dispersion relation does not appear to have any redshift dependence, while the [CN/Fe]–velocity dispersion relation is steeper at higher redshift, may be related to the timescale for the formation of the α-elements (magnesium in this case) versus carbon and nitrogen and may reflect a real difference in the enrichment of magnesium versus carbon and nitrogen.

Our result for the combined [M/H]–age–velocity dispersion relation is similar to the results by Johansson et al. (2012). A similar relationship was also noticed in the study of the Coma cluster galaxies by Jørgensen (1999). In agreement with our result of only a very weak age dependence of [Mg/Fe] (if any), Johansson et al. noted that [Mg/Fe] does not depend on age. These results support the idea that [Mg/Fe] appears to be set very early in the evolution of the galaxies, while later star formation primarily leads to lower mean ages and higher total metallicities of the galaxies’ stellar populations.

8.3. Cluster-to-cluster Variations

The agreement between the results for the four clusters covered in the present paper may be used to set limits on the allowed cluster-to-cluster differences in passive cluster galaxies. To recap, for the four clusters in our study, median ages, [M/H], [CN/Fe], and [Mg/Fe] may vary by ±0.08, ±0.06, ±0.07, and ±0.03 dex, respectively. In our study of the formula (7), the [Mg/Fe] does not depend on age. These results suggest that the idea of [Mg/Fe] appears to be set very early in the evolution of the galaxies, while later star formation primarily leads to lower mean ages and higher total metallicities of the galaxies’ stellar populations.

On the other hand, we found two cases of large [α/Fe] deviations from the median: RX J0152.7–1357 with [α/Fe] 0.25 dex higher than the median, and RX J1347.5–1154 with [α/Fe] 0.16 dex lower than the median. A binary cluster at redshift z = 0.83, RX J0152.7–1357 is possibly in the process of merging (Maughan et al. 2003; Jones et al. 2004). At z = 0.45, RX J1347.5–1154 has been the topic of debate regarding its mass, as its high X-ray luminosity seems at odds with mass estimates based on the cluster velocity dispersion (Cohen & Kneib 2002). However, improved measurements of the cluster velocity dispersion (Lu et al. 2010) and correction of the X-ray mass for diffuse substructure (Ettori et al. 2004) bring agreement between the X-ray properties and the cluster velocity dispersion (Jørgensen et al. 2017). If the galaxies in these two clusters evolve passively, they will maintain their [α/Fe], and the clusters’ galaxy populations will at the present epoch not resemble those of our four reference clusters. These abundance ratio measurements were based on CN3883 versus Fe4383 and should therefore be compared to [CN/Fe] in the present paper. The deviations are significant at the 3.5σ and 2.3σ level. If, in fact, no z ~ 0 clusters exist that deviate to that extent from the median [CN/Fe], then this continues to be a challenge to a simple passive evolution model for the bulge-dominated passive galaxies in these clusters; see Jørgensen et al. (2017).

We stress that our reference sample contains four out of 20 known clusters at z < 0.1 and at least as massive as the Coma cluster. It cannot be ruled out that more variation in [CN/Fe] exists among these 20 clusters than is found from the four we have studied. However, in our study of nine z = 0.2–0.9 clusters, we found two clusters with significantly deviating [CN/Fe]. If a similar frequency (20%–25%) of clusters with unusual [CN/Fe] is present (randomly) among the 20 massive z < 0.1 clusters, then we would have a 60%–70% chance of detecting at least one of them in our sample of four clusters.

9. Summary and Conclusions

We have presented consistently calibrated velocity dispersions and absorption-line indices for large homogeneous samples of galaxies in the four low-redshift massive clusters Perseus, Coma, A2029, and A2142. The samples are magnitude-limited to an absolute B-band magnitude of M_B,abs = −18.5 mag (Vega magnitudes) and between 71% and 99% complete. The systematic errors in velocity dispersions are estimated from external comparisons to be <0.022 log σ. The data presented here form the low-redshift reference sample for the Gemini/HST GCP aimed at studying the evolution of z = 0.2–2.0 cluster galaxies and are suitable as a low-reference sample for other studies of medium-to-high-redshift galaxies.

We used luminosity-weighted average absorption-line indices to derive ages, metallicities [M/H], and abundance ratios for the galaxies binned in velocity dispersion. We also derived these parameters from the individual line index measurements for the Perseus and Coma galaxies, limiting this study to spectra with S/N > 50 Å^-1. We selected the subsample of passive bulge-dominated galaxies based on a combination of colors, and the SDSS provided information on the fraction of the luminosity modeled by an r^{1/4} profile. Our main conclusions from the analysis of the properties of this subsample are as follows.

1. The galaxies in the four clusters follow the same scaling relations between absorption-line indices and velocity dispersions. All zero-point differences are within 3σ. The internal scatter is very low at 0.015 for the higher-order Balmer lines and 0.02–0.03 for all other indices. The relations are in agreement with recent literature results for low-redshift clusters.

2. The clusters follow relations between [M/H], abundance ratios, and velocity dispersions with no cluster-to-cluster variations in the slope. Any zero-point differences in ages, [M/H], [CN/Fe], and [Mg/Fe] are limited to ±0.08, ±0.06, ±0.07, and ±0.03 dex, respectively. The limit on [CN/Fe] variations poses a challenge for our previous results from z = 0.2–0.9 clusters, which showed two cases of [CN/Fe] deviating 0.16–0.25 dex from the median value. We find an internal scatter in ages at a fixed velocity dispersion of 0.15 dex, while the scatter in [M/H], [CN/Fe], and [Mg/Fe] is 0.06–0.10 dex.

3. The [M/H]–age–velocity dispersion relation has significantly lower measured scatter in [M/H] than found for the [M/H]–velocity dispersion relation and no significant internal scatter. A similar reduction in the scatter is not seen if including an age term in the relations for [CN/Fe] or [Mg/Fe]. We speculate that the reason for this may be related to the epoch at which the abundance ratios are established for the stellar populations.
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This research made use of the “k-corrections calculator” service available at http://kcor.sai.msu.ru/.

This paper makes use of photometry and spectroscopy from the Sloan Digital Sky Survey (SDSS). Funding for SDSS-IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. The SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS website is http://www.sdss.org.

Appendix

Spectroscopic Data

A.1. Spectroscopic Parameters: Systematic Effects in Derived Velocity Dispersions

Following the techniques used in Jørgensen & Chiboucas (2013) and Jørgensen et al. (2017), we used simulations to quantify any systematic effects on the derived velocity dispersions. Model spectra were made using the average of the two oldest SSP models from Maraston & Strömbäck (2011) used for our template fitting. These are the models with (age, Z) = (5 Gyr, 0.02) and (15 Gyr, 0.04). We then used information from the real noise spectra to add random noise to the model spectra. The simulations cover velocity dispersions between 50 and 350 km s\(^{-1}\) and S/N = 6–50 Å\(^{-1}\). Simulations were performed for both the GMOS-N and SDSS data. The results are shown in Figure 16. The behavior of the two sets of simulations is very similar, though not identical. At S/N = 6 Å\(^{-1}\) (crosses in Figure 16), the simulations deviate significantly from the behavior at higher S/N. Thus, these simulations are omitted from the analysis, and for the real data, we require S/N ≥ 10 Å\(^{-1}\) in order for the velocity dispersion and other parameters to be included in our final measurements. We then fit second-order polynomials to the difference between input and output as a function of the output velocity dispersions. The correction for the GMOS-N data was derived by omitting the lowest velocity dispersion simulations, as these deviate significantly from the remainder of the simulations. The resulting correction for the GMOS-N data is

\[
\log \sigma_{\text{corrected}} = \log \sigma_{\text{out}} - 0.060 + 0.296 (\log \sigma_{\text{out}} - 2.1) - 0.367 (\log \sigma_{\text{out}} - 2.1)^2, \tag{6}
\]

while the correction for the SDSS data is

\[
\log \sigma_{\text{corrected}} = \log \sigma_{\text{out}} - 0.041 + 0.274 (\log \sigma_{\text{out}} - 2.1) - 0.422 (\log \sigma_{\text{out}} - 2.1)^2, \tag{7}
\]

A.2. Comparison of Measurements from Repeat Observations

The SDSS and GMOS-N repeat observations are compared in Figures 17 and 18. Table 11 summarizes the comparison. The table lists the ratios between the median internal measurement uncertainties based on the S/N of the spectra and the scatter in the comparisons. The ratios are correlated, with the SDSS ratios being generally larger than the GMOS-N ratios, possibly due to inadequate accounting for all uncertainties in the error spectra of the SDSS spectra. We estimate uncertainties for samples of galaxies by deriving the median values of the internal measurement uncertainties and then for each line index scale with the average of the two ratios from Table 11. The results for the bulge-dominated passive galaxies in each cluster (our main samples for the analysis) are summarized in Table 12. These uncertainties are shown as typical error bars for the line indices in the figures in the main text.
A.3. Spectroscopic Parameters

Table 13 lists the spectral parameters from the LCS data of the Perseus galaxies. Table 14 lists the spectral parameters from the GMOS-N data of the A2029 and A2142 galaxies. Table 15 lists the spectral parameters derived from the SDSS spectra of all four clusters. Table 16 gives the final calibrated spectral parameters for all four clusters. Only a portion of each of these tables are shown here; the tables are available in their entirety as machine-readable tables. The velocity dispersions and line indices have been corrected to a standard size aperture equivalent to a circular aperture with a diameter of 3.4 at the distance of the Coma cluster. The velocity dispersions from the GMOS-N and SDSS data have been corrected for systematic effects as explained in Appendix A.1. The line indices have been corrected to zero velocity dispersion. The calibration of all data to consistency is detailed in Section 4.6. Table 17 explains the columns in these tables other than the line indices and matching uncertainties.
Table 17
Columns in Data Tables

| Cluster/ID   | Table 13 | Table 14 | Table 15 | Table 16 | Description                                                                 |
|--------------|----------|----------|----------|----------|-----------------------------------------------------------------------------|
| Cluster name if more than one cluster in table, galaxy ID number |
| R.A. (J2000) | 1        | 1        | 1        | 1        | R.A. (J2000) in deg                                                         |
| decl. (J2000)|          |          |          | 3        | decl. (J2000) in deg                                                        |
| Sample       |          |          |          |          |                                                                             |
| Sample number: 1 = passive bulge-dominated brighter than analysis limit, 2 = emission-line bulge-dominated brighter than analysis limit, 3 = bulge-dominated fainter than analysis limit, 4 = disk-dominated brighter than analysis limit, 5 = disk-dominated fainter than analysis limit |
| $F$          |          |          |          |          | Product of fracdev from SDSS, $f_g \times f_r \times f_i$                   |
| $g'_{\text{ext}}$ |          |          |          |          | SDSS $cmodelmag$ in $g'$, calibrated to rest frame                        |
| $(g'-r')_{\text{rest}}$ |          |          |          |          | SDDS color based on $modelmag$, calibrated to rest frame                    |
| Redshift     | 2        | 2        | 2        | 8        |                                                                             |
| log $\sigma$ | 3        | 3        | 3        | 9        | Logarithm of the velocity dispersion in km s$^{-1}$, calibrated to standard aperture diameter of 3'4 at the distance of the Coma cluster and corrected for systematic effects |
| $\sigma_{\text{log } \sigma}$ | 4        | 4        | 4        | 10       | Uncertainty on log $\sigma$                                               |
| $f_{1 \text{ Gyr}}$ |          |          |          |          |                                                                             |
| $f_{5 \text{ Gyr}}$ |          |          |          |          |                                                                             |
| $f_{15 \text{ Gyr}}$ |          |          |          |          |                                                                             |
| $\chi^2$     | 5        | 8        | 8        | 11       |                                                                             |
| $S/N_{\text{43}}$ |          |          |          |          |                                                                             |
| $S/N_{\text{47}}$ |          |          |          |          |                                                                             |
| Emis.        |          |          |          |          |                                                                             |
| $S/N$ per Å in the rest frame for LCS grating 43 observations |
| 0 or blank = no emission, 1 = emission, 7 = line is outside wavelength coverage |
## Table 18

Average Parameters, Ages, $[\text{M}/\text{H}]$, $[\text{CN}/\text{Fe}]$, and $[\text{Mg}/\text{Fe}]$

| Cluster | N   | $\log \sigma$ | $\sigma_{\log \sigma}$ | $\text{CN3883}$ | $\sigma_{\text{CN3883}}$ | $(\text{H}_0 + \text{H}_\gamma)^{'}$ | $\sigma_{(\text{H}_0 + \text{H}_\gamma)^{'}}$ | $\log \text{Fe}4383$ | $\sigma_{\log \text{Fe}4383}$ | $\log \text{C}4668$ | $\sigma_{\log \text{C}4668}$ | $\log \text{H}_2$ | $\sigma_{\log \text{H}_2}$ | $\log \text{Mg}b$ | $\sigma_{\log \text{Mg}b}$ | $\log (\text{Fe})$ | $\sigma_{\log (\text{Fe})}$ |
|---------|-----|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Perseus | 13  | 1.874         | 0.005           | 0.176           | 0.007           | −0.063          | 0.002           | 0.013           | 0.013           | 0.013           | 0.013           | 0.017           | 0.001           | 0.373           | 0.008           | 0.555           | 0.007           | 0.446           | 0.008           |
| Perseus | 7   | 1.975         | 0.007           | 0.191           | 0.007           | −0.074          | 0.003           | 0.013           | 0.013           | 0.013           | 0.013           | 0.016           | 0.001           | 0.332           | 0.012           | 0.579           | 0.008           | 0.454           | 0.008           |
| Perseus | 12  | 2.070         | 0.003           | 0.190           | 0.005           | −0.070          | 0.002           | 0.002           | 0.002           | 0.002           | 0.009           | 0.012           | 0.006           | 0.319           | 0.007           | 0.590           | 0.006           | 0.450           | 0.006           |
| Perseus | 8   | 2.130         | 0.004           | 0.201           | 0.007           | −0.077          | 0.003           | 0.016           | 0.016           | 0.016           | 0.016           | 0.016           | 0.016           | 0.331           | 0.014           | 0.599           | 0.009           | 0.426           | 0.010           |
| Perseus | 8   | 2.181         | 0.004           | 0.205           | 0.006           | −0.076          | 0.003           | 0.013           | 0.013           | 0.013           | 0.013           | 0.015           | 0.015           | 0.275           | 0.018           | 0.605           | 0.010           | 0.440           | 0.010           |
| Perseus | 10  | 2.237         | 0.004           | 0.216           | 0.007           | −0.093          | 0.004           | 0.012           | 0.012           | 0.012           | 0.012           | 0.013           | 0.013           | 0.311           | 0.020           | 0.649           | 0.009           | 0.464           | 0.010           |
| Perseus | 11  | 2.274         | 0.003           | 0.256           | 0.006           | −0.092          | 0.002           | 0.009           | 0.009           | 0.009           | 0.010           | 0.010           | 0.310           | 0.012           | 0.630           | 0.006           | 0.460           | 0.007           |
| Perseus | 19  | 2.322         | 0.002           | 0.236           | 0.006           | −0.093          | 0.003           | 0.011           | 0.011           | 0.011           | 0.011           | 0.015           | 0.015           | 0.278           | 0.015           | 0.659           | 0.006           | 0.457           | 0.007           |
| Perseus | 9   | 2.384         | 0.003           | 0.274           | 0.006           | −0.101          | 0.003           | 0.010           | 0.010           | 0.010           | 0.010           | 0.015           | 0.015           | 0.266           | 0.015           | 0.686           | 0.008           | 0.463           | 0.009           |
| Perseus | 8   | 2.477         | 0.003           | 0.293           | 0.011           | −0.101          | 0.006           | 0.017           | 0.017           | 0.017           | 0.017           | 0.259           | 0.023           | 0.707           | 0.009           | 0.478           | 0.009           |

| log age | $\sigma_{\log \text{age}}$ | $[\text{M}/\text{H}]$ | $\sigma_{[\text{M}/\text{H}]}$ | $[\text{CN}/\text{Fe}]$ | $\sigma_{[\text{CN}/\text{Fe}]}$ | $[\text{Mg}/\text{Fe}]$ | $\sigma_{[\text{Mg}/\text{Fe}]}$ |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.70    | 0.03            | 0.14            | 0.04            | −0.00           | 0.04            | 0.04            | 0.14            | 0.02            |
| 0.80    | 0.04            | 0.17            | 0.04            | 0.04            | 0.04            | 0.04            | 0.16            | 0.02            |
| 0.75    | 0.05            | 0.20            | 0.04            | 0.12            | 0.04            | 0.03            | 0.19            | 0.02            |
| 0.84    | 0.05            | 0.22            | 0.04            | 0.08            | 0.03            | 0.03            | 0.26            | 0.02            |
| 0.78    | 0.04            | 0.22            | 0.03            | 0.08            | 0.03            | 0.03            | 0.27            | 0.02            |
| 0.90    | 0.04            | 0.25            | 0.03            | 0.19            | 0.03            | 0.03            | 0.27            | 0.02            |
| 0.88    | 0.04            | 0.40            | 0.04            | 0.28            | 0.02            | 0.03            | 0.31            | 0.02            |
| 0.83    | 0.04            | 0.40            | 0.06            | 0.30            | 0.03            | 0.03            | 0.32            | 0.02            |
| 0.75    | 0.04            | 0.47            | 0.06            | 0.30            | 0.03            | 0.03            | 0.32            | 0.02            |

(This table is available in its entirety in machine-readable form.)
Table 18 gives the average velocity dispersions and line indices for bins in velocity dispersion. The table also lists ages, [M/H], [CN/Fe], and [Mg/Fe] derived from these.

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