Stellar Population Properties of Ultracompact Dwarfs in M87: A Mass–Metallicity Correlation Connecting Low-metallicity G4ular Clusters and Compact Ellipticals

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Abstract

We derive stellar population parameters for a representative sample of ultracompact dwarfs (UCDs) and a large sample of massive globular clusters (GCs) with stellar masses \( \gtrsim 10^6 \, M_\odot \) in the central galaxy M87 of the Virgo galaxy cluster, based on model fitting to the Lick-index measurements from both the literature and new observations. After necessary spectral stacking of the relatively faint objects in our initial sample of 40 UCDs and 118 GCs, we obtain 30 sets of Lick-index measurements for UCDs and 80 for GCs. The M87 UCDs have ages \( \gtrsim 8 \) Gyr and \( [\alpha/Fe] \approx 0.4 \) dex, in agreement with previous studies based on smaller samples. The literature UCDs, located in lower-density environments than M87, extend to younger ages and smaller \( [\alpha/Fe] \) (at given metallicities) than M87 UCDs, resembling the environmental dependence of the stellar nuclei of dwarf elliptical galaxies (dEs) in the Virgo cluster. The UCDs exhibit a positive mass–metallicity relation (MZR), which flattens and connects compact ellipticals at stellar masses \( \gtrsim 10^8 \, M_\odot \). The Virgo dE nuclei largely follow the average MZR of UCDs, whereas most of the M87 GCs are offset toward higher metallicities for given stellar masses. The difference between the mass–metallicity distributions of UCDs and GCs may be qualitatively understood as a result of their different physical sizes at birth in a self-enrichment scenario or of galactic nuclear cluster star formation efficiency being relatively low in a tidal stripping scenario for UCD formation. The existing observations provide the necessary but not sufficient evidence for tidally stripped dE nuclei being the dominant contributors to the M87 UCDs.

Key words: galaxies: clusters: individual (Virgo) – galaxies: dwarf – galaxies: formation – galaxies: star clusters: general – galaxies: stellar content – globular clusters: general

1. Introduction

In the size–luminosity plane, the division once thought to exist between globular clusters (GCs) and compact elliptical galaxies (cEs) has been blurred by the discovery of so-called ultracompact dwarfs (UCDs; Hilker et al. 1999; Drinkwater et al. 2000; Philipp et al. 2001; Haægæn et al. 2005). UCDs have been observationally defined (e.g., Hilker 2009; Brodie et al. 2011) to be compact stellar systems (CSSs) with luminosities \( (10^6 \lesssim L_V \lesssim 10^7 \, L_\odot) \) \( \sim 0.5–2.5 \) orders of magnitude higher than typical GCs and half-light radii \( (10 \lesssim r_h \lesssim 100 \, \text{pc}) \), which is at least several times larger than that of a typical GC. The intermediate nature of UCDs suggests that they may be either of galactic origin (e.g., remnants of tidally disrupted nucleated galaxies; Bekki et al. 2003; Goerdt et al. 2008; Pfeffer & Baumgardt 2013; Pfeffer et al. 2014) or the scaled-up version of otherwise “normal” GCs (amalgamation of super star clusters (SSCs); Fellhauer & Kroupa 2002; monolithic collapse of giant gaseous clumps; Murray 2009).

It is non-trivial to differentiate between different formation mechanisms for UCDs, due partly to the lack of a complete theory for the formation of massive star clusters (see Kruĳssen 2015; Pfeffer et al. 2018, for some recent development), and partly due to the utmost difficulty in detecting kinematical signatures of dark matter halos (if any) in CSSs (e.g., Frank et al. 2011). Circumstantial evidence for the galactic origin of some UCDs include kinematical signatures of massive black holes (e.g., Mieske et al. 2013; Seth et al. 2014; Ahn et al. 2017), signatures of tidal accretion events (e.g., Norris & Kannappan 2011; Jennings et al. 2015; Voggel et al. 2016), extended stellar envelopes (e.g., Liu et al. 2015), and extended star formation histories (Norris et al. 2015). The richness of both the UCD and GC systems appears to be most strongly correlated with the gravitational potential well in which the host galaxies reside (e.g., Liu et al. 2015; Harris...
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Section 2.1. GCs and UCDs around M87

The parent samples of GCs and UCDs around M87 are selected based on the optical $u^*$, $g$, $r$, $i$, $z$ imaging data from the Next Generation Virgo Cluster Survey (NGVS; Ferrarese et al. 2012) and the near-IR $K_s$-band imaging data from the NGVS-IR project (Muñoz et al. 2014). The broad available wavelength coverage, from $u^*$ to $K_s$, gives great leverage to efficiently distinguish the majority of Virgo CSSs and galaxies from the foreground stars and background galaxies (Muñoz et al. 2014). In addition, the exquisite spatial resolution of the NGVS images (PSF FWHM ~0.5 pixel in $i$ band) of the NGVS images allows us to separate the Virgo UCDs ($r_h \geq 10$ pc) from GCs ($r_h < 10$ pc). Details about the selection of the UCD and GC samples are given, respectively, in Liu et al. (2015) and E. Peng et al. (2018, in preparation). As in Zhang et al. (2015), the full samples of GCs and UCDs are divided into “blue” and “red” subpopulations at $(g-i) = 0.89$ mag.

2.1.2. Lick Indices of GCs and UCDs from New Spectroscopic IMACS Observations

We obtained optical spectra of 18 UCDs and 51 GCs with $g \leq 22$ mag, using the IMACS multi-slit spectrograph on the 6.5 m Magellan Baade telescope in 2016 March (observing run CN2016A-58). The observations were made with the t/2 camera (FOV: ~27.5 × 27.5, the 300 mm $^{-1}$ grism (1.341 Å/pixel), and a slit width of 1”. The wavelength coverage is ~3900–9000 Å. The spectral resolution is ~6.5 Å.

We used the photometric sample as an input catalog for mask design and observed two masks, with one centered on M87 and the other one offset by 15$'$ to the NW along the major axis of M87 (see Figure 1). The integration time was 3.5 hr per mask. We also observed seven Lick/IDS standard stars of different spectral types (F9 to K1) for calibration purposes. The raw data were reduced with the COSMOS16 package. The spectral extraction and redshift measurement were respectively carried out using the IRAF APALL and FXCOR tasks. Finally, the spectra were degraded to the wavelength-dependent Lick/IDS resolution (see, e.g., Puzia et al. 2013), and then de-redshifted to the rest frame to be prepared for measuring the four Lick indices $H/\beta$, $Mgh$, Fe5270, and Fe5335.

The spectral S/N steadily decreases for fainter objects, with an $S/N$ at 5000 Å of ~30 pixel$^{-1}$ at $g \approx 19.5$ mag and ~5 pixel$^{-1}$ at $g \approx 22$ mag. For objects brighter than 19.5 mag, the Lick indices are directly measured on the individual spectrum. For objects fainter than 19.5 mag, the Lick indices are measured on the stacked spectra of the blue or red subpopulations in three $g$ mag bins divided at $g = 20$ and 21 mag (see Figure 2). The stacking is made over each Lick-index spectral window (encompassing both the feature and pseudo-continuum bandpasses) separately. For each index, the uncertainty is calculated using the standard deviation of the fits.

15 The corresponding paper lists the index values for $H/\beta$, $Mgh$, Fe5270, and Fe5335.

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The red and blue small dots, respectively, represent the photometrically selected GCs and UCDs. The red and blue circles, respectively, show the GCs and UCDs with geometric average radius of 30 Lick-index measurements. The thin dashed ellipse marks one effective radius of the number density profile of the UCD system, and the thick dashed ellipse marks a geometric average radius of 30', which encloses the GCs and UCDs with Lick-index measurements.

Within the same magnitude limit and maximum radius, there are 143 UCDs and 1565 GCs in our photometric sample. The spatial distribution of the photometric and Lick-index samples at $g < 22$ mag is shown in Figure 1.

Figure 2 shows the $(g-i)$ versus $g$ color–magnitude distribution of different subsamples. Normalized running-bin histograms of the colors and magnitudes are also shown. The Lick-index sample of UCDs is fairly representative of the corresponding photometric sample both in color and magnitude. The Lick-index sample of GCs has a disproportionately larger fraction of redder and brighter GCs than the photometric sample.

2.2. Lick Indices of dE Nuclei, cEs, and Non-M87 UCDs from the Literature

Besides the M87 GCs and UCDs, we also consider the literature Lick-index samples of the nuclei of Virgo dE galaxies, cEs, and UCDs not belonging to M87, for comparison purposes. We restrict the selection of literature samples to those with either published Lick/IDS indices or stellar population parameters estimated with the same population model adopted in this work, for optimal consistency.

Paudel et al. (2011, hereafter P11) and Spengler et al. (2017, hereafter S17) respectively presented Lick/IDS index measurements for 26 and 19 dE nuclei in the Virgo cluster. To avoid potential biases of the Lick-index measurement at low spectral $S/N$, we opt to only include the dE nuclei with the measurement uncertainties of the H/β and Mg$b$ indices $\delta_{H/\beta, \text{Mg} b} < 0.5$ Å and of Fe5270 and Fe5335 indices $<0.6$ Å, corresponding to a spectral $S/N \geq 15 \text{ Å}^{-1}$. With these selection criteria, we end up with 24 unique dE nuclei (20 from P11 and 4 from S17).
In addition, Janz et al. (2016) presented Lick-index-based stellar population modeling of a sample of 1 ultra-luminous GC (M85-HCC1), 1 M87 UCD, 10 non-M87 UCDs, and 17 cEs in the Virgo cluster and other environments. These objects have been discovered by various earlier studies (see Janz et al. 2016 for references). The 10 non-M87 UCDs include 4 (M59-UCD3, M60-UCD2, M60-UCD1, M59cO) in the Virgo cluster and 6 associated with S0 or ellipticals in group environments. Janz et al. (2016) did not publish their Lick-index measurements. However, Janz et al. (2016) used the stellar population model of Thomas et al. (2011, hereafter T11), as we have done in this work (see below), for fitting the Lick indices. So we can directly use the stellar population parameters published by Janz et al. (2016) in our comparative analysis. Lastly, Lick/IDS indices of 5 cEs in the Coma cluster as reported by Price et al. (2009) will also be included in our analysis.

3. Analysis

3.1. Stellar Population Parameters

We estimate the ages, metallicities [Z/H], and [α/Fe] of M87 GCs and UCDs by fitting the T11 models to the measured Lick/IDS indices, following a procedure similar to that in Puzaia et al. (2005) and Graves & Schiavon (2008). In particular, we adopt the Hβ–[MgFe]' and Mg b–(Fe) diagnostic diagrams (Figure 3), where

\[
[MgFe]' = \sqrt{Mg b(0.72 \times Fe5270 + 0.28 \times Fe5335)}
\]

\[
(Fe) = (Fe5250 + Fe5335)/2
\]

(see Thomas et al. 2003), and iteratively invert the location of the measured indices on the two diagrams to stellar population parameters until a convergence is achieved. At each iteration, the ages and [Z/H] constrained by the Hβ–[MgFe]' diagram are used as input to constrain the [α/Fe] through the Mg b–(Fe) diagram. Because P11 and S17 adopted stellar population models that are different from our choice for fitting Lick/IDS indices, we choose to re-determine the stellar population parameters of their samples with the T11 model, in order to avoid model-dependent systematic biases in our comparative analysis. It is no doubt that using more Lick indices would offer stronger stellar population diagnostic power. Our choice of the four most commonly used Lick/IDS indices in the analysis is driven by the availability of such measurements in the literature.

The uncertainties of [Z/H], ages, and [α/Fe] are estimated by repeating the grid inversion for 150 realizations of the Lick indices of each object generated by randomly adding noise to the fiducial values according to their uncertainties. For objects that fall outside the model grid along the [Z/H] (−2.25 to +0.67 dex) and [α/Fe] (−0.3 to +0.5 dex) dimensions, we do a linear extrapolation of the model grid. To those objects...
Table 1

Lick Indices of M87 UCDs and GCs Measured Based on Magellan/IMACS Observations

| ID               | N    | $g$ (mag) | $\mu(g)$ (mag) | $(g - i)$ (mag) | $\mu(g - i)$ (mag) | Hβ (Å) | Mg$b$ (Å) | Fe5270 (Å) | Fe5335 (Å) | SNR/pix | Age (Gyr) | [Z/H] (dex) | [$\alpha$/Fe] (dex) | log($M_*/M_{\odot}$) | Comment |
|------------------|------|-----------|----------------|----------------|-------------------|---------|-----------|-----------|-----------|---------|-----------|--------------|-------------------|------------------|----------|
| bGC_stack.g20.6  | 21   | 19.95–20.96 | 20.63 | 0.64–0.89 | 0.78 | 2.18 ± 0.15 | 1.84 ± 0.13 | 1.20 ± 0.13 | 0.93 ± 0.14 | 68.4 | 12.2±0.3 | −1.1±0.2 | 0.66±0.1 | 6.5±0.3 | 7 in C98 |
| bGC_stack.g21.4  | 15   | 21.19–22.00 | 21.42 | 0.66–0.83 | 0.72 | 2.36 ± 0.34 | 1.45 ± 0.29 | 1.55 ± 0.30 | 1.17 ± 0.32 | 31.4 | 7.8±5.8 | −0.96±0.16 | 0.11±0.01 | 0.25 | 6.0±0.27 |
| rGC_stack.g20.7  | 4    | 20.29–20.90 | 20.69 | 0.91–1.04 | 0.94 | 2.28 ± 0.33 | 3.32 ± 0.28 | 2.21 ± 0.30 | 1.83 ± 0.30 | 31.5 | 3.6±4.7 | −0.02±0.17 | 0.42±0.10 | 0.24 | 6.4±0.26 |
| rGC_stack.g21.3  | 11   | 21.16–21.45 | 21.31 | 0.90–1.02 | 0.93 | 1.87 ± 0.37 | 3.43 ± 0.32 | 2.06 ± 0.32 | 2.02 ± 0.31 | 29.1 | 10.6±6.4 | −0.23±0.16 | 0.41±0.14 | 0.15 | 6.4±0.24 |
| bUCD_stack.g19.7 | 4    | 19.59–19.99 | 19.74 | 0.66–0.88 | 0.78 | 2.16 ± 0.19 | 1.62 ± 0.18 | 1.48 ± 0.18 | 1.29 ± 0.19 | 33.4 | 11.2±3.9 | −1.0±0.12 | 0.31±0.21 | 0.13 | 6.8±0.11 |
| bUCD_stack.g20.4 | 12   | 20.14–20.87 | 20.42 | 0.64–0.81 | 0.71 | 2.22 ± 0.18 | 1.06 ± 0.16 | 1.31 ± 0.17 | 1.02 ± 0.17 | 56.4 | 11.1±3.3 | −1.31±0.14 | 0.1±0.19 | 0.19 | 6.5±0.12 |
| H55930 (bUCD)    | 1    | 19.16–19.16 | 19.16 | 0.75–0.75 | 0.75 | 2.52 ± 0.23 | 2.20 ± 0.21 | 0.80 ± 0.24 | 0.24 ± 0.27 | 38.7 | 8.6±3.4 | −1.2±0.2 | 0.1±0.34 | 0.15 | 7.0±0.12 |
| VUCD3 (rUCD)     | 1    | 18.78–18.78 | 18.78 | 1.07–1.07 | 1.07 | 1.22 ± 0.17 | 5.18 ± 0.14 | 2.66 ± 0.15 | 2.37 ± 0.15 | 61.8 | 15.0±0.0 | 0.12±0.1 | 0.48±0.08 | 0.05 | 7.7±0.02 |

Note. (1) ID. “bGC” and “rGC” respectively refers to blue and red GC, and “bUCD” and “rUCD” respectively refer to blue and red UCD. (2) Number of objects used for the spectral stacking. (3) $g$-mag range. (4) Median $g$ mag. (5) $g − i$ color range. (6) median $g − i$. (7–10) Lick/IDS indices. (11) S/N at 5000 Å of the stacked or single spectra used for Lick-index measurement. (12–14) Stellar population parameters derived by fitting with the Thomas et al. (2011) model. (15) Stellar masses. (16) Number of objects in common with Cohen et al. (1998, hereafter C98) or Evstigneeva et al. (2007, hereafter E07).
falling below the oldest iso-age grid of 15 Gyr (see the “Hβ anomaly” in Figure 3, see also Poole et al. 2010), we assign an age of 15 Gyr. We emphasize that an extrapolation of model grids is necessary mainly for ([α/Fe]) but not for [Z/H] for our objects, so the following analysis in this paper will be mostly quantitative for [Z/H] but qualitative for [α/Fe] and ages. The prime model-dependent uncertainties in our stellar population modeling are from the age estimates, due to the uncertain modeling of the Hβ index. As we will present below, all of the UCDs and a vast majority of GCs have best-fit ages ≥ 8 Gyr. A scatter of age estimates from 8 to 15 Gyr induces <0.2 dex uncertainty in the estimates of [α/Fe] and [Z/H] (T11).

3.2. Stellar Masses

Since the T11 models do not make predictions on the stellar mass-to-light ratio, $M_*/L$ and thus $M_*$, of M87 GCs, UCDs, de nuclei, and the cEs from Price et al. (2009), with the ages and [Z/H] from our Lick-index-modeling as input. For the non-M87 UCDs and the remaining cEs, we use the stellar mass as reported in Janz et al. (2016).

We note that several recent studies of extragalactic GCs found an apparent anti-correlation between the dynamical mass-to-light ratios and metallicities (e.g., Strader et al. 2011b), which is contrary to the predictions of the current stellar population synthesis models. Such anti-correlation, if real, may be driven by a metallicity-dependent variation of the stellar initial mass function (IMF). Nevertheless, more sophisticated modeling of the internal kinematics of MW GCs did not find such an anti-correlation, and instead found dynamical mass-to-light ratios that were in general agreement with those predicted by current stellar population models with a Kroupa or Chabrier IMF, with a possible exception for the metal-rich GCs (Baumgardt 2017).

4. Results

4.1. Distributions of GCs and UCDs in the Lick/IDS Index–Index Diagrams

The strength of the Hβ and [MgFe]′ indices respectively serve as the optimal age and [Z/H] indicators, whereas the index ratio $\text{Mgb}/(\text{Fe})$ serves as a good indicator of the α-element enhancement, especially at higher [Z/H] (Thomas et al. 2003). We have performed a weighted linear orthogonal distance regression (ODR) to the respective distributions of M87 GCs and UCDs in the two diagrams in Figure 3. The best-fit lines are overplotted, and the best-fit equations are listed below:

$$H\beta = -0.23[\text{MgFe}]′ + 2.33, \ \sigma = 0.29 \, \text{Å}, \ \text{GCs},$$
$$H\beta = -0.32[\text{MgFe}]′ + 2.52, \ \sigma = 0.19 \, \text{Å}, \ \text{UCDs},$$
$$\text{Mgb} = 2.20(\text{Fe}) - 1.04, \ \sigma = 0.19 \, \text{Å}, \ \text{GCs},$$
$$\text{Mgb} = 2.23(\text{Fe}) - 0.98, \ \sigma = 0.22 \, \text{Å}, \ \text{UCDs}.$$
than UCDs. For the $\mathrm{Mg}\,b – \mathrm{Fe}$ distributions, GCs and UCDs have about the same $\sigma$ around their best-fit relations.

4.2. Relations between $[\mathrm{Z}/\mathrm{H}]$, $[\alpha/\mathrm{Fe}]$, $M_*$, and Ages of CSSs

Before proceeding to present our findings for Virgo UCDs and GCs and comparing with other types of CSSs, we briefly mention the relevant results from previous studies that are based on samples overlapping with ours. For Virgo UCDs, previous studies of a dozen luminous UCDs (see references in Section 2.1.1) found that UCDs generally have old ages ($\gtrsim 8–10$ Gyr) and super-solar $[\alpha/\mathrm{Fe}]$. For Virgo dE nuclei, Paudel et al. (2011) found a luminosity-metallicity correlation and a positive correlation between $[\alpha/\mathrm{Fe}]$ and a local projected number density of galaxies. They also found that the dE nuclei in lower-density environments span a larger range of ages and $[\mathrm{Z}/\mathrm{H}]$ that extends to younger and higher values. Regarding the comparison of the luminous Virgo UCDs and dE nuclei, Paudel et al. (2010) found that dE nuclei located in high-density environments share similar stellar population properties (old ages and higher metal abundances) to UCDs. Lastly, Janz et al. (2016) noticed that, unlike lower-mass CSSs, which have a large range of $[\mathrm{Z}/\mathrm{H}]$, CSSs more massive than a few times $10^7 \, M_\odot$ are exclusively metal-rich and deviate from the mass–metallicity relation (MZR) of ordinary galaxies toward higher metallicities at given stellar masses.

Having collected a larger sample of Virgo UCDs and GCs with available spectroscopic stellar population parameters, we revisit the relationship between the $[\mathrm{Z}/\mathrm{H}]$, $[\alpha/\mathrm{Fe}]$, $M_*$, and ages of different types of CSSs. The relevant diagrams are shown in Figures 4 and 5. In the following subsections, we describe the most noteworthy trends shown in the figures.

4.2.1. $M_*–[\mathrm{Z}/\mathrm{H}]$ Relations

We observe a positive mass–metallicity, i.e., $M_*–[\mathrm{Z}/\mathrm{H}]$, relation (MZR) for UCDs, with a Spearman’s rank correlation coefficient $\rho$ of 0.76 for the M87 UCDs alone. The probability $p$ of the null hypothesis of no MZR is $9.9 \times 10^{-7}$. We fit a linear relation to the M87 UCDs with the weighted ODR method. The line of the best fit is overplotted in Figure 4, and the best-fit parameters are given in Table 2. The standard deviation of $[\mathrm{Z}/\mathrm{H}]$ around the best-fit relation is 0.35 dex, which is larger than the median of the measurement uncertainties of $[\mathrm{Z}/\mathrm{H}]$ (0.12 dex). The MZR of UCDs extends up to $\log(M_*/M_\odot) \approx 8.0$ and $[\mathrm{Z}/\mathrm{H}] \approx 0.2–0.3$. At log $(M_*/M_\odot) \gtrsim 8.0$, the massive UCDs overlap with cEs on the $M_*–[\mathrm{Z}/\mathrm{H}]$ plane, and the MZR flattens and “saturates” at $[\mathrm{Z}/\mathrm{H}] \approx 0.2$ dex, with a substantial scatter (see also Janz et al. 2016).

The Lick-index sample of GCs is not very representative of the photometric sample on the color–magnitude diagrams (e.g., Figure 2). We alleviate the potential effect of this sample bias on the weighted MZR fitting of GCs by re-weighting the data points. In particular, we divide the $(g – i)$ versus $g$ plane into 0.05 × 1.0 mag cells, and then in each cell the data points are re-weighted by multiplying the measurement uncertainties by the square root of the number count ratio of the Lick-index sample and the photometric sample. The best-fit MZR for the re-weighted sample of GCs is overplotted in Figure 4, and the best-fit parameters of MZRs with/without re-weighting the data points are given in Table 2. We note that the best-fit MZRs do not change significantly after re-weighting the data points.

The GCs as a whole exhibit a much weaker mass–metallicity correlation than the UCDs (Table 2). However, if only considering GCs with ages as old as UCDs, i.e., $\gtrsim 8$ Gyr (e.g., panel (b) of Figure 5), there is a stronger and more significant MZR than the full sample of GCs. The GCs follow a steeper MZR than the UCDs, and the systematic offset between the average MZRs of the two becomes larger at higher stellar masses. To further quantify the significance of the difference between the mass–metallicity distributions of GCs and UCDs, we perform a two-dimensional KS test, following the numerical recipes described in Press et al. (2002). The KS test suggests a 0.4% (or 1.8%) chance that the UCDs and GCs (or GCs $\gtrsim 8$ Gyr) are drawn from the same underlying distribution. The stronger MZR of the (M87) UCDs as compared to the GCs can be partly attributed to a larger range of stellar masses. In particular, if dividing the UCDs at $\log(M_*/M_\odot) = 7.0$ (i.e., the upper mass limit for GCs), neither the higher-mass nor the lower-mass UCDs exhibit a correlation with a significance level $p$ comparable to that of the full sample (Table 2).

All but three of the M87 UCDs in our sample are classified as blue UCDs, so we do not attempt to discuss the difference between the mass–metallicity distributions of the blue and red UCDs. For GCs, we present the best-fit MZR parameters for the blue and red subpopulations in Table 2. The mass–metallicity correlations for the blue and red GCs are generally weak.

The Virgo dE nuclei appear to mostly follow the MZR established by UCDs, with $\rho = 0.55$ and $p = 0.006$. However, we point out that there may be a population of low-mass dwarf nuclei that did not pass our data quality selection function due to their low luminosities. Such objects may, in fact, have stellar masses and metallicities similar to those of red GCs. Deeper spectroscopic observations are required to illuminate this aspect.

4.2.2. $[\mathrm{Z}/\mathrm{H}]–[\alpha/\mathrm{Fe}]$ Relations

The Lick indices analyzed here provide weaker constraints on $[\alpha/\mathrm{Fe}]$ at lower $[\mathrm{Z}/\mathrm{H}]$ (see Figure 3). With this limitation in mind, we note that the M87 UCDs have overall higher $[\alpha/\mathrm{Fe}]$ at given $[\mathrm{Z}/\mathrm{H}]$ (with substantial scatter) than the non-M87 UCDs, which are located in lower-density environments. At $[\mathrm{Z}/\mathrm{H}] \lesssim -0.5$, dE nuclei, M87 UCDs, and blue GCs occupy a very similar parameter space in $[\alpha/\mathrm{Fe}]$ and $[\mathrm{Z}/\mathrm{H}]$. However, at $[\mathrm{Z}/\mathrm{H}] \gtrsim -0.5$, the Virgo dE nuclei generally have lower $[\alpha/\mathrm{Fe}]$, approaching solar abundance ratios, compared to the M87 UCDs, (red) GCs, and cEs.

4.2.3. Trends with Ages

As a primary age indicator, the H/β absorption index is subject to various modeling uncertainties, such as the uncertain HB morphology, blue straggler stars, and stellar chromospheric emission fill-in from flaring stars (e.g., Lee et al. 2000; Poole et al. 2010). Therefore, the age estimates presented here should be interpreted with caution. With these uncertainties in mind, we note that the youngest UCDs, GCs, and dE nuclei are nearly exclusively the metal-rich ones, while those with older ages span a larger range of $[\mathrm{Z}/\mathrm{H}]$ (panel (b) of Figure 5). In addition, the lower-mass GCs span a larger range of ages toward younger values (panel (c)), which, if real, might be explained if the recently accreted dwarf galaxies host a large...
fraction of relatively younger and lower-mass GCs (e.g., Usher et al. 2015; Y. Ordenes-Briceño et al. 2018, in preparation).

5. Discussion and Summary

5.1. The Mass–Metallicity Relation (MZR) of UCDs

A tight optical color–magnitude relation for M87 UCDs was first noticed by Brodie et al. (2011), who also found that the color–magnitude relation of UCDs is offset to colors that are bluer than that of blue GCs, but has a good coincidence with that of Virgo dE nuclei. A recent study by Liu et al. (2015) with larger samples largely corroborated these findings. Here, we confirm that the color–magnitude relation of UCDs results from a remarkable MZR, and the offset from blue GCs or coincidence with dE nuclei is also explained by their different or similar average MZR.

The existence of an MZR might suggest a mass-dependent self-enrichment (e.g. from supernova ejecta and stellar winds) within proto-cluster clouds. The deeper potential well of more massive systems means a higher retention efficiency of self-enriched gas that may be incorporated into the nearly simultaneous formation of low-mass stars or even the formation of subsequent stellar generations. This self-enrichment scenario (e.g., Bailin & Harris 2009) has been invoked to explain the observed color–magnitude correlation, also known as the “blue tilt,” of the blue GCs (e.g., Mieske et al. 2006; Strader et al. 2006; Peng et al. 2009).

The observed MZR of UCDs appears to “define” the lower bound of the metallicity distribution of GCs at a given stellar mass (Figure 4). In a self-enrichment scenario, this might be simply explained by the larger physical size of UCDs. If the UCDs were born (through monolithic clump collapse) with larger half-mass radii, either due to the larger sizes or the shallower density profiles of the proto-cluster clouds, then at a given mass and star formation efficiency, the proto-cluster clouds of UCDs have lower gravitational potential energy (i.e. lower escape velocities, see also Janz et al. 2016), and thus lower metal retention efficiencies than those of normal GCs.

Alternatively, if UCDs were primarily formed as dissipationless mergers of SSCs or ordinary GCs, they would also be expected to be larger and less metal-rich than GCs (formed in monolithic collapsed clouds) of the same masses, because the merge increases the masses but not metallicities. Such merging can happen in extreme starburst environments (Fellhauer & Kroupa 2002) or nuclear regions of galaxies (e.g., Lotz et al. 2001; Milosavljević 2004; McLaughlin et al. 2006; Antonini et al. 2015). The latter possibility corresponds to the stellar cluster infall (driven by dynamical friction) scenario commonly invoked to interpret the formation of nuclear stellar clusters. Nevertheless, it is still to be seen how these dissipationless processes can result in a remarkable MZR rather than a wide spread of masses (or metallicities) for given metallicities (or masses). Lastly, if UCDs were initially formed as the stellar nuclei of (dwarf) galaxies and star formation efficiency in the nuclei was lower than similarly massive star

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**Figure 4.** Mass–metallicity distributions of the whole sample of CSSs. In the figure legend, “rGC” and “bGC” refer to the red and blue GCs, respectively. M85-HCCI is the densest known star cluster (r<sub>90</sub> ≈ 1.8 pc) discovered by Sandoval et al. (2015). The best-fit MZRs of M87 UCDs and GCs, as derived from a weighted ODR method, are marked as thick blue and thin black solid lines, respectively, with the dashed lines being the median 1σ scatter of [Z/H] around the relations. The best-fit parameters are given in Table 2. The black dashed line marks the average MZR followed by dwarf galaxies with masses log(M/M<sub>☉</sub>) < 9.5 (Kirby et al. 2013) and massive galaxies with log(M/M<sub>☉</sub>) > 9.5 (Gallazzi et al. 2005).
clusters formed in isolation, they would also be expected to have lower metallicities than ordinary GCs for given stellar masses.

Pfeffer et al. (2016) studied the formation of tidally stripped nuclei in the Fornax- and Virgo-like galaxy clusters using a semi-analytic galaxy formation model (Guo et al. 2011), and they predicted an average MZR for the stripped dE nuclei (log [Fe/H] = −2.0 + 0.2 log (M*/M⊙) for the Fornax and Virgo combined) that is much shallower than our observed MZR of M87 UCDs. This difference appears to be in disfavor with most UCDs (regardless of masses) being formed as tidally stripped dE nuclei. However, we note that the Pfeffer et al. (2016) model does not have a self-consistent treatment of the formation of nuclear clusters in galaxies of different masses and instead assigns metallicities to the stripped nuclei based on a fixed metallicity offset between the nuclei and their host galaxies. Therefore, it might still be premature to draw firm conclusions based on a comparison between the observed UCDs and the predicted stripped dE nuclei.

5.2. Implications for the Origin of UCDs

The Virgo dE nuclei have ages ranging from ~2 to 14 Gyr, whereas the M87 UCDs are almost exclusively ≥ 8 Gyr, in agreement with previous studies based on smaller samples. Moreover, at [Z/H] ≥ −0.5, the dE nuclei have smaller [α/Fe] ratios and thus star formation timescales longer than M87 UCDs (assuming equal IMFs and pre-enrichment). It is known that these young, metal-rich, and less α-enhanced dE nuclei are almost exclusively found in relatively low-density environments (Paudel et al. 2011; Liu et al. 2016). Nevertheless, we find a similar environment-dependent difference between the M87 UCDs and non-M87 UCDs that are located in lower-density regions, in the sense that the non-M87 UCDs have...
overall lower [$\alpha$/Fe] enhancements and extend to younger ages than the M87 UCDs. Despite the above differences, the similar MZR of UCDs and dE nuclei implies a similar mass-dependent metal-enrichment history. The offset of the M87 blue GCs toward higher metallicities relative to this MZR is in line with an offset of blue GCs of other brightest cluster galaxies toward redder colors relative to the average color–magnitude relation of dE nuclei (Harris et al. 2006). While these observations do not necessarily mean that tidally stripped present-day dE nuclei are the primary contributors to the UCD population, they do suggest that the majority of GCs do not originate as stripped dE nuclei observed today. As discussed above, the difference between the mass–metallicity distribution of UCDs and normal GCs can be qualitatively understood as being simply due to a size difference, and (thus) the similar MZR of UCDs and dE nuclei could merely be a coincidence.

Above all, there is no significant difference between the stellar population parameters of UCDs and dE nuclei, as long as the environmental dependence is taken into account. This probably provides a necessary condition for favoring a galactic origin for most UCDs, but not a sufficient condition for ruling out that many UCDs (at least in M87) can be formed as the most massive and extended tails of the GC populations. In the former scenario, the system of UCDs is expected to have radially biased orbital structures, because only on highly radially biased orbits can nucleated dEs plunge deep into the central potential of the host galaxy in order to be tidally shredded to a naked nucleus. Such radially biased orbital anisotropies are indeed inferred for the M87 UCDs (Zhang et al. 2015). In the latter scenario, the UCD population may have been primarily formed in situ at early epochs or accreted from halos of earlier generations of dwarf galaxies that were characterized by larger average masses and more radially biased orbital structures than the more recently accreted dwarfs. The observed velocity field of blue GCs in M87 resembles that of the dE galaxies better than the UCDs, indicating that the blue GC population may have been continuously growing through accretion until the present-day. Whichever scenario is true for the Virgo core region, the present-day UCD system has been formed or/and assembled over a shorter timescale than the blue GC system.

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Table 2

Orthogonal Distance Regression to log[Z/H] = a + b × log(M/M_☉)

| Subpopulation | a   | b   | $q_{\chi2}$ | $q_{\chi2}$ | $\rho$ | $\rho$ |
|---------------|-----|-----|-------------|-------------|-------|-------|
| UCD           | −10.17 | 1.07 | 1.32 | 0.15 | 0.35 | 0.76 | 9.4e-7 |
| UCD(>10^7 M_☉) | −12.05 | 1.77 | 1.25 | 0.24 | 0.26 | 0.75 | 7.3e-3 |
| UCD(<10^7 M_☉) | −2.89 | 1.95 | 1.25 | 0.29 | 0.41 | 0.41 | 8.2e-2 |
| GC            | −16.08 | 2.03 | 2.31 | 0.31 | 0.58 | 0.32 | 4.4e-3 |
| GC(rw)        | −17.61 | 2.47 | 2.56 | 0.38 | 0.76 | 0.32 | 4.4e-3 |
| GC(>8 Gyr)    | −16.60 | 2.16 | 2.38 | 0.32 | 0.47 | 0.60 | 2.5e-7 |
| GC(>8 Gyr, rw)| −16.98 | 2.38 | 2.45 | 0.37 | 0.51 | 0.60 | 2.5e-7 |
| bGC           | −6.48 | 1.40 | 0.83 | 0.21 | 0.52 | 0.20 | 1.4e-1 |
| bGC(>8 Gyr)   | −7.08 | 1.45 | 0.91 | 0.22 | 0.42 | 0.45 | 1.9e-3 |
| rGC           | −5.86 | 2.08 | 0.84 | 0.31 | 0.50 | 0.11 | 6.1e-1 |
| rGC(>8 Gyr)   | −6.67 | 2.18 | 0.95 | 0.32 | 0.32 | 0.42 | 7.2e-2 |

Note. The weighted orthogonal distance regression to the mass–metallicity distributions of different subpopulations in M87 are given in columns 2–5 and the standard deviations of [Z/H] around the best-fit relations are given in column 6. The spearman’s ranking correlation coefficient $\rho$ and the two-sided p-values are given in columns 7–8. GC(rw) and GC(>8 Gyr, rw) respectively refer to the fitting to the samples of GC and GC(>8 Gyr) by re-weighting the data points in order to account for the biases of the Lick-index sample with respect to the photometric sample on the (q – i) versus q color–magnitude diagram (see Section 4.2.1 for details).
